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A multi-period optimization model for energy planning with CO_2 emission consideration

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ABSTRACT

A novel deterministic multi-period mixed-integer linear programming (MILP) model for the power generation planning of electric systems is described and evaluated in this paper. The model is developed with the objective of determining the optimal mix of energy supply sources and pollutant mitigation options that meet a specified electricity demand and CO_2 emission targets at minimum cost. Several time-dependent parameters are included in the model formulation; they include forecasted energy demand, fuel price variability, construction lead time, conservation initiatives, and increase in fixed operational and maintenance costs over time. The developed model is applied to two case studies. The objective of the case studies is to examine the economical, structural, and environmental effects that would result if the electricity sector was required to reduce its CO_2 emissions to a specified limit.

1. Introduction

The optimization of the power system planning problem is a very challenging undertaking that requires consideration of various drivers and decision criteria. There are various supply technologies that may be used in order to meet the demand of a power system. These supply options differ based on several factors; including economical variability, environmental impact, operational characteristics, and construction lead time. For instance, some technologies offer lower capital and operating cost at high emission rates, while others have higher associated costs but lower environmental impacts. In addition to the different supply technologies, there are several pollutant mitigation options, such as Carbon Capture and Storage (CCS), which may be utilized. The underlining question then becomes, what is the optimal mix of supply technologies and pollutant mitigation options that should be selected in order to meet the annual electricity demand and environmental limits of a given power system, while minimizing the overall cost? This question is further complicated by introducing additional external multi-period factors such as annual fuel price fluctuations and conservation and demand management (CDM) strategies.

Numerous works have been published on using multi-period optimization methods for planning purposes. Iyer et al. (1998) have developed a multi-period mixed-integer linear programming (MILP) model for the planning and scheduling of offshore oil field facilities. This mathematical model employs a general objective function that optimizes a selected economic indicator. Maravelias and Grossmann (2001) proposed a complex multi-period optimization model to address the challenge of planning for the production of a new product in highly regulated industries, such as pharmaceuticals and agrochemicals. The model uses a multi-period MILP model that maximizes the expected net present value of a multi-period project. The model, although comprehensive, does not account for the lead time required for construction of new plants. Mo et al. (1991) developed a stochastic dynamic model for handling the uncertainties in generation expansion problems. The model makes it possible to identify the connection between investment decisions, time, construction periods, and uncertainty.

Hashim et al. (2005) and Elkamel et al. (2009) developed a single-period deterministic MINLP optimization model aimed at predicting a fleet-wide system configuration which simultaneously satisfies electricity demand and CO_2 emission constraints at minimum cost. The mathematical model developed was linearized using exact linearization techniques in order to overcome the inherent problems with solving non-linear models. Although the model developed by Elkamel et al. (2009) is very comprehensive and complex, its single-period mathematical structure does not allow the incorporation of multi-period factors such as construction lead time and fuel price fluctuations over time. A number of other studies that deals with energy planning models appeared

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also in the literature. We refer the reader to the survey paper by Hobbs (1995) that provides a review of optimization models for electric utility resource planning. Jebaraj and Iniyan (2006) also presented a comprehensive review of the literature on the various emerging issues related to the energy modeling problem.

In this paper, a novel deterministic optimization model was developed. This model considers multi-period factors and CO_2 mitigating technologies in order to select the optimal mix of energy supply sources that will meet current and future electricity demand and CO_2 emission targets, and will minimize the overall cost of electricity. In the following section we present the mathematical formulation for the deterministic multi-period MILP model. The mathematical formulation includes an objective function that minimizes the overall cost, and several model constraints to satisfy energy demand, CO_2 emission limits, operational restrictions, and logic-defined limitations. We then apply the developed model to two case studies directed towards the electricity sector of the province of Ontario, Canada. The results of the two case studies are presented and analyzed in order to examine the economical and structural impact on Ontario's electricity sector when forced to comply with a given CO_2 emission limit.

2. Model formulation

The indices, sets, variables, and parameters used in the planning model are as follows.

Indices

t	Time period (years)
i	Boiler
j	Fuel type (coal or natural gas)
l	Load block (peak or base load)
k	Carbon capture technology

Sets

F	Fossil fueled power plants
F^c	Coal Power Plant
NF	Non-fossil fueled
new	New power plants
new^{cap}	New power plants with carbon capture

Parameters

F_{ijt}	Fixed operating cost of boiler i using fuel j during period t ($/MW)
V_{ijt}	Variable operating cost of boiler i using fuel j during period t ($/MWh)
C_{ij}	Capacity of boiler i using fuel j (MW)
P_{lt}	Duration of load block l during period t (hrs)
U_{jt}	Fuel cost for fuel j during period t ($/GJ)
G_{ij}	Heat rate of boiler i using fuel j (GJ/MWh)
R_{it}	Cost associated with fuel-switching coal-fired boiler i during period t ($/MW)
S_{it}	Capital cost of power plant i during period t ($/MW)
T	Time horizon (year)
$[(CCost)]_t$	Cost of carbon credits during period *t* ($/tonne of CO_2)
$(CO2)_{ij}$	CO_2 emission from boiler *i* using fuel *j* (tonne of CO_2/MWh)
E_k^{max}	Maximum supplemental energy required for *k*th capture technology
ε_{ikt}	Percent of CO_2 captured from boiler *i* using carbon capture technology *k* during period *t* (%)
β_i	Construction lead time for power station *i* (years)
Q_i	Cost of carbon capture and storage for boiler *i* ($/tonne of CO_2)
D_{tl}	Electricity demand during period *t* for load *l* (MWh)
B_{tl}	Conservation and demand management during period *t* and load block *l* (MWh)
ρ	Factor for transmission and distribution losses
$CLimit_t$	Specified CO_2 limit during period *t* (tonne of CO_2)
α_{ijktl}	Parameter used in linearizing cross terms

Binary variables

n_{it}	$= 1$ if power plant *i* is built during period $t = 0$ otherwise
y_{it}	$= 1$ if power plant *i* is operational during period $t = 0$ otherwise
x_{ijt}	$= 1$ if coal-fired boiler *i* is operational while using fuel *j* during period $t = 0$ otherwise
z_{ijkt}	$= 1$ if the carbon capture technology *k* is used on boiler *i*, which uses fuel *j*, during period $t = 0$ otherwise
h_{it}	$= 1$ if coal-fired boiler *i* undergoes fuel-switching during period $t = 0$ otherwise

Continuous variables

E_{ijlt}	Power allocation from boiler i using fuel j for load block l during period t (MW)
E_{ilt}	Power allocation from boiler i for load block l during period t (MW)
$[(Cre)]_t$	Carbon credits purchased during period t (tonne of CO_2)

All parameters listed above and which are related to costs represent discounted present values.

2.1. Objective function

The objective function of the deterministic multi-period MILP model is to minimize the total discounted present value of the cost over a specified planning horizon, and is presented as follows:

$$
\begin{aligned}
\min f(i,j,k,l,t) = {} & \underbrace{\sum_{i\in F}\sum_{j}\sum_{t} F_{ijt}^{F} C_{ij}^{F} x_{ijt} + \sum_{i\in NF}\sum_{t} F_{it}^{NF} C_{i}^{NF} y_{it}^{NF}}_{\text{Fixed O\&M cost of existing power plants}} + \underbrace{\sum_{i\in F}\sum_{j}\sum_{l}\sum_{t} V_{ijt}^{F} E_{ijlt}^{F} P_{lt} + \sum_{i\in NF}\sum_{l}\sum_{t} V_{it}^{NF} E_{ilt}^{NF} P_{lt}}_{\text{Variable O\&M cost of existing power plants}} + \\
& \underbrace{\sum_{i\in F}\sum_{j}\sum_{l}\sum_{t} U_{jt} G_{ij}^{F} E_{ijlt}^{F} P_{lt}}_{\text{Fuel cost for fossil fuel plants}} + \underbrace{\sum_{i\in F}\sum_{t} R_{it} h_{it}}_{\text{retrofit cost for fuel switching}} + \underbrace{\sum_{i\in new}\sum_{t} S_{it}^{new} C_{i}^{new} n_{it}}_{\text{capital cost for new power plant}} + \underbrace{\sum_{i\in new}\sum_{t} F_{it}^{new} C_{i}^{new} y_{it}^{new}}_{\text{Fixed O\&M cost of new power plant}} + \\
& \underbrace{\sum_{i\in new}\sum_{l}\sum_{t} V_{it}^{new} E_{ilt}^{new} P_{lt}}_{\text{Variable O\&M cost of new power plant}} + \underbrace{\sum_{i\in new}\sum_{l}\sum_{t} U_{it} G_{i}^{new} E_{ilt}^{new} P_{lt}}_{\text{Fuel cost for new power plant}} + \underbrace{\sum_{t} (Cre)_t (CCost)_t}_{\text{Cost of purchasing CO}_2\text{ emission credits}} + \\
& \underbrace{\sum_{i\in F}\sum_{j}\sum_{k}\sum_{l}\sum_{t} Q_i (CO2)_{ij} \varepsilon_{ikt} \alpha_{ijktl} P_{lt}}_{\text{Carbon capture and storagecost for existing power plants}} + \underbrace{\sum_{i\in new^{cap}}\sum_{l}\sum_{t} Q_i (CO2)_i \varepsilon_{ikt} E_{ilt}^{new} P_{lt}}_{\text{Carbon capture and storage cost for new power plants}}
\end{aligned}
$$