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A spatially and temporally resolved model of the electricity grid – Economic vs environmental dispatch

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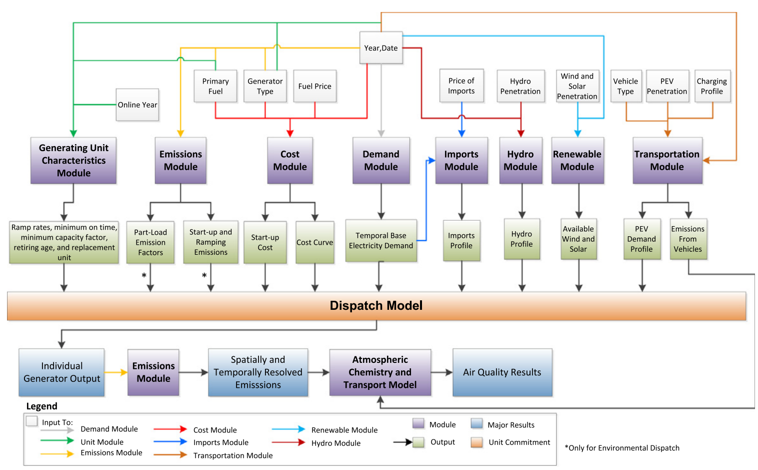
HIGHLIGHTS

- A spatially and temporally resolved dispatch model is developed.
- MCP and average price of electricity are determined for 2050 base case.
- Economic and environmental dispatch strategies are assessed.
- Environmental dispatch results in significant NO_x reduction and higher prices.
- A combination of economic and environmental strategies is the preferred method.

GRAPHICAL ABSTRACT



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ABSTRACT

Substantial changes need to occur in the electricity generation sector in order to address greenhouse gas and urban air quality goals. These goals, combined with increasing energy prices, have led to elevated interest in alternative, low to zero carbon and pollutant emission technologies in this sector. The challenge is to assess the impacts of various technologies, policies, and market practices in order to develop a roadmap to meet energy and environmental goals.

To this end, a spatially and temporally resolved resource dispatch model is developed that simulates an electricity market while taking into account physical constraints associated with various components of an electricity grid. Multiple technology simulation modules are developed to provide inputs to the model.

The model is used to design a market-based grid, and to develop and evaluate different dispatch strategies. To maintain the system cost at acceptable levels and reduce emissions, the results reveal that the best approach is a combination of economic and environmental dispatch strategies. The methodology and the tools developed provide a means to examine various aspects of future scenarios and their impacts on different sectors, and can be used for both decision making and planning.

1. Introduction

Electricity demand in the U.S. increased from 690 kW h per capita in 1930 to 12,158 kW h per capita in 2000. The energy and

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Nomenclature

AB32	Assembly Bill 32
CAISO	California Independent System Operator
FERC	Federal Energy Regulatory Commission
GDP	Gross Domestic Product
LCOE	Levelized Cost of Energy
LP	Linear Programming
LR	Lagrangian Relaxation
MCP	Market Clearing Price
MINLP	Mixed Integer Non-Linear Programming
MIP	Mixed Integer Programming
ND	Net Demand
NERC	North American Electric Reliability Corporation
PEV	Plug-in Electric Vehicle
RPS	Renewable Portfolio Standard
SB32	Senate Bill 32
SC	Scheduling Coordinator
SCED	Security-Constrained Economic Dispatch
SCUC	Security-Constrained Unit Commitment
SoCAB	South Coast Air Basin
UE	Unserved Energy

electricity demand are estimated to increase 44% and 77% from 2006 to 2030, respectively [1], and fossil fuels are projected to remain the number one source of primary energy for years to come. In the United States, coal and natural gas are the major fuels for generating electricity.

Electricity has become an inseparable part of everyday life, essential to power homes, businesses, and industry, and directly impact thereby the quality of life, economy, and gross domestic product (GDP). With increasing concerns about air quality and climate change, inflexibility of the demand side, and increasing requirements for reliability, attention in the electricity sector is focused on exploring strategies to promote a more efficient and environmental-friendly industry, keeping energy prices relatively unchanged, and providing the necessary generation to meet the future demand while ensuring that the grid meets the resiliency needs of the community.

The power generation industry has progressed from the localized distributed generation and monopoly of the *Pearl Street Station* days. Advances in technologies such as high-voltage transmission lines and computer systems facilitate the long-distance transmission of electricity. However, electricity is different from other commodities and energy sources (oil or natural gas for instance) because of its physical characteristics that require matching injection and withdrawal at each point and instant in the system (at least until massive storage becomes economically viable and pervasive for more widespread use). This characteristic makes the scheduling of electricity generation crucial. In the state of California, the California Independent System Operator (CAISO) is the responsible entity for scheduling electricity generation and also ensuring the reliability of the system. Those who wish to sell power in this market have to participate and bid into the CAISO various electricity markets including energy and ancillary services markets. The CAISO processes the bids and announces the schedule while making sure that all system constraints are met at all times.

The model developed in this work mimics the operation of the CAISO market. Not only is the model consistent with business practices and goals of the ISO, the model also has the capability to introduce advanced power generation (e.g. higher market penetration of renewable resources including wind and solar, and distributed generation such as fuel cells) in order to (1) evaluate the future economic and environmental impacts of these technologies, and (2) assess various possibilities and scenarios for the future grid from different perspectives. With California's stringent environmental policies such as Assembly Bill 32 (AB32) that requires reduction in greenhouse gas emissions to 1990 levels by 2020 [2], renewable portfolio standards (RPS) requiring that 33% of electric energy sold in the state come from renewable sources by 2020 [3], and Senate Bill 350 (SB350) that requires 50% of electric energy sold in the state come from renewable sources by 2030 [4], it is inevitable that the penetration of renewable sources of energy will increase in the future. The current model and research can help clarify (1) how the addition of renewable sources can affect the electricity market, and (2) if and how the market procedures should change in order to better accommodate these new technologies.

The model is capable of resolving the spatial and temporal operation of the utility grid network. It is temporally resolved in order to predict the market results with a resolution of down to 5 min. It is spatially resolved in order to include the amount of electricity that each specific generator produces. Resolving the spatial and temporal electricity generation also allows the amount of pollutants emitted from each generator to be established as a function of space and time, thereby providing the opportunity to study air quality impacts associated with various market and generator dispatch strategies [5].

Currently, several ISOs use the Security Constraint Unit Commitment (SCUC) to clear their energy and ancillary services markets and find the corresponding Market Clearing Price (MCP) for these markets. SCUC commits generating units in the day-ahead market and allocates the necessary reserves. In the real-time markets, the Security Constrained Economic Dispatch (SCED) algorithm is used and, for all intents and purposes is the same as the SCUC but with more accurate inputs and network parameters.

The objective of the SCUC is to find a dispatch schedule that minimizes the electricity price (which results in minimizing the social cost in most cases), and also ensure the reliability of the system (and hence the term Security-Constrained). Moreover, the SCUC is subject to several constraints, most of which are associated with the physical characteristics of the generating units and reliability of the electric utility network, while other constraints are due to various regulations and laws (e.g., environmental regulations). The solution of the SCUC problem results in a challenging Mixed-Integer Nonlinear Programming (MINLP) problem.

1.1. Previous related studies

After deregulation and development of competitive markets for electricity, many studies have modeled the restructured electricity market. In competitive markets, each participant in the market tries to maximize profit. Some of the previous studies have focused upon modeling a single firm's profit and determining how they could effectively participate in the market. In these studies, Linear Programming (LP) and MINLP methods are used to obtain the solution. If the price uncertainty is taken into account, the scheduling of each unit of the firm can be treated independently, thus simplifying the problem. This strategy has been used in [6] to optimize self-commitment under uncertain energy and reserves prices, and in [7] for portfolio managent. These sets of problems have been typically solved using backward Dynamic Programming solution strategies.