Applied Energy 193 (2017) 540–549

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Electricity production scheduling under uncertainty: Max social welfare vs. min emission vs. max renewable production

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HIGHLIGHTS

- Power generation is scheduled with wind power uncertainty and dispatchable loads.
- Objectives are: max social welfare, min emission, and max renewable production.
- A multi-objective stochastic scheduling model is formulated and tested.
- Scheduling outcomes under different policies are discussed.

ARTICLE INFO

Article history:
Received 18 September 2016
Received in revised form 30 January 2017
Accepted 18 February 2017
Available online 8 March 2017

Keywords:
Generation schedule
Emission
Renewable integration
Social welfare
Multi-objective

ABSTRACT

Some areas in China are facing pressing air pollution problems. Measures from the power sector can be taken to cope with air pollution issues, including reducing emission levels of thermal units and integrating wind and solar power. Social welfare, emission, and renewable integration are three major concerns in modern power system operations. This paper describes three stochastic scheduling models aiming at maximizing social welfare (SW), minimizing emission (EM) and maximizing renewable production (RE). A multi-objective scheduling model (MT) is also proposed that properly balances the above objectives. Wind power uncertainty and dispatchable loads are considered in the model. The outcomes of the three models are compared through an illustrative example and a 57-node case study. Results show that model EM results in 36% of the social welfare of model SW, 27% of its emissions, and 43% of its wind spillage, while model RE results in 55% of the social welfare of model SW, 56% of its emissions and 28% of its wind spillage. Additionally, we analyze how the optimal generation scheduling is affected by the weights in model MT. This work provides insight to policy makers on how to balance social welfare, emissions and renewable production.

1. Introduction

1.1. Motivation and aim

Some areas in China face significant air pollution problems. The power sector contributed 35% of SO_2 emissions and 38% of NO_x emissions in 2014 [1]. Measures are being implemented in the power sector to alleviate this air pollution problem. On one hand, the overall emission characteristics of thermal units have been greatly improved. On the other hand, the capacity of renewable energy, such as wind and solar power, has grown rapidly in the last decade.

Wind power has low marginal cost compared with thermal units, and involves neither air pollution emissions nor CO_2 emissions. Wind power capacity is growing rapidly. However, the stochastic characteristics of wind power increase the possibility of energy curtailment. Wind spillage reached 15% of wind production in China in 2015 [2].

Besides deployment of up/down reserves by thermal units, dispatchable loads provide an appropriate mechanism to deal with uncertainty. Dispatchable loads can be scheduled and re-dispatched like generators to achieve the scheduling objective. Dispatchable loads increase the flexibility of the system, which is helpful in system with high renewable production.

To minimize the operating cost is the main objective for most Independent System Operators (ISO), but nowadays other objectives appear. For some highly-polluted areas, the ISO may seek to minimize emissions to ensure air quality. For areas with high

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http://dx.doi.org/10.1016/j.apenergy.2017.02.051
0306-2619/

renewable integration, the ISO may seek to maximize renewable production to make electricity production as "green" as possible. These distinct objectives result in different generation scheduling outcomes.

Considering the pressing problems of air pollution and wind curtailment in China, this paper focuses on the comparison of three stochastic scheduling models taking into account wind power uncertainty and dispatchable loads. The objectives are to maximize social welfare, to minimize emissions, and to maximize renewable integration, respectively. A multi-objective scheduling model that properly combines the above objectives is proposed as well. A similar methodology has not been reported in the technical literature. An illustrative example and a 57-node case study are considered to illustrate the proposed models.

1.2. Literature review

Relevant works pertaining to electricity generation scheduling models with different objectives are reviewed below. Minimizing cost (or maximizing social welfare) is the most common goal [3,4] in unit commitment problems. Soares et al. [3] formulates a day-ahead generation scheduling model to minimize the cost considering system reserves, and proposes a two-stage optimization method to solve the model. Wang et al. [4] proposes a security-constrained unit commitment model that minimizes cost considering the volatility of wind power generation. Jiang et al. [5] compares maximizing social welfare and minimizing cost in a day-ahead wholesale electricity market considering demand side management. Gent and Lamont [6] propose a dispatch model to minimize NO_x emissions. An optimal power flow model to minimize wind spillage is proposed in [7].

To deal with multiple targets in power system scheduling, multi-objective optimization models are used. Many works co-optimize cost and emission in deterministic or stochastic unit commitment problems [8–12]. Glotic and Zamuda [8] compare minimizing fuel cost and minimizing emissions in a hydro thermal power system, and formulate a decomposition model to co-optimize these two objectives together. In [9,10], similar power generation scheduling models with thermal and hydro units are formulated, and the cost vs. emission curve are provided using Pareto optimality. Sadeghian and Ardehali [11] build a generation scheduling model with the objective of maximizing profit and minimizing emissions considering heat and electricity supply. A stochastic model with the goal of cost and emission minimization that considers the uncertainty of wind power and photovoltaic units and market price is proposed in [12]. Refs. [13,14] minimize cost and emissions in generation scheduling problems considering wind power uncertainty and demand response. Prebeg et al. [15] focuses on the long-term energy planning of the Croatian power system with renewable energy and electric vehicles, and considers the objectives of minimizing the net present value, minimizing the net present value divided by the energy produced, and maximizing the renewable energy production.

Note that generally these objectives conflict with each other and cannot be optimized simultaneously. A variety of methodologies such as the weighted sum method [11], goal programming [16,17], and ε-constrained method [9,18] can be used to solve multi-objective optimization problems. In the weighted sum method, the decision maker states the relative importance of each objective function with weight factors and then add the weighted objective functions together. In goal programming, the targets are set for all the objectives, and the idea is to minimize the deviation from the goals. In the ε-constrained method, one objective is selected, and the other objectives are converted into constraints. Recently, Charitopoulos and Dua [18] propose a unified framework for multi-objective energy optimization considering uncertain parameters, and develop an algorithm based on the ε-constrained method to solve it. Trivedi et al. [19] formulates a multi-objective day-ahead thermal generation scheduling model that considers operation cost, emission cost, loss of load probability and expected unserved energy, as objective functions or constraints.

In some works, specific optimal results are not obtained directly, but a Pareto-optimal frontier (or Pareto-optimal set) is obtained [10,13,20] instead. Li and Qiu [20] consider a system with hydro power and photovoltaic power and seek to minimize the variance of power output and/or maximizing total energy generated by this renewable energy production system. The Pareto-optimal set is obtained using a modified version of a non-dominated sorting genetic algorithm [21]. Fuzzy decision-making is a methodology used to find the final optimal solution considering the decision maker's preferences about the objectives after a Pareto optimal solution set is obtained [13,22]. Hozouri et al. [22] uses a fuzzy decision-making method to balance minimum wind energy curtailment, minimum social cost, and maximum energy storage revenue.

Finally, we note that since wind power is stochastic, stochastic unit commitment is generally used in systems with important wind power uncertainty [23–27].

1.3. Contributions

Contributions of this paper are threefold:

1. To propose a versatile two-stage stochastic scheduling model considering wind power uncertainty and dispatchable loads pursuing three objectives: maximum social welfare, minimum emissions, and maximum renewable energy integration.
2. To formulate a comprehensive multi-objective scheduling model that combines these three objectives.
3. To analyze the generation scheduling results under different government policies.

Note that the novelty of the proposed analysis regarding the interactions of cost vs. emissions vs. renewable-integration in systems with demand flexibility and important renewable penetration. Moreover, we use a rigorous two-stage stochastic programming modeling framework.

1.4. Paper organization

This paper is organized as follows. Section 2 formulates the stochastic scheduling problems with the three different objectives and a parameterized combination of these objectives. Case studies are provided in Section 3. Conclusions are given in Section 4.

2. Model formulation

In this section, the three single-objective models and the multi-objective model are presented. They follow the model structure proposed in [28–30].

2.1. Notation

Indexes	
i	Index of thermal units
j	Index of demands
n	Index of nodes
p	Index of air pollutants, such as SO_2 and NO_x

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