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Integrated multiperiod power generation and transmission expansion planning with sustainability aspects in a stochastic environment

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ABSTRACT

This paper presents a multistage stochastic programming model to address sustainable power generation and transmission expansion planning. The model incorporates uncertainties about future electricity demand, fuel prices, greenhouse gas emissions, as well as possible disruptions to which the power system is subject. A number of sustainability regulations and policies are considered to establish a framework for the social responsibility of the power system. The proposed model is applied to a real-world case, and several sensitivity analyses are carried out to provide managerial insights into different aspects of the model. The results emphasize the important role played by sustainability policies on the configuration of the power grid.

1. Introduction

Reliable power generation and transmission are essential parts of accelerating economic development, and are key concerns of power systems management, especially in a stochastic environment. Power generation and transmission include various aspects that have intensive impacts on society and the environment, such as greenhouse gas emissions, air and noise pollution and social expectations. These impacts become even more severe when disruption events occur, particularly in natural and human-caused disasters. Moreover, uncertainty regarding future electricity demand and fuel prices also impacts on planning and results in a more complex and multi-dimensional problem.

GEP (generation expansion planning) is typically formulated as a mixed-integer programming model, which deals with the expansion capacity of different generating units over a long-term planning horizon to minimize the total cost, including the establishment cost for new generating units and their operating and maintenance costs. Many researchers have studied GEP under deterministic assumptions. Ref. [32] formulates GEP as a nonlinear programming model and proposes an improved genetic algorithm to solve it. Ref. [16] develops an iterative genetic algorithm to solve GEP. Ref. [2] presents a multi-objective mixed-integer linear programming model for GEP that includes DSM (demand-side management). Ref. [51] proposes an adaptive simulated annealing genetic algorithm to solve GEP. Ref. [22] considers GEP as a multi-objective problem. It applies an elitist non-dominated sorting genetic algorithm to solve the problem. Furthermore, some researchers study GEP under uncertainty. Ref. [21] formulates GEP considering uncertainty about future electricity demand and fuel prices. It proposes a stochastic process model to describe the evolution of these parameters and to construct a scenario tree for the problem. Ref. [35] incorporates a long-term dynamic simulation into GEP to estimate the evolution of the demand and of the electricity price. Ref. [15] presents a new scenario reduction algorithm for GEP considering uncertainty in future fuel prices and electricity demand through statistical extrapolation of long-term historical trends.

TEP (transmission expansion planning) deals with determining the optimal configuration of the power network over a long-term planning horizon to meet the power demand in each node at a minimum cost, which includes the cost of building new lines as well as the operating and maintenance costs of the power grid. Ref. [1] presents a mixed-integer linear programming approach to solve the long-term TEP. Ref. [7] formulates TEP under uncertainty. Ref. [24] reviews the literature of the proposed meta-heuristics for solving TEP. Ref. [12] considers risk aversion and presents a mean-risk mixed-integer linear programming model for TEP.

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Integrated GTEP (generation and transmission expansion planning) has been one of the main lines of research on power systems management in recent years, due to the close relationship between GEP and TEP. Ref. [42] considers fuel acquisition and transportation costs in GTEP. Ref. [36] presents a three-level equilibrium model for the integrated expansion of an electrical network. Ref. [9] proposes a model for integrating generation and transmission expansion planning to identify an expansion plan for the total sector at the macro level.

Environmental impacts have recently been included in GEP in a number of studies. Ref. [27] formulates GEP as a single-period multi-objective mixed-integer nonlinear programming model considering CO_2 emissions and fuel price risks. Ref. [43] develops GEP by incorporating environmental costs and limitations for air pollutant emissions (SO_2 and PM_{10}). Ref. [10] incorporates the impacts of various low-carbon factors into GEP. It presents a compromised modeling approach to adapt the characteristics of the proposed model. Ref. [48] proposes a multi-objective optimization model for GEP that considers environmental impacts (CO_2 and NO_x emissions). It captures uncertainty in demand and availability of units, using Monte Carlo simulation. Ref. [8] considers the impacts of feed-in tariffs, quota obligations, emissions trading and a carbon tax on GEP and solves the problem using the generalized Benders' decomposition method. Ref. [39] formulates GEP with environmental constraints as a non-smooth convex constrained optimization problem. It solves the problem using a bundle-type method. Ref. [17] proposes a multi-objective mixed-integer linear model for GEP, in which CO_2 emissions and energy price risk are considered. Ref. [40] incorporates the environmental costs associated with the construction and operation of power plants into the long-term expansion planning process of hydrothermal generation systems. Ref. [41] develops a risk-averse single-stage model for GEP with sustainability concerns.

This paper presents for the first time a multistage stochastic programming model for integrated planning of a power system's generation and transmission network, with stochastic future electricity demand, fuel prices, greenhouse gas emissions and disruptions. The proposed GTEP model employs a social-responsibility framework to address sustainability issues concerning power generation and transmission. The proposed model is applied to Iran's northwestern power grid. Finally, the computational results are presented and discussed.

The remainder of the paper is organized as follows. Section 2 introduces the notation and develops the stochastic programming model based on a sustainable approach to power system planning. Section 3 presents the implementation of the proposed model in Iran's northwestern power grid as a case study. Section 4 analyzes the computational results to achieve managerial insights. Finally, Section 5 concludes the paper.

2. Problem description and formulation

The goal of the proposed integrated GTEP is to simultaneously locate new generating units, build new transmission lines, and determine the power generated and the power flow in the resulting network, in order to fulfill the power requirements in a multiperiod planning horizon, at a minimum total establishment, transmission, environmental and load shedding cost. We consider a power grid consisting of a number of existing generating units and transmission lines, along with some potential locations for new generating units and transmission lines. The power grid is subject to disruptions; and demand, fuel prices and emissions are stochastic. The linear DC power flow method is used to model power flow in the transmission network. Moreover, a social-responsibility framework is employed to consider socio-environmental issues involved in the GTEP.

Social responsibility is an emerging topic both in industry and academia that has received much interest in recent years [34,37,49]. Under the social responsibility concept, organizations and individuals are responsible for the impacts of their decisions on society and on the environment.

ISO 26000 provides a classification of issues related to social responsibility in the seven core subjects, which consist of organizational governance, human rights, labor practices, the environment, fair operating practices, consumer issues, and community involvement and development. ISO 26000 is used here due to its comprehensiveness [20].

Power generation and transmission expansion have different impacts on society and the environment. Table 1 presents the different issues considered in this study and relates them to each core subject of social responsibility given in ISO 26000.

CO_2 (carbon dioxide) is the primary greenhouse gas. The main impact of greenhouse gas emissions is global warming. It can result in extreme weather conditions that can lead to global climate change. CO_2 emissions are also a major source of ocean acidification, where CO_2 dissolves in water to form carbonic acid [30]. CO_2 emissions fall under the core subject of the environment, and different countries have a range of environmental regulations on CO_2 emissions. The environmental cost of CO_2 emissions is considered in the objective function (1) of the model proposed in the next section.

Satisfying power demand is the principal function of electric power generation, transmission and distribution. It is crucial, as it leads to community development. This matter is related to the core subject of community involvement and development. In our model, this issue is considered in Constraints (6) which enforce demand at each node must be satisfied unless a load shedding cost is paid. The total load shedding cost is included in the objective function (1).

Noise emissions can cause hearing impairment, hypertension and ischemic heart disease, annoyance, sleep disturbances and decreased school performance [33]. These issues affect local laborers and residents. Hence, noise exposure falls under the core subject of labor practices and consumer issues. Noise emissions must be less than an allowable rate at each location, which imply the set of Constraints (9) regarding the total noise emitted at each node in our model.

Finally, the community expects managers to apply socially acceptable planning to the expansion of the power system. This ensures that the power system does not face considerable opposition from the community. Social acceptance can be categorized under the core subject of fair operating practices.

The social acceptance of establishing a new generating unit (or transmission line) can be evaluated by the percentage of people who agree with it. These estimations are computed based on a sampling method and on surveys of people living in different potential locations for new generating units and transmission lines.

Table 1
The social issues involved in the proposed GTEP problem.

Issue	Type	Impact	Core subject
CO_2 emissions	Greenhouse gas	Global warming	The environment
Power requirements	Utility	Community development	Community involvement and development
Noise emissions	Health hazard	Hearing impairment	Labor practices and consumer issues
Social acceptance	Public expectation	Active public involvement	Fair operating practices