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Combined economic and emission dispatch considering conventional and wind power generating units

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Abstract

Combined economic and emission dispatch (CEED) is an optimization solution to the short-term demand and supply balancing in the power network. Given that wind power is playing an increasing role in the UK, this paper develops a CEED model for a combined conventional and wind power system under the UK energy policies. The proposed model aims to determine the optimal operation strategy for the given system with the consideration of wind power curtailment and reservation and also the environmental aspect, especially the carbon price of greenhouse gases (GHG) and emission limits of decarbonisation scenarios. From two case studies, increasing the carbon price at a low emission limit leads to an increase in the total cost, but the rate of the increase is mitigated on decreasing the emission limits. Moreover, dispatch is dominated by the carbon price at high emission allowance levels and by the emission allowance at low emission allowances.

Keywords: Combined economic and emission dispatch; wind power; carbon price.

1. Introduction

With the rise in the global development, energy plays an increasingly important role in the world; recognising that concern over increasing greenhouse gas emissions is

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driving a replacement of conventional power sources with renewables. In the context of the UK, the main energy resources are coal, oil, natural gas, nuclear, and some renewables, such as solar PV and wind [1], with a growing emphasis on wind.

Wind energy constituted 20.8 % of the renewable energy production in the UK in 2015 [2]. The Department of Energy and Climate Change (DECC) indicated that in 2020, wind power will increase to 24 % to 38 % of the total renewable energy in the UK.

In addition, to improve the environmental conditions and reduce the greenhouse gases, the greenhouse gases that are emitted by the power plants, factories and other fixed installations are limited by emission allowances. These emission allowances are stipulated by the European Union Emissions Trading System (EU ETS). Also, the EU ETS sets the carbon price [3]. In the longer term, the UK government committed that emissions will be reduced by over 80 % of the 1990 level, by 2050 [4].

Moreover, the UK government has three energy policy objectives, which are to keep the lights on, to keep energy bills affordable, and to decarbonise energy generation [5, 6]. In the energy market, enough energy supply is able to keep the lights on, a lower levelized cost of electricity will make energy bills affordable, and low carbon resources can help with decarbonisation. Nevertheless, most of the low carbon resources are high in cost [7]. Therefore the balance between fuel and emission cost is important to the future energy market.

Therefore, in order to balance fuel and emission cost, improved dispatch in the electricity grid is proposed. Initially, to consider the electricity grid balance in economic terms, the economic dispatch (ED) is introduced. The ED of thermal power generating units was proposed since 1920 or even earlier [8]. The selling and buying cost of the electricity is very important for cost estimation in an electrical market, especially the National Service Provider (NSP) and Independent Power Producer (IPP) owners contracts. Further, there are a number of research publications focusing on this aspect using the price or bid based ED models. The primary aim of the price-based ED model is to maximize the profit of the generation companies, which means maximizing the difference between the revenue and cost of generation [9]. Also, the bid-based ED models aim to maximize the social benefit, i.e. to maximize the difference between the benefit of the customer and cost of the generator, for the system operator, namely the NSP [10].

In this research, the objective is to minimize the generation and emission cost for a given electrical system for the NSP. The conventional generators belong to the NSP and the wind farm is owned by the IPP. In the UK electricity market, the Contracts for Difference (CFD) is specifically for the low carbon technology. The selling price of a low carbon electricity generator is split into the strike price of the technology and reference price of the electricity market. The difference between the strike price and the reference price will be paid by the Low Carbon Contracts Company (LCCC) [7]. In the UK electricity system, the NSP only needs to pay a fixed buying price (reference price) to wind power. Thus the selling price of the IPP does not impact on the NSP. In this paper, the profit of the NSP or IPP is not considered in this model. However, taking into consideration the real-time selling and buying cost of the electricity in an ED model can give the IPP or NSP a good view of the economic benefit.

With the growing environmental problems, combined economic and emission dispatch (CEED) models have been developed for an electrical system consisting of fossil-fired power plants in the 1990s [11-13]. Initially, the CEED considered only conventional powered generators [11-16]. Although the optimization algorithms are different, most of these studies used multi-objective optimisation to accomplish the balance between cost and emission minimizations. With the ever-increasing use of renewable power, the power system network now is not only allocating system power from conventional generators but also from renewable power plants, such as wind farms [17, 18], solar PV plants [19, 20] and hydro power stations [21, 22]. Due to the negligible emissions in renewable power generation, the dispatch of renewable resources does not have emission dispatch [8, 23]. Nowadays, wind power is in the top two of the renewable energies in the UK and still increasing [24]. Nonetheless, in the ED model that incorporates wind power, the unpredictable wind power outputs become a non-negligible problem. Uncertainty of conventional energy sources, such as cost and fuel inputs, are much lower and controllable than that of the wind power output.

In order to determine the uncertainty in wind power, some research has been performed on modelling the stochastic nature of the wind speed and the penalty and the reserves of wind power cost [17, 18, 23, 25]. First of all, Hetzer et al. [23] created a new ED model of a combination of the conventional power and wind-powered generators. They introduced direct, penalty and reserves wind power costs in to the ED problem. They also considered the uncertain nature of the wind speed by the Weibull distribution to solve the stochastic dispatch problem. In this model, the wind power scheduled from a particular generator is strongly dependent on the value of the reserves and penalty cost factors associated with that generator. This research transformed the wind power to a linear relationship with the wind speed. Further, Roy et al. [26] used the wind power of the turbine directly calculated from the wind speed, which is a cubic relationship between wind speed and wind power. This relationship has a smoother wind power output but is more complex in the wind power distribution expression. Then, Mondal et al. [27] introduced emission dispatch to the ED model by Hetzer et al. [23] using a gravitational search algorithm. They used price penalty factors to blend the emission with the normal fuel cost. However, they did not consider the emissions of penalty and reserve power emissions of the wind power in their research. Moreover, Jin et al. [18] added an environmental objective function of the emission as well as the penalty and reserves wind power costs. Also, they modelled the wind power output by the Weibull Gamma distribution. Additionally, Dubey et al. [25] applied a hybrid flower pollination algorithm to the CEED model by Jin et al. [18] with the time dimension.

With increasing carbon price [3], the carbon cost rises in proportion to the levelized cost of electricity (LCOE) and the carbon cap that was proposed by the EU ETS leads to a limited emission of a power plant/system. However, as of now, there appears to be no CEED model that considers the emission levels and carbon prices in the currently available technical literature. Therefore, a CEED model that considers wind powered generators and the emission allowances and carbon prices is investigated in this paper.

For most conventional power generation, there are three main types of emissions of greenhouse gases, namely CO_2, SO_x and NO_x [29, 30]. In the previous CEED problems that incorporate wind power, the investigations have only considered one emission function. Most of the recent papers that have focused on the optimisation algorithms have considered only NO_x emission [30-33]. In order to better analyse the effect of the carbon prices and emission levels for practical scenarios, all three emissions will be considered in the model developed in this research [5, 7].

This paper therefore develops a novel short-term CEED model, based on a one hour time step that can handle carbon price, emission levels and wind penetration level in future electrical systems in order to determine the optimal operation strategy. The proposed model aims to minimize the fuel and environmental cost for a system by considering the reservation and curtailment wind power cost and the carbon price of GHG. Moreover, the emission level is considered as the emission constraint to obtain the optimal results for different levels of decarbonisation scenarios. Three cases for each of the two electrical systems with six and nine conventional generators, respectively, and a large scale wind farm have been considered. Different levels of wind energy penetration are investigated, and the results demonstrated the interactions between carbon price, emission limits and wind penetration. The proposed CEED model showed the ability to optimize solutions effectively for the cases studied. The results show that at a low emission limit, increasing the carbon price leads to an increase in the total cost, but the rate of the increase is mitigated by decreasing the emission limits. Furthermore, the carbon price shows a high impact on the dispatch at high emission allowance levels and the emission limits dominate the dispatch at low emission allowance levels.

2. Methodologies

This paper is to investigate a CEED model that considers the emission allowances and carbon prices in a CEED problem incorporating conventional power and wind power generations, and investigate the influence of carbon price and emission limit on the dispatch in the power system.

2.1. *Objective functions*

The aim of the CEED is to operate the system under the minimum fuel cost and pollution conditions within the emission allowance. Thus two types of objective function should be considered. One of the objective functions is the cost function that is used to obtain the optimal power output with the minimal costs. As a short term ED, only fuel cost as a function of the generator power output is required for the conventional power generation. For wind power, in addition to the direct cost of wind powered generators, the costs for the overestimation and the underestimation of wind power generation have to be considered due to the uncertainty of the wind power.

The other type of the objective functions are emission functions that are used to obtain the minimal emission costs. Three objective functions will be used focusing on the minimization of the emissions of NO_x, SO_x and CO_2. By suitable manipulations, the generation cost and emissions can be placed on a comparable basis leading to a single fitness function encapsulating both costs and emissions. No contribution to the emission from wind power is considered.

2.1.1. *Cost functions*

The cost function $C(t)$ aims to minimize the running cost of the generators in the electrical power system. Both the conventional and the wind-powered generators need to pay an operational cost. Therefore, this cost function consists of four terms: the cost of conventional powered generators, the direct cost of wind powered generators, the costs of an overestimation and underestimation of wind power generation [16, 21, 23, 32]. It is defined as follows:

$$min\ C = \sum_{i=1}^{N} C_{\mathrm{p,i}}(P_{\mathrm{i}}) + \sum_{j=1}^{M} C_{\mathrm{W,j}}(W_{\mathrm{j}}) + \sum_{j=1}^{M} C_{\mathrm{OW,j}}(W_{\mathrm{j}} - W_{\mathrm{AV,j}}) + \sum_{j=1}^{M} C_{\mathrm{UW,j}}(W_{\mathrm{AV,j}} - W_{\mathrm{j}}) \tag{1}$$

The cost function of the conventional generator is usually assumed to be a cubic or quadratic function, consistent with the input-output curves of the particular types of fuel generators [35, 36]. The universal expression of the cost function is given as follows:

$$C_{\mathrm{p,i}}(P_{\mathrm{i}}) = a_{\mathrm{i}}P_{\mathrm{i}}^{3} + b_{\mathrm{i}}P_{\mathrm{i}}^{2} + c_{\mathrm{i}}P_{\mathrm{i}} + \alpha_{i} \tag{2}$$

The direct cost function of the wind powered generator is calculated from the scheduled wind power used in the electrical network. It is assumed to be a linear function of the scheduled wind power and reflects the payment to the wind farm operator for the wind power [18, 23]. It is defined as follows:

$$C_{\mathrm{W,j}}(W_{\mathrm{j}}) = g_{\mathrm{j}}W_{\mathrm{j}} \tag{3}$$

If the wind farm is owned by the system operator, then there is no wind power cost [18, 23] and g_{j} is 0.

The overestimation cost function of the wind powered generator is due to the available wind power being less than the scheduled wind power. The available wind power is the wind power available from the wind farm without any manipulations. This cost is for the reserve requirement related to the difference between the available wind power and the scheduled wind power [18, 23], namely

$$\begin{aligned} C_{\mathrm{OW,j}}(W_{\mathrm{j}} - W_{\mathrm{AV,j}}) &= k_{\mathrm{O,j}} \times (W_{\mathrm{j}} - W_{\mathrm{AV,j}}) \\ &= k_{\mathrm{O,j}} \times (\int_{0}^{W_{\mathrm{j}}} (W_{\mathrm{j}} - w) f_{\mathrm{W}}(w) dw + W_{\mathrm{j}} \times Pr\{w = 0\}) \end{aligned} \tag{4}$$

where $Pr\{w = 0\}$ is the probability of wind power being zero. This equation is used to find the cost when the available wind power is less than the scheduled wind power. Similar to the overestimation cost function, the underestimation cost function of the wind powered generator is due to the penalty cost for not using all the available wind power [18, 23], namely

$$C_{\mathrm{UW,j}}\left(W_{\mathrm{AV,j}} - W_{\mathrm{j}}\right) = k_{\mathrm{U,j}} \times \left(W_{\mathrm{AV,j}} - W_{\mathrm{j}}\right)$$

$$= k_{\mathrm{U,j}} \times \left(\int_{W_{\mathrm{j}}}^{W_{\mathrm{j,rated}}} (w - W_{\mathrm{j}}) f_{\mathrm{W}}(w) dw + (W_{\mathrm{j,rated}} - W_{\mathrm{j}}) \times Pr\{w = W_{\mathrm{j,rated}}\}\right) \quad (5)$$

where $Pr\{w = W_{\mathrm{j,rated}}\}$ is the probability that the wind power is rated. Similar to Equation (4), this equation is used to find the cost when the available wind power is higher than the scheduled wind power.

2.1.2. Emission functions

The emission function is to minimize the pollutant emission from conventional power generation including the oxides of carbon, sulphur and nitrogen. Assuming that the wind power does not produce these pollutants, and the reserve power is from energy storage that also does not produce pollutants, the emission function contains the conventional power generators only [31], namely

$$min\, E = \sum_{i=1}^{N} E_{\mathrm{p,i}}^{\mathrm{NO_x}}(P_{\mathrm{i}}) + E_{\mathrm{p,i}}^{\mathrm{SO_x}}(P_{\mathrm{i}}) + E_{\mathrm{p,i}}^{\mathrm{CO_2}}(P_{\mathrm{i}}) \quad (6)$$

The emission function of the conventional powered generator is related to the cost function with the emission rate of the energy output for a given type of generator [31, 36], namely

$$E_{\mathrm{p,i}}^{\mathrm{NO_x}}(P_{\mathrm{i}}) = cf_{NOx} \times (d_{\mathrm{i}}^{\mathrm{NO_x}} P_{\mathrm{i}}{}^3 + e_{\mathrm{i}}^{\mathrm{NO_x}} P_{\mathrm{i}}{}^2 + f_{\mathrm{i}}^{\mathrm{NO_x}} P_{\mathrm{i}} + \beta_{\mathrm{i}}^{\mathrm{NO_x}}) \quad (7)$$

$$E_{\mathrm{p,i}}^{\mathrm{SO_x}}(P_{\mathrm{i}}) = cf_{SOx} \times (d_{\mathrm{i}}^{\mathrm{SO_x}} P_{\mathrm{i}}{}^3 + e_{\mathrm{i}}^{\mathrm{SO_x}} P_{\mathrm{i}}{}^2 + f_{\mathrm{i}}^{\mathrm{SO_x}} P_{\mathrm{i}} + \beta_{\mathrm{i}}^{\mathrm{SO_x}}) \quad (8)$$

$$E_{\mathrm{p,i}}^{\mathrm{CO_2}}(P_{\mathrm{i}}) = d_{\mathrm{i}}^{\mathrm{CO_2}} P_{\mathrm{i}}{}^3 + e_{\mathrm{i}}^{\mathrm{CO_2}} P_{\mathrm{i}}{}^2 + f_{\mathrm{i}}^{\mathrm{CO_2}} P_{\mathrm{i}} + \beta_{\mathrm{i}}^{\mathrm{CO_2}} \quad (9)$$

In this paper, carbon dioxide equivalent (CO_2e) is used to measure all three types of emissions. CO_2e describes the term of the different type of pollutant gases, such as NO_x and SO_x, that creates the equivalent global warming impact of a unit of CO_2. [3] The conversion factor of NO_x is 2.98 and SO_x is 0.44. [37, 38] Therefore, we can have a single emission constrained cost function to express the total effects of the emissions.

2.1.3. Emission constrained costs

It is noted that the number of variables is greater than the number of the objective functions. Therefore, the multi-objective function system can have several optimal solutions. To solve this multi-objective problem and find one of the reasonable results for each case being investigated, normally the multi-objective problem is transferred to a single-objective function [32].

In this paper, an emission constrained cost function F is employed that consists of the generation cost C and emission cost r x E as follows:

$$min\, F = C + r \times E \tag{10}$$

where r is the carbon price that is the amount that must be paid to emit one tonne of CO_2. With the carbon price, the effect of the emissions can be related to the cost. In this paper, in order to illustrate the proposed model, the carbon price in the UK from 2020 to 2050 are used in the model according to the Fourth Carbon Budget by the Committee on Climate Change [39], which are shown in Table 1.

2.2. Constraints

Three typical types of constraints are considered in this CEED model.

The first constraint is the real power balance, which is relevant to the system security and the minimization of the cost. It is assumed that the system demand D is equal to the rated power capacity of the sum of the conventional P and wind power W so there is no loss of load being considered. And the system power balance equation may be expressed as follows [23]:

$$\sum_{i=1}^{N} P_{\mathrm{i}} + \sum_{j=1}^{M} W_{\mathrm{j}} = D_{\mathrm{t}} \tag{11}$$

The second constraint is the generator limit. The output limit for a conventional generator and the limit of the wind farm may be expressed as follows [23]:

$$P_{\mathrm{i}_{min}} \leq P_{\mathrm{i}} \leq P_{\mathrm{i}_{max}} \tag{12}$$

$$0 \leq W_{\mathrm{j}} \leq W_{\mathrm{j,rated}} \tag{13}$$

The last constraint is the emission allowance, which gives the emission levels of each generator or the total emission limits at each time stamp. The emission allowance is an important constraint to satisfy the carbon cap in the electricity system. The emission allowances of the conventional generators are given by

$$0 \leq E \leq EE_{\mathrm{limit}} \tag{14}$$

The generator ramp rates can have a noticeable impact on the power output and levels of emissions from a generator when the rat of change in the demand is sufficiently high in a dynamic system. In this research, ramp rate for the conventional generation units is not considered as this is a steady state CEED model.

2.3. Wind power uncertainty modelling

In the CEED problem in an electrical system with conventional and wind resources, the stochastic nature of the wind speed and wind power generation is usually modelled by the Weibull distribution [18, 23].

The probability density function (pdf) for a Weibull distribution of wind speed can be mathematically expressed as follows [23]:

$$f_v(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} exp\left(-\left(\frac{v}{c}\right)^{k}\right) \tag{15}$$

The Weibull cumulative distribution function (cdf) of wind speed can be expressed as [23]

$$F_v(v) = \int_0^v f_v(v)dv = 1 - exp\left(-\left(\frac{v}{c}\right)^{k}\right) \tag{16}$$

Because of the uncertainty in the wind speed, the power output of a wind turbine is uncontrollable and the power output for a given wind speed can be categorized as follows [23]:

$$w = \begin{cases} 0, for\ v < v_{\mathrm{i}}\ or\ v > \ v_{\mathrm{o}} \\ w_{\mathrm{rated}} \dfrac{v - v_{\mathrm{i}}}{v_{\mathrm{r}} - v_{\mathrm{i}}}, for\ v_{\mathrm{i}}\ \leq v \leq v_{\mathrm{r}} \\ w_{\mathrm{rated}}, \quad for\ v_{\mathrm{r}} \leq v \leq v_{\mathrm{o}} \end{cases} \tag{17}$$

When wind speed is less than the cut-in wind speed or higher than the cut-out wind speed, there is no power output. It is assumed that if wind speed is between cut-in and rated wind speed, the power output is linear to the rated power. Else, if the wind speed is between rated and cut-out wind speed, the power output is equal to the rated power.

For the discrete portions of the power output, the probability of $w = 0$ can be calculated with equation (16) as follows [23]:

$$Pr\{w = 0\} = F_v(v_i) + \left(1 - F_v(v_o)\right) = 1 - exp\left(-\left(\frac{v_{\mathrm{i}}}{c}\right)^{k}\right) + exp\left(-\left(\frac{v_{\mathrm{o}}}{c}\right)^{k}\right) \tag{18}$$

Similarly, the probability of the wind equals to the rated wind speed, $w = w_{rated}$ can be expressed by [26]:

$$\begin{aligned} Pr\{w = w_{\mathrm{rated}}\} &= F_v(v_o) + \left(1 - F_v(v_r)\right) \\ &= exp\left(-\left(\frac{v_{\mathrm{r}}}{c}\right)^{\mathrm{k}}\right) + exp\left(-\left(\frac{v_{\mathrm{o}}}{c}\right)^{k}\right) \end{aligned} \tag{19}$$

And for the continuous portion, the wind speed distribution should be converted to the wind power distribution. This transform can be expressed by a linear relationship from the second line in equation (17), namely [23]:

$$\mathrm{W} = \mathrm{T(V)} = \mathrm{aV} + \mathrm{b}, v_i \le v \le v_r \tag{20}$$

Therefore, the wind power Weibull probability density function (pdf) can be expressed as follows [23]:

$$\begin{aligned} f_{\mathrm{w}}(w) &= f_v\left(\mathrm{T}^{-1}(\mathrm{w})\right)\left[\frac{d\mathrm{T}^{-1}(\mathrm{w})}{dw}\right] = f_v\left(\frac{w-b}{a}\right)\left|\frac{1}{a}\right| \\ &= \frac{klv_{\mathrm{i}}}{cw_{\mathrm{rated}}}\left(\frac{(1+\rho l)v_{\mathrm{i}}}{c}\right)^{k-1} exp\left(-\left(\frac{(1+\rho l)v_{\mathrm{i}}}{c}\right)^{k}\right) \end{aligned} \tag{21}$$

2.4. Optimisation Algorithm

The optimization problem here is a bounded and constrained one, requiring some kind of constraint handling technique to be resolved.

2.4.1. Genetic algorithm

The genetic algorithm (GA) is a stochastic method to solve global optimization problems. GA is a good technique to avoid local optimization due to its crossover operator and it has good converge ability [40]. Also, it can be noted that a number of other researchers have used GA in their dispatch models, such as [13, 16, 32, 33, 40-45].

The implementation of the GA contains five main stages:

i. An initial generation population *t* is generated randomly. In this model, the generation population consists of the outputs of all power generators.

ii. The fitness of the population *t* is formed and it is determined by the objective functions. The fitness of this model is the emission constrained costs, which is equation (10).

iii. The selection of parent generation from the population *t*. The better individuals, which have a better fitness, are selected to be parents of the next generation.

iv. The use of a crossover operator on the population *t* is employed to create the next generation population t+1. The crossover choses two parents from the population *t* using the selection operator and the values of the two bit strings are exchanged at randomly chosen points. Therefore, the two new created individuals are the next generation population *t*+1. This stage aims to create better individuals.

v. Perform mutation of the population t+1 for low probability. The mutation operator flips some bits in the population t+1 to generate the next generation. This step makes GA a noise-tolerant algorithm.

Repeat stages ii to v until the individuals are good enough. Results become more and more optimal with time because only better individuals survive. Thus, the balance between optimization and simulation time is considered.

2.4.2. Sequential quadratic programming

The sequential quadratic programming (SQP) method is one of the state-of-the-art iterative algorithms for solving smooth nonlinear optimization problems. The SQP method mimics Newton's method closely for constrained optimization problems. Then an approximation is made of the Hessian matrix of the Lagrangian function by using the quasi-Newton method at each iteration. Therefore, subproblems of the quadratic programming (QP) are generated to form the original search direction to a line search procedure [46-48]. Theoretically, the resolution of the constrained smooth nonlinear optimization problem is very accurate through SQP, especially when the Karush-Kuhn-Tucker (KKT) conditions are applied [40, 49-53].

2.4.3. Hybrid GA-SQP algorithm

The GA algorithm is good for the global search. However, it needs a long simulation time and may not be very accurate in the local search [47]. Moreover, from previous research [40, 49-54], the SQP is a very accurate technique but it is very sensitive to its initial points. A hybrid GA-SQP algorithm can reduce the computational time and ensure the accuracy and it is applied in the present paper [40,47,54].

Firstly, using GA as a first stage global optimizer, in order to obtain some decent starting points, by exploiting GA's global search ability. Secondly, use the obtained solution as found by GA as a starting point to the second stage local searching method SQP in order to refine the first stage result.

A MATLAB program that is based on the CEED model is developed for various scenarios investigated using the GA with an additive form penalty function for constraint handling. If no violation occurs, the penalty term will be zero. Otherwise, the penalty term will be a very large positive number to the epsilon in MATLAB, which is 2^{-52} [55]. Then a constrained nonlinear optimization algorithm, SQP solver, is applied by using the result found by GA as a starting point.

3. Case study and discussion of the results

In addition to proposing a CEED model that deals with both the conventional and wind powered generators considering carbon prices and emission allowances, the other objectives of this research are to investigate the effect of carbon prices and emission allowances on the cost of power generation using the proposed model. In the future electrical grid, conventional power, renewable power and nuclear power will supply most of the electricity [4]. The nuclear power is stable in the system in the short-term, therefore it is not necessary to be considered in a dispatch model. In this paper, two power grid systems have been considered. One consists of an IEEE 30 bus system with six thermal generators and one large-scale wind farm and the other consists of an electrical system with nine thermal generators and one large-scale wind farm. Different levels of wind power penetration, carbon price and emission allowances have been investigated concerning their effect on the optimal solutions and how the future energy and costs could behave with and without wind power. All the results presented in this paper are obtained using the hybrid GA-SQP algorithm. For the particular scenarios investigated, the SQP search only slightly improved the final optimisation.

3.1. Scenario 1: Electric grid system with 6 generation units and a wind farm

In this scenario we consider the IEEE 30 bus system which consists of 6 fossil fuel powered generators with a total capacity of 2600 MW, and total demand of 1800 MW. The capacity and power limits of each individual conventional power generator can be found in [28]. The capacity of the wind farm between 180 - 540 MW has been considered, which represents a 10-30% penetration of total demand. In the IEEE 30 bus system, coefficients in the quadratic cost and emission functions and constraints of power outputs of the IEEE 30 buses system with 6 thermal generators are collected from case study 4 in [28].

There are a number of wind turbines of the same type in the investigated wind farm. For different cases studied, the wind farm is considered to have different numbers of operational wind turbines. The wind turbine's rated power is 1.5 MW and the critical wind speeds are $v_{\mathrm{i}} = 5\ \mathrm{m/s}$, $v_{\mathrm{rated}} = 15\ \mathrm{m/s}$, and $v_{\mathrm{o}} = 25\ \mathrm{m/s}$. The direct wind power cost coefficient is $g = 30\ \$/\mathrm{MWh}$, the overestimation coefficient is $k_{\mathrm{o}} =$

$4.0\ \$/\mathrm{MWh}$ and the underestimation coefficient is $k_{\mathrm{u}} = 2.2\ \$/\mathrm{MWh}$ [32]. The resulting costs are converted to sterling in the model with the exchange rate £1 = \$1.40. However, the decrease in the exchange rate after the start of the process of Brexit has led to an increase in the cost. Assuming that the wind site is flat, then the wind speed can be expressed by the Weibull distribution. The Weibull distribution factors are $k = 2$ and $c = 15\ \mathrm{m/s}$ [34].

The reactive power is very important to the electrical system control, especially the voltage control. Excessive reactive power will lead to the voltage rising and poor reactive power leads to the voltage falling. In power transmission, high reactive power increases the current in the system and increases the power loss, which increases the cost. Furthermore, the reactive power causes inefficient use of power capacity [55-57]. According to the Grid code, the reactive power must be capable of supplying the rated power output between the 0.85 power factor lagging and 0.95 power factor leading [58]. Further, the reactive power output should be under steady state conditions within the voltage range $\pm5\%$ at high voltage. In this model, it is assumed that the power factor of the wind farm is 1 and the wind farm connects to the grid after compensating by an automatic power factor correction unit, which is within the requirement of the Grid code. In addition, it is assumed that the demand D_{t} is made always equal to the power supply of 1800 MW [28]. Therefore, the system has no expectations of power loss and the voltage in the transmission system is constant.

According to the Fifth Carbon Budget, wind power will have a penetration of about 35 % of the UK's overall electricity power capacity in the go green scenario in 2030 [4] and the carbon budget level will be reduced to 50 % of the baseline in 2025 and 80 % in 2050, where the baseline is the 1990 level [39]. Hence, we assume various wind power penetrations. According to [28], the minimum total conventional power generation of this electrical system is 1145 MW. Therefore, the demand that can be supplied by wind power is a maximum of 655 MW in this system, which is about 36 % of the total demand. Thus, wind power capacities of 0 MW, 180 MW, 360 MW and 540 MW have been investigated, which represent 0 %, 10 %, 20 % and 30 % wind energy penetration, respectively.

Moreover, with the decarbonisation objective in the EMR and the increasing renewable power planned for the future, the different scenarios consider the varying wind power capacities, emission allowances and carbon prices. Also, the minimum emission that may be achieved for each case are computed when all the wind power capacity is used in the system.

3.1.1. IEEE 30 bus system without wind power

As a baseline case, we considered a scenario with no wind power (0 % penetration) and there is no emission limit to the power generation. Therefore, all the power demand is met by the conventional power. Table 1 lists the optimized costs and emissions of the IEEE 30 bus electrical system with conventional power at different wind power capacities to meet a demand of 1800 MW. The influence of varying the carbon price from 0 to 200 £/tCO2e is also shown in the Table. It can be seen in Table 1 that with a zero wind power penetration the optimized conventional power costs have a negligible increase by only 29 £/h in the carbon price range of 0 and 200 £/tCO2e. The total emission falls significantly initially from a carbon price of zero to a price of 27 £/tCO_2e, after which the emissions only marginally decrease as the carbon price increases further to 200 £/tCO_2e. This trend can also be seen in AlRashidi's research [28]. From [28], the maximum emission and minimum fuel cost appear when there are weight factors, which gives the different weight of the fuel cost and different type of emissions in [28], of the emission and fuel equal to 1, respectively. With increase of the weight factors, the emission reduced while the fuel cost increased.

In this scenario, the total cost at a carbon price of 200 £/tCO_2e is approximately 2.1 times higher than at the zero carbon price mainly because of the emission charges. For an electrical system with conventional resources only, this increase is high. As one of the aims of EMR is to 'keep energy bills affordable', renewable resources should be considered to reduce the emission charges.

3.1.2 IEEE 30 bus system with a wind farm

It can be seen in Table 1, when an installed wind farm with three different capacities of 10 %, 20 % and 30 % penetration, are considered at zero carbon price the system emission level reduced to 60, 50 and 40 tCO_2e/h, respectively, from approximately 73 tCO_2e/h with no wind power at the lowest costs.

Figure 1 shows the total costs of the IEEE 30 bus electrical system with 10 %, 20 % and 30 % wind power penetration installed wind power capacity as a function of carbon price and for various emission allowances from 40 to 75 tCO_2e/h. With rising carbon price from 0 to 200 £/tCO_2e, it can be observed from (a) in Figure 1 that the total costs increase significantly. The costs at high emission allowances of 75 tCO_2e/h and 70 tCO_2e/h are very similar to the costs when without wind power. This is because the wind power is rarely used at these emission limits. At zero carbon price, as the emission limits reduce to the point where wind power does begin to play a role, as illustrated by the 60 tCO_2e/h data, the total cost increases, by 16 % in this instance. Only the fuel costs can affect the total costs at zero carbon price, thus the wind power with higher costs than conventional power are responsible for these increases, although it reduce the emissions. However, Figure 1 exhibits that when the carbon price goes up to 200 £/tCO_2e, the total costs of all the emission levels converge. This is because the emission cost dominates at high carbon prices scenarios. With the increasing carbon price, in order to satisfy the 'keep energy bills affordable' objective, increasing the renewable resources capacities are necessary. Thus within the EU ETS, the drive is for the renewable resources to become the economic choice for an electrical system owner.

Comparing to other scenarios, the scenarios using all the wind power have a higher wind power cost and a lower emission, and the effect of the emission cost in these scenarios is not as large as the others. Thus they have much higher cost and are not converged with the others.

As the emission limits reduce, a higher proportion of the power demand is supplied by wind power, and a manifestation of the higher wind power costs in relation to conventional power is that although the total cost does still increase with increasing carbon price, it's relative change is reduced in comparison to the no wind scenario, for example, at the 60 tCO_2e/h emission limit, the factor in total cost from zero to maximum carbon price is about 1.8, compared to the factor of 2.1 in Scenario 1.

Similarly, (b) and (c) of Figure 1, which give the total costs of proposed power systems installed with a 20 % and 30 % wind power penetration, demonstrate that the total costs increase significantly with the increase in the carbon prices. At the 50 tCO_2e/h emission limit of the power system with 20 % penetration, the total cost of 200 £/tCO_2e in the carbon price is about 1.6 times that at the zero carbon price. And that cost in the system with 30 % penetration with the 40 tCO_2e/h emission limit is approximately 1.4 times that at the zero carbon price. However, the total costs of these systems are higher than the costs when there is no wind, and this is due to the high wind power cost in this case. The more wind power used, the less cost difference between the different carbon prices and this is because the emission costs are reduced due to the lower emissions with the higher wind power.

As expected, it can be seen that the total cost of the proposed system without wind power is the cheapest at zero carbon price. However, the most expensive carbon price more than doubles the cost of the system without wind power. Introducing wind power along with emission limits affects the total cost in two ways, firstly, wind power itself is more expensive than the conventional power solutions, so the total cost does increase with increasing wind power, but this total cost is then less sensitive to carbon price increases as the total emissions are reduced by the fraction of the demand supplied from the wind power that is emission free.

Figure 2 shows the emissions of the various cases. It can be seen that the emissions with no wind and the emission of the 75 tCO_2e/h emission limit are very similar over the carbon price range up to 135 £/tCO_2e. However, at the 200 £/tCO_2e carbon price, the emission of the 75 tCO_2e/h emission limit drops, while the system without wind power is unchanged from that of the lower carbon price range. This indicates that the wind power costs become lower than the emission costs with the 135 £/tCO_2e carbon price. At zero carbon price, the system with the 70 tCO_2e/h emission limit is lower than that of the 75 tCO_2e/h emission limit. This illustrates that without the effect of carbon price, the emission limits have a strong effect on the emissions. The emissions of the systems using all of the wind power have the same trends as the emission with no wind power in the system. They are at their maximum at zero carbon price and then initially decrease as the carbon price rises, but once the carbon price is above 27 £/tCO_2e they only marginally decrease with further carbon price increase. These two cases depict the carbon price effects on the system effectively without an emission limit. Also, the emissions of the lower emission limit cases are steady, and this is because the governable wind power is reduced at the lower emission limits. Furthermore, the emission of the system without wind power, and using all of the wind power, are still high at the zero carbon price due to no emission optimisation.

The emission costs with different wind and emission limits are shown in Figure 3. As expected, the emission costs increase with an increasing carbon price, and the greatest difference is between "all wind power" and "no wind power" at the maximum carbon price, equating to a 19 % decrease in the 10 % penetration, rising to a 45 % decrease in the 30 % penetration scenario. In those cases with a defined emission limit, it can be seen that for the lower emission limits, the costs increase linearly with increasing carbon price, and hence the cost changes between different emission limits also follow a linear trend. This is because in these cases, as can also be seen from Figure 2, the emissions are almost constant with carbon price, being very close to the defined emission limits. A divergence from a purely linear trend can be seen in the 70 and 75 tCO_2e/h cases because at the highest carbon price, the optimal emission is significantly less than the emission limit.

In addition, from the optimal results in the emissions and emission costs, it can be observed that the carbon price can dominate the dispatch at high emission allowance levels. Since the emissions do not reach their minimum to obtain a minimum cost in those cases, and the wind power cost is higher than the conventional power cost and emission cost. In the high emission allowance scenarios with low carbon price, the optimal choice is to use low cost conventional power with low cost emissions. However, with the increase in the carbon price, the emission costs become dominant and the wind power with no air pollution showed that it is benefited in the emission costs. In the proposed system, the wind power only shows its benefit at very high carbon price and this is due to the high wind power price.

Moreover, the emission allowances dominate the dispatch in this model at low emission allowances condition. In order to decarbonise energy generation, when the renewable capacity is increased, the reduction in the emission allowances leads to a significant decrease in the emission costs, nevertheless, there is an increase in the total costs due to the high cost of the renewable resources used. Therefore, the wind power with a high cost is used as little as possible in order to reduce the total cost and the wind power becomes less flexible. Thus the lower emission allowance is highly dominant in the electrical system.

3.2. Electrical system with 9 generation units and a wind farm

In order to test the proposed model for a larger system, in this section a large electrical system with nine conventional generation units and a large wind farm is considered. The coefficients in the cubic cost and emission functions and constraints in the power outputs of the nine conventional generation units are collected from [36]. Due to the availability of the data, the emission in this system considers NO_x and SO_x only. The total demand of the system is 2500 MW and it is equal to installed capacity in Northern Ireland excluding wind and solar power [59]. The model of wind turbines are the same as discussed earlier and the capacity of wind farm is assumed to be 30 % wind power penetration.

The emission levels investigated for this case are between the lowest cost emission of the system without the wind power and that when all the wind power is used, namely about 22 to 16 t/h emission. Furthermore, the carbon price range is the same as before, i.e. from 0 to 200 £/tCO_2e.

Figure 4 shows the model predicted optimal (a) total cost, (b) total emission and (c) emission cost of the electrical system as a function of the carbon price. It can be seen that the trends of the total cost, emission and emission cost are similar to the IEEE 30 bus system discussed earlier at low carbon price. The difference in the result between this and the IEEE 30 bus system are the emission and emission cost at high carbon price, which is due to the amount of emission considered. In this scenario, the CO_2 emission is not considered, thus the total emission is about one sixth of the system emission considering CO_2 from the result for the IEEE 30 bus system. The low emission leads to less domination of the emission in the dispatch.

For the IEEE 30 bus system, the CO_2 emission in CO_2e is 3.8 times of NO_x and SO_x on average. Figure 5 indicates the optimised cost and emissions of this system if the CO_2 emission is considered with this ratio in this scenario. The emission and cost increase, but the trends are still same. It is noticed that the CEED model developed can be applied to different sizes of the system with the conventional and wind power resources effectively.

It should be noted that maintenance is an important aspect for a good energy management system and this should be considered in large scale long term dispatches. There are two types of maintenance for the electrical grid, which are preventive maintenance and corrective maintenance [60]. Most of preventive maintenance is fixed to a given generator. However, it can be preferable to base the maintenance cost on a per kWh rate. This is because of the wear and tear increase on the generator with increasing production [61]. In an electrical grid with a wind farm, the preventive maintenance will be higher due to the additional wind turbines in the grid. With the high penetration of the wind power, the preventive maintenance of the wind turbines will increase. Meanwhile, the preventive maintenance of a conventional generator may reduce. Thus the total preventive maintenance of a system depends on the number of generators and power production.

Corrective maintenance of a power system may be scheduled to minimise the risk through minimizing the loss of load expectation (LOLE), which considers the probability of the supply that cannot meet the demand [45]. While in this research, the system demand is assumed to be equal to the system supply, so the probability of the loss of load is zero. Moreover, the corrective maintenance of a wind turbine may be caused by the changes in the wind speed. This can cause sudden power output changes, especially for a system with a large wind site at the same location. The power output changes may cause voltage flicker and this may lead to gearbox damage [62]. In this research, only the PDF of the wind speed is considered and the real-time wind speed is not taken into account in this model.

4. Conclusions

This paper develops an optimally combined economics and emission dispatch model taking in to account fossil fuel-powered generators and wind-powered generators by considering wind power curtailment and reservation and carbon price of GHG and emission levels of decarbonisation scenarios. This CEED model considers both the economic and environmental aspects in the electrical system. It minimizes the total fuel cost and the emission cost of the system while satisfying the demand and power system constraints, which determines the optimal operation strategy in the economics aspect for the given system. This novel model introduces the carbon price and emission levels in the optimisation in order to model the future decarbonised electrical system scenarios. Two case studies of an electrical system with six and nine conventional-powered generators, respectively, and a large-scale wind farm are performed for demonstrating the interactions between carbon price, emission levels and renewable power penetration. It is observed from the computational results that the proposed CEED model has the ability to effectively generate solutions. Moreover, on increasing the carbon price at a low emission limit leads to an increase in the total cost of an electrical system with renewable resources, but the increasing cost rate is mitigated by decreasing the emission limits. Furthermore, the carbon price is able to dominate the dispatch at high emission allowance levels in this model with renewable energy penetration. Nevertheless, at low emission allowances, the emission allowance has a high impact in the power dispatch.

5. Abbreviations and acronyms

a_i, b_i, c_i, α_i	Coefficients in the cost function of the i^{th} conventional generator
a	$w_{rated}/(v_r\text{-}v_i)$
b	$w_{rated} \times v_i /(v_r\text{-}v_i)$
c	Scale factor of Weibull distribution
C	Total fuel cost in the electrical system
cf_{NOx}, cf_{SOx}	CO_2e conversion factor of NO_x and SO_x
$C_{OW,j}$, $C_{UW,j}$	Overestimation and underestimation in the cost of j^{th} wind powered generator respectively
$C_{p,i}$	Cost of the i^{th} conventional generator
$C_{W,j}$	Direct cost of the j^{th} wind powered generator
d_i^{NOx}, e_i^{NOx}, f_i^{NOx},	Coefficients in the emission function of the i^{th} conventional

$\beta_i^{NO_x}$	generator of NO_x, SO_x, CO_2, respectively
d_i^{SOx}, e_i^{SOx}, f_i^{SOx}, $\beta_i^{SO_x}$	
d_i^{CO2}, e_i^{CO2}, f_i^{CO2}, $\beta_i^{CO_2}$	
D_t	Total demand on the electrical system
E	Total emission in the electrical system
$E_{p,i}^{NOx}$, $E_{p,i}^{SOx}$, $E_{p,i}^{COx}$	Emission of NO_x, SO_x CO_2 of the i^{th} conventional generator, respectively
EE_{limit}	The emission limits of each conventional generator
F	Fitness function
g_j	Coefficient of the cost function of the j^{th} wind powered generator
k	Dimensionless shape factor of Weibull distribution
$k_{o,j}$, $k_{u,j}$	Coefficient of the overestimation/underestimation cost function of the j^{th} wind powered generator
l	$(v_r-v_i)/v_i$
M	Number of wind powered generators
N	Number of conventional powered generators
P_i	Power output of the ith conventional generator
P_{imin}, P_{imax}	Minimum and maximum power output of the i^{th}

	conventional generator
$Pr\{w = 0\}$	The probability of wind power is zero
$Pr\{w = W_{j,rated}\}$	The probability of wind power being rated
r	Carbon price
T	A transformation
V	Wind speed random variable
v	Wind speed (a realization of the wind speed random variable)
v_i	Cut-in wind speed
v_r	Rated wind speed
v_o	Cut-out wind speed
W	Wind power random variable
w	Wind power (a realization of the wind power random variable)
w_{rated}	Rated wind power
W_j	Scheduled power output of the jth wind powered generator
$W_{j,rated}$	Rated wind power of the j^{th} wind powered generator
$W_{AV,j}$	Available power output of the j^{th} wind powered generator
ρ	w/w_{rated}

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8. *Tables and figures*

Table 1 Costs and emissions of the IEEE 30 buses electrical system with conventional power and different wind power capacities at 1800 MW demand.

Wind power capacity (MW)	**Conve-ntional power demand (MW)**	**Costs and emissions**	**Year**				
				2020	**2030**	**2040**	**2050**
			Carbon price (£/tCO_2e)				
			0	**27**	**70**	**135**	**200**
0	**1800**	Conventional power cost (£/h)	12,463	12,483	12,489	12,491	12,492
		Total emission (tCO_2e/h)	74.26	69.00	68.86	68.83	68.83
		Emission cost (£/h)	0	1,863	4,820	9,292	13,765
		Total cost (£/h)	12,463	14,348	17,310	21,788	26,271
180	**1620**	Conventional power cost (£/h)	11,298	11,317	11,322	11,325	11,326
		Total emission (tCO_2e/h)	59.94	55.88	55.74	55.72	55.71
		Emission cost (£/h)	0	1,509	3,902	7,521	11,142
		Total wind power cost (£/h)	4,371	4,371	4,371	4,371	4,371
		Total cost (£/h)	15,669	17,197	19,596	23,218	26,839
360	**1440**	Conventional power cost (£/h)	10,157	10,172	10,180	10,183	10,185
		Total emission (tCO_2e/h)	46.58	45.13	44.94	44.90	44.89
		Emission cost (£/h)	0	1,218	3,146	6,062	8,978
		Total wind power cost (£/h)	8,742	8,742	8,742	8,742	8,742
		Total cost (£/h)	18,900	20,134	22,069	24,988	27,906
540	**1260**	Conventional power cost (£/h)	9,050	9,054	9,062	9,067	9,069
		Total emission (tCO_2e/h)	38.24	37.40	37.24	37.19	37.17
		Emission cost (£/h)	0	1,010	2,607	5,021	7,435
		Total wind power cost (£/h)	13,114	13,114	13,114	13,114	13,114
		Total cost (£/h)	22,164	23,178	24,782	27,201	29,618

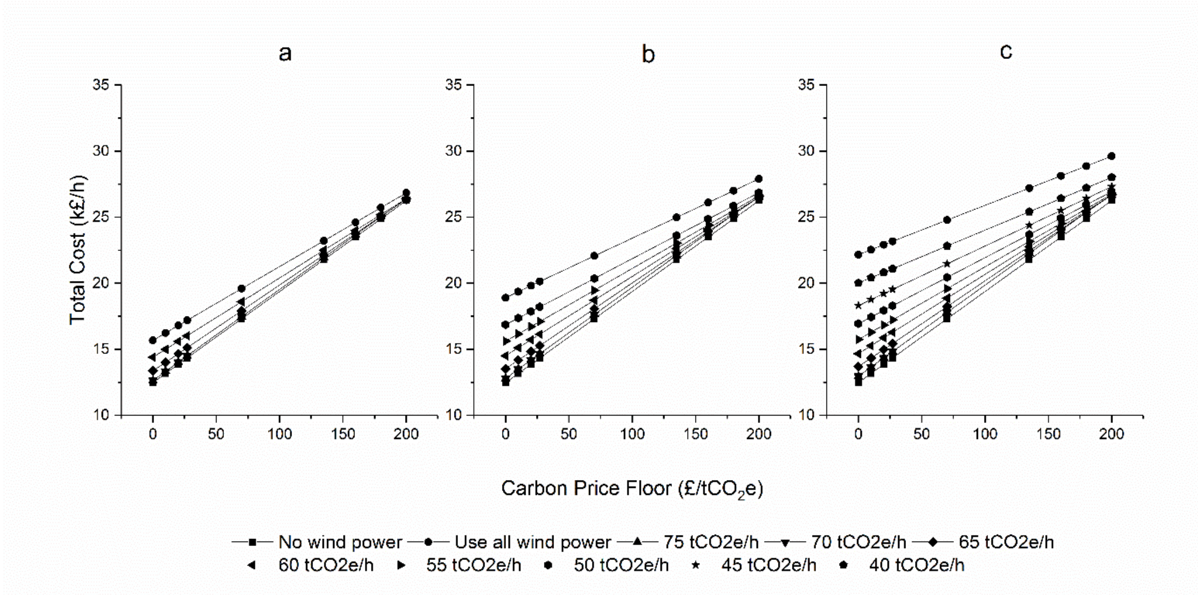

Figure 1 Total costs of IEEE 30 bus electrical system installed. (A) 10%, (B) 20%, and (C) 30% wind power capacity with different emission limit

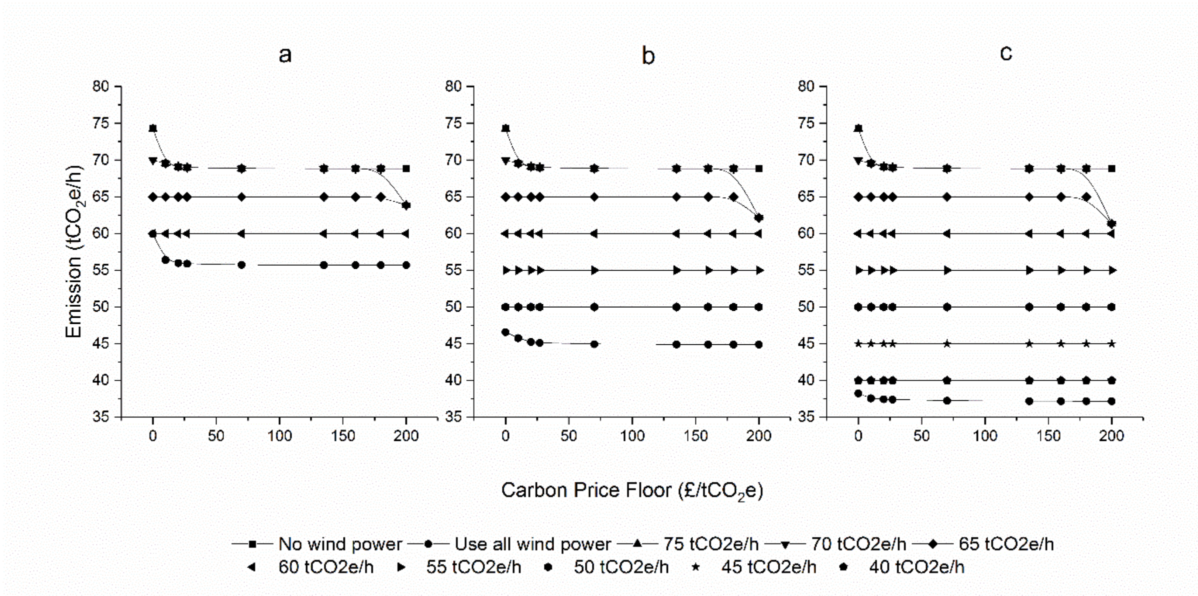

Figure 2 Total emissions of IEEE 30 bus electrical system installed. (A) 10%, (B) 20%, and (C) 30% wind power capacity with different emission limit

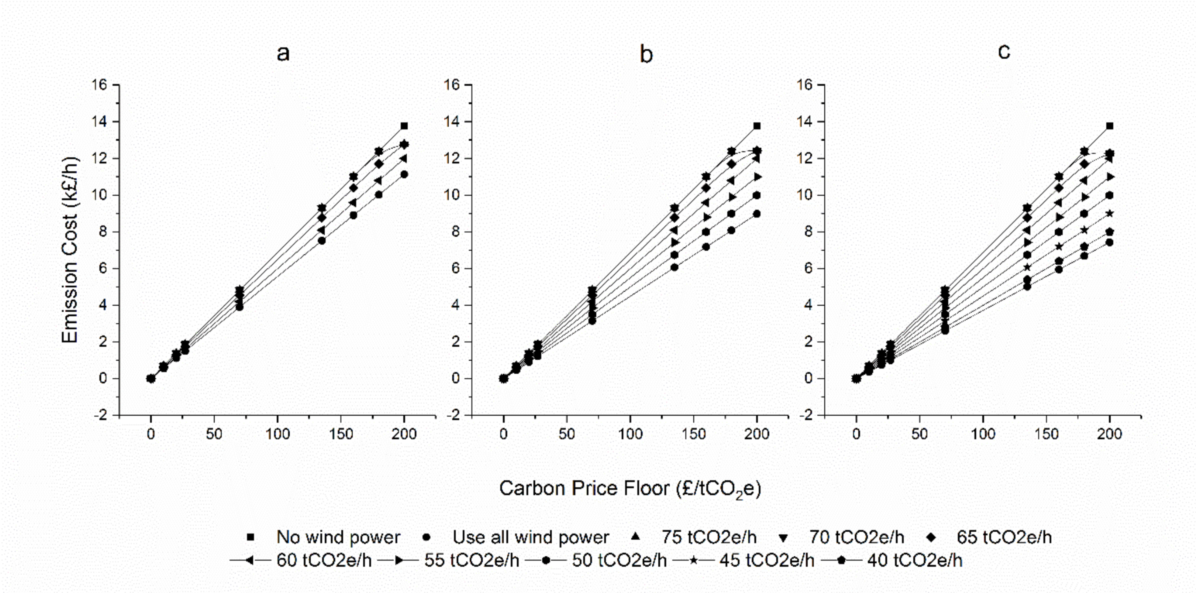

Figure 3 Total emission costs of IEEE 30 bus electrical system installed. (A) 10%, (B) 20%, and (C) 30% wind power capacity with different emission limit

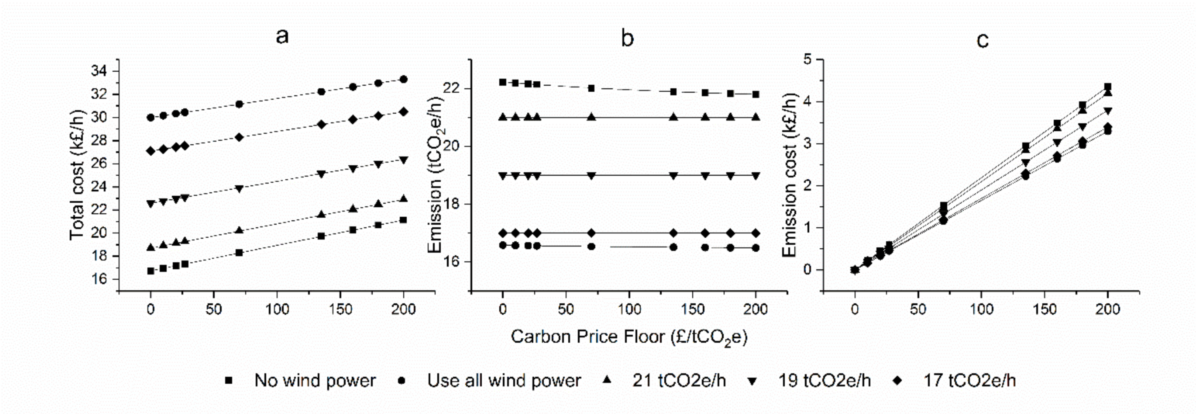

Figure 4 Optimal result. (A) Total cost, (B) total emission, and (C) emission cost of an electrical system with 9 conventional generators and installed 30% wind power capacity with different emission limit

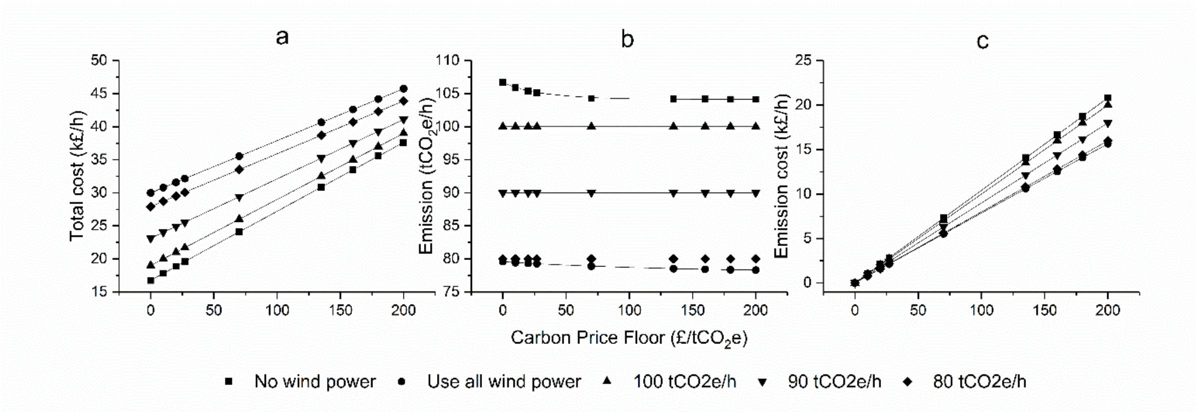

Figure 5 Optimal result. (A) Total cost, (B) total emission, and (C) emission cost of an electrical system with 9 conventional generators and installed 30% wind power capacity considering CO2 emission