



Robust environmental-economic dispatch incorporating wind power generation and carbon capture plants



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HIGHLIGHTS

- A bi-objective robust optimization model of EED is proposed.
- Operation of carbon capture plants and wind power uncertainty are considered.
- Nash bargain criterion is used to determine a compromise Pareto solution.
- A MILP based golden section search algorithm is developed to locate the bargaining solution.
- Operational benefits brought by carbon capture plants are demonstrated.

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ABSTRACT

Utilizing clean renewable generation and carbon capture plants (CCPs) can remarkably reduce the carbon emission from electricity production. Because operating carbon capture facility consumes additional energy, minimizing the production cost and reducing the carbon emission may conflict with each other. To compromise these two objectives and cope with uncertain wind generation, this paper proposes a robust environmental-economic dispatch (EED) method that jointly optimizes energy and reserve schedules in the upcoming dispatch period. The operating characteristic of CCP and the volatility of wind energy are considered in the proposed model. Because both objectives are convex functions, the Pareto front can be readily computed by using the ε -constraint method. The Nash bargaining criterion is adopted to determine a fair trade-off between the generation cost and the carbon emission in the absence of a clear carbon tax or emission cap. A second-order cone program (SOCP) is proposed to locate the bargaining solution on the Pareto front. An adaptive scenario generation algorithm is derived to solve the robust EED problem in a tractable manner. The PJM 5-bus system is used to illustrate the obtained dispatch strategy, and demonstrate the contribution of CCPs on reducing the carbon emissions and enhancing the operational flexibility. Case studies on the IEEE 118-bus system corroborate the applicability of the proposed method.

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1. Introduction

The economic dispatch (ED) that seeks the optimal generation portfolio among committed units subject to security operating constraints plays an important role in power system operations. However, the optimal ED solution may no longer be satisfactory when environmental concern is taken into account, which is attracting more and more public attention. To incorporate such

consideration, the emission-constrained ED (ECED) [1] and the environmental-economic dispatch (EED) [2] have been proposed.

Given an admissible emission quota, ECED incorporates a constraint on the total amount of emission into the conventional ED model. ECED is easy to implement by solving a standard optimization problem. If the emission quota is not available or unclear, the EED is another remedy. The EED is a bi-objective optimization problem that simultaneously optimizes the generation cost and CO₂ emission. Methods for solving the EED can be divided into two categories. The first category transforms the EED into a single-objective optimization problem to procure only one solution that compromises two goals, including the goal programming

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Nomenclature**Indices**

l	index for transmission lines
i	index for carbon capture plants (CCPs)
j	index for conventional units
k	index for wind farms
q	index for loads
s	index for scenarios in the uncertainty set

Parameters

a_i, b_i	generation cost coefficients of CCP i
a_j, b_j	generation cost coefficients of conventional unit j
c_i	reserve cost coefficient of CCP i
c_j	reserve cost coefficient of conventional unit j
e_i	emission factor of CCP i
e_j	emission factor of conventional unit j
F_l	capacity of transmission line l
N_W	the number of wind farms
p_i^l, p_i^u	minimal/maximal output of CCP i
p_j^l, p_j^u	minimal/maximal output of conventional unit j
p_i^B	fixed energy consumption of CCP i
D_q	power demand of load q
R_i^a	ramping limit of CCP i
R_j^a	ramping limit of conventional unit j
Δt	duration of period t
w_k^l, w_k^u	minimal/maximal output of wind farm k
w_k^u	maximal output of wind farm k
w_k^f	predicted output of wind farm k , vector $w^f = \{w_k^f\}, \forall k$
w_k^h	half length of the output interval, $w_k^h = 0.5(w_k^u - w_k^l)$
w_i^C	energy consumption of CCP i to absorb unit CO ₂
γ_i	CO ₂ capture efficiency of CCP i
Γ	budget parameter used in the uncertainty set

ε_r	bound of total normalized forecast error
π_{il}	power transfer distribution factor from CCP i to line l
π_{jl}	power transfer distribution factor from unit j to line l
π_{kl}	power transfer distribution factor from wind farm k to line l
π_{ql}	power transfer distribution factor from load q to line l

Variables

E_i^{Cf}	CO ₂ captured by CCP i in pre-dispatch, $E^{Cf} = \{E_i^{Cf}\}, \forall i$
E_i^{Cr}	CO ₂ captured by CCP i in re-dispatch, $E^{Cr} = \{E_i^{Cr}\}, \forall i$
p_i^{Cf}	gross power of CCP i in pre-dispatch, $p^{Cf} = \{p_i^{Cf}\}, \forall i$
p_i^{Nf}	net injection power of CCP i in pre-dispatch, $p^{Nf} = \{p_i^{Nf}\}, \forall i$
p_j^f	output of conventional unit j in pre-dispatch, $p^f = \{p_j^f\}, \forall j$
p_i^{Gr}	gross power of CCP i in re-dispatch, $p^{Gr} = \{p_i^{Gr}\}, \forall i$
p_i^{Nr}	net injection power of CCP i in re-dispatch, $p^{Nr} = \{p_i^{Nr}\}, \forall i$
p_j^r	output of conventional unit j in re-dispatch, $p^r = \{p_j^r\}, \forall j$
r_i^C	spinning reserve capacity offered by CCP i , $r^C = \{r_i^C\}, \forall i$
r_j^G	spinning reserve capacity offered by unit j , $r^G = \{r_j^G\}, \forall j$
v_k	lifting variable in the uncertainty set, vector $v = \{v_k\}, \forall k$
w_k^r	possible output of wind farm k , uncertain variable, $w^r = \{w_k^r\}, \forall k$
w	extend uncertainty vector, $w = \{w^r, v\}$
x	pre-dispatch strategy, $x = \{p^{Cf}, p^{Nf}, E^{Cf}, r^C, p^f, r^G\}$
y	re-dispatch strategy in response to $w^r, y = \{p^{Gr}, p^{Nr}, E^{Cr}, p^r\}$

method, the weighted-sum method, and the compromise programming method [3,4]. A common question for these methods would be how to determine a convincing weight parameter for the two objectives, such as the carbon tax. The second category provides system operators the entire Pareto front or multiple non-dominated solutions. The operator is eligible to select a reasonable decision. Most studies in this direction focus on how to generate the Pareto front or a set of uniformly-distributed non-dominated solutions, such as the evolutionary algorithms [5] and the normal boundary intersection method [6]. Recently, the EED problem has been modeled as a polynomial optimization and solved by semi-definite programming relaxation method [7], in which a nonlinear weight selection approach is proposed to improve the distribution of the Pareto points.

During the past decade, new technologies have inspired more measures for controlling the carbon emissions. Massive integrations of the wind power generation and wide utilization of carbon capture facilities on coal-fired units can remarkably reduce the CO₂ emitted into the atmosphere. However, they also bring new challenges. On the one hand, although wind generation is clean and cheap, its variability exerts great pressure on the power system dispatch [8–10]. Some studies use probability distributions to model the uncertain factors in the EED, such as [11–13], giving rise to various stochastic programming models. In practice, an exact probability distribution is usually difficult to acquire. Recently, the two-stage robust optimization (TSRO) appears to become a powerful modeling framework for decision-making problems under uncertainties, and has been successfully applied to the unit

commitment [14–16], the economic dispatch [17–19], and the optimal power flow [20], showing quite appealing features. Compared with probabilistic models, TSRO uses a deterministic set to characterize the underlying uncertainty, which only requires moderate data and information. To the best of our knowledge, TSRO has not been used in power system applications following a bi-objective setting. On the other hand, although the carbon capture plants (CCPs) are more flexible to dispatch, however, the energy consumption in the capture facilities may increase the generation cost. Recent progress in the carbon capture technology has been reported in extensive literatures, such as [21–23]. This paper will not go into technical details about carbon capture. Instead, the impact of CCPs on system operation will be the main focus. Along this line, the operating characteristic of CCP is studied in [24]. Based on the carbon tax and wind power forecast, a low-carbon dispatch model considering CCPs and is proposed in [25], which is a special kind of the weighted-sum approach.

This paper intends to develop a comprehensive method to address the EED problem of bulk power systems with large-scale wind power integration, which concerns both the generation cost and CO₂ emission without a clear carbon tax or emission quota. The contribution of this paper is twofold:

- (1) We propose a robust EED model that jointly considers the operation of CCPs and uncertainty of wind generation in the framework of TSRO. The robust ED model in [17] mainly focuses on the economic issue, which requires solving a single objective TSRO. The robust EED in this paper considers

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