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Planning sustainable electric-power system with carbon emission abatement through CDM under uncertainty

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HIGHLIGHTS

- An innovative optimization method is proposed for handling uncertainties.
- The method is applied to a real case of municipal electric power system planning.
- Sustainable electric power system's transition pathways are explored.
- Benefits of introducing CDM into Shenzhen's electric power system are analyzed.
- Results can support enactment of future policies with carbon emission abatement.

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ABSTRACT

In this study, a fuzzy-interval possibilistic programming (FIPP) method is developed for supporting sustainable electric power system (EPS) planning with carbon emission abatement under uncertainty. In FIPP, systematic uncertainties expressed as crisp intervals and fuzzy-boundary intervals can be effectively tackled. A FIPP-based clean development mechanism (FIPP-CDM) model is formulated for realizing CO_2-emission reduction and adjusting energy mix of Shenzhen's EPS with cost-effective and sustainable ways. Located in the south of Guangdong Province of southern China, the City of Shenzhen is one of fastest-growing cities in the world and has experienced high-speed economic development, accelerated industrialization process, and increased population growth. This is the first attempt to introduce CDM into Shenzhen's EPS with carbon emission abatement, while sustainable EPS's transition pathways are explored through FIPP-CDM model. Results demonstrate that (a) city's energy supply structure tends to the transition from coal-dominated into clean energy-dominated; (b) local renewable energy development is motivated through CDM projects; (c) city's power generation mix is diversified by wind power and solar power, while renewable energy accounts for 2.12%; (d) an additional capacity of [4.88, 5.82] GW of CDM projects is added, contributing to a [15.91, 17.22] % reduction in CO_2 emission of fossil fuel-fired power (i.e., corresponding to emission-reduction of [71.59, 85.51] million tonne). Decision alternatives under CDM can facilitate policy enactment of carbon-emission abatement, reformation of Shenzhen's EPS through market-oriented mechanism, as well as achievement of sustainable EPS planning.

1. Introduction

Over the recent decades, in virtue of continued incredible economic growth and soaring carbon-intensive fossil-fuel consumption, global carbon dioxide (CO_2) emission has been experiencing a rapid increase [1,2]. Electric power industry made the largest contribution and accounted for 41% of global CO_2 emission in 2010 [3]. A large number of studies have demonstrated that such a significant increment of CO_2 emission may induce global temperature increase, climate change, sea level rise, shoreline erosion, and even catastrophic consequences, such as flooding of coastal cities and island nations, disruptions to agriculture and drinking water, the spread of diseases and the extinction of species [4–7]. These environmental and climatic impacts of energy consumption have forced decision makers to carry out the electric power system's transitions towards more sustainable ways [8–11]. A market-oriented mechanism is imperative for electric power industry reform to alter traditional energy consumption pattern and curb carbon emission. Being

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one of flexibility mechanisms defined in Kyoto Protocol under United Nations Framework Convention on Climate Change (UNFCCC), clean development mechanism (CDM) is capable of identifying innovative and sustainable ways of carbon emission abatement through establishing a system which encourages developing countries to implement emission-reduction projects and earn certified emission reduction (CER) credits [12–14]. Through trading and selling the CERs in emission trading schemes, emission reduction targets could be achieved with a cost-effective way.

Previously, many research works for electric power system (EPS) planning focused on the assessment of CO_2 mitigation potential, and economic, social and environmental benefits of CDM projects [15–22]. For example, Gilau et al. [16] identified optimal energy supply options of renewable energy technologies to achieve substantial CO_2 emissions reduction under CDM, while both the marginal investment cost and marginal net present cost for emission reduction were calculated. Resnier et al. [18] proposed CDM tax/subsidy optimization model to evaluate the CDM projects' economic and environmental benefits and optimize corresponding internal rate of return among electricity generation CDM projects; the results implied that CDM projects with the greatest benefits in terms of sustainable development were given priority in the subsidy flux. Purohit [20] employed macro-level assessment method to estimate CO_2 mitigation potential of solar home system under CDM in India; it could be found that CDM could help to foster the dissemination of solar home system in the country and promote sustainable development. Couth et al. [21] assessed the viability of landfill gas to electricity CDM projects in Africa, while the implementation of CDM projects in eThekwini Municipality and complexities of CDM process were discussed. Amatayakul and Berndes [22] analyzed the determining factor for the development of a CDM biomass power project in Brazil, India and Thailand based on empirical analysis and econometric analysis, and results showed that implementing policies and regulations that guarantee access for biomass power developers to sell electricity to the grid at an attractive price could lead to the development of CDM biomass power projects in a larger number of developing countries.

In practical EPS planning problems, uncertainties associated with modeling inputs and parameters are of importance to generate a precise estimation for decision alternatives [23–26]. These uncertainties, being manifested in institutional obstacles, varied commitments and policy factors associated with climate change, may be crucial in determining the actual CDM project activities [15,27]. For instance, carbon emission is relevant to local electricity generation mix which lies on the development of alternative energy (i.e., nuclear and renewable energy) and uncertain economic growth rate. CERs are proportional to the effectiveness of curbing carbon emission of CDM project, and may be influenced by varied market, policy and environmental concerns, such as the type and availability of CDM projects, change to international climate change framework and local legislation, baseline emission factor of regional power grids and accurate calculation of carbon emission. Besides, optimal power-supply schemes with emission reduction would be influenced by fluctuating cash flow, imprecise fuel costs, different operation and maintenance costs and dynamic capacity expansions. Furthermore, energy demands are associated with demographic, policy, environmental and technological factors, and predicted values are fluctuated and usually inaccurate; these factors can influence the effectiveness of energy distribution in EPS and may lead to potential risk of violating supply–demand balance. Unfortunately, confronted with above-mentioned complexities, traditional deterministic optimization techniques become infeasible and few studies focus on tackling these intrinsic uncertainties in carbon emission abatement through CDM [27,28]. Thus, an appropriate reflection of uncertainty is crucial to explore the link between parameter uncertainty through to decision uncertainty and their interactions and implications.

Previously, a number of mathematical programming approaches were undertaken for tackling intrinsic uncertainties existing in carbon emission abatement problems [29–36]. For example, Muela et al. [29] formulated a fuzzy possibilistic model for power generation planning to investigate the effect of uncertainties on CO_2 emission level. Tan et al. [30] developed a fuzzy integer programming model for planning carbon capture retrofit in power generation sector with carbon emissions reduction, while fuzzy carbon footprint goal with a linear membership function was reflected. Li et al. [31] proposed an interval-valued minimax regret analysis method for planning greenhouse gas (GHG) abatement, where uncertain GHG-emission rate for fossil-fired facilities and end-users expressed as interval values were addressed. Weber and Martinsen [34] introduced fuzzy linear programming into the IKARUS (instruments for greenhouse gas mitigation strategies) model to tackle fuzzy uncertainties related to sustainability target of CO_2 mitigation, while IKARUS was a technology oriented bottom-up energy system optimization model of Germany in the form of cross-linked processes from primary energy supply to energy services. Zhang et al. [35] put forward an inexact management model to identify optimal strategies for planning CO_2 capture and sequestration with a carbon capture and storage system under the uncertainties presented as interval numbers.

Generally, interval-parameter programming (IPP) is effective for dealing with uncertainties expressed as crisp intervals whose lower and upper bounds are both deterministic and definitely known; however, IPP has difficulties in incorporating other formats of uncertainties presented as possibilistic and/or probabilistic distributions within the optimization framework [37,38]. Fuzzy possibilistic programming (FPP) is an attractive tool to tackle the decision problems of EPS planning under fuzzy goal and constraints and handle epistemic uncertainty in the form of ambiguous parameters presented as fuzzy membership functions; nevertheless, FPP has limitations in solving practical problems when various complicated intermediate models are formulated, and model complexities and computational requirements are markedly raised [39,40]. In real-world planning problems, owing to the inherent economic fluctuations, lower and upper bounds of cost parameters may be provided as subjective judgments from a number of stakeholders and decision makers; with regard to unavailable stochastic distribution information and various influence factors, demand parameters in the right-hand side of constraints are acquired by limited data and presented by fuzzy membership functions. Conventional IPP and FPP fall into a dilemma and lose valuable information when two bounds of intervals in the objective function and constraints are presented by possibility distributions (i.e., fuzzy-boundary intervals). Thus, one potential approach for better accounting for uncertainties and CDM issue is to develop a fuzzy-interval possibilistic programming (FIPP) method, through coupling IPP with FPP technique. FIPP method can not only effectively address uncertainties presented in terms of crisp intervals and fuzzy-boundary intervals both in the objective function and constraints, but also enhance the traditional fuzzy mathematical programming by choosing necessity degree of constraints based on decision maker's preference and avoiding complicated intermediate models with high computational efficiency.

Therefore, the objective of this study is to develop such a FIPP method for solving such complexities and interactions. Then, a FIPP-based clean development mechanism (FIPP-CDM) model will be formulated for realizing CO_2-emission reduction of Shenzhen's electric power system (EPS) with cost-effective and sustainable ways. Located in the south of Guangdong Province of southern China, the City of Shenzhen is one of fastest-growing cities in the