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An optimization model for natural gas supply portfolios of a power generation company

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HIGHLIGHTS

- An optimization model for daily operation of a natural gas-fired generation company is proposed.
- The model considers uncertainties in electricity price and natural gas price.
- The model is formulated to capture the hedging decisions by the company.
- The solution yields quantities of natural gas, generating schedule and purchasing quantities of electricity.
- Higher profit can be achieved by adapting inventory and production to the actual spot prices of natural gas and electricity.

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ABSTRACT

This paper considers a deregulated electricity market environment where a natural gas-fired generation company can engage in different types of contracts to manage its natural gas supply as well as trade on the electricity market. If the contracts are properly designed, they can protect the company from fluctuations in electricity price and demand, at some cost to the company's expected profit. This reduction in profit can be mitigated by trading on the natural gas and electricity spot markets, but this trading activity may also sometimes result in losses. A stochastic programming model is formulated to capture the hedging decisions made by the company, as well as the interactions between the natural gas and electricity markets. The benefits offered by this approach for profit maximization in a variety of business scenarios, such as the case where the company can hold some amount of gas in storage are studied and presented. It is found that the stochastic model enables the company to optimize the electricity generation schedule and the natural gas consumption, including spot price transactions and gas storage management. Several managerial insights into the natural gas market, natural gas storage, and distribution profit are given.

1. Introduction

Deregulation of the energy industry has exposed companies that operate natural-gas plants to risks stemming from price and demand fluctuations. At the same time, deregulation has created new opportunities for increased profit for companies with access to natural gas and electricity spot markets. Where such companies were once concerned solely with generating electricity at minimum cost (perhaps receiving a fixed profit margin), they can now obtain larger profits by building appropriate hedging strategies using available market instruments. These opportunities can be realized, for instance, by concurrently optimizing a company's natural gas supply as well as its energy trading strategy.

In this paper, we consider the operation of an electric power company in a deregulated market. The company acts as a price-taker in both electricity and natural gas spot markets. At the beginning of a planning horizon of four weeks, the company sets the contract terms for natural gas procurement. A part of the total volume of gas is delivered as a 24-h constant block, as in a take-or-pay type of contract. This volume is called *baseline gas*. Another part of the total volume is delivered daily as a block of constant height over a fixed period of some hours. This is called *intra-day natural gas*. The company can also buy (and sell) natural gas from the spot market on an hourly basis. This volume of gas is referred to as *swing gas*. In addition, the company has access to gas storage capacity, with the option of withdrawing or storing gas in every hour, or even selling gas back to the spot market. The amount of natural gas traded by the company in every hour is limited. Natural gas procurement through baseline and intra-day gas contracts

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Nomenclature

Indices

i	index of hours, $i = 1, \ldots, 24$
j	index of days, $j = 1, \ldots, \mathcal{D}$
$\mathbb{I}$	set of hours in each day receiving intra-day natural gas; $\mathbb{I} \subset \{1, \ldots, 24\}$
ω	index for scenarios, $\omega = 1, \ldots, \mathcal{W}$
k	index of gas-fired generation units, $k = 1, \ldots, \mathcal{K}$

Decision variables

$y^{gen}_{\omega kij}$	energy generated in scenario ω by generation unit k at hour i on day j (MW-h)
$y^{sell}_{\omega ij}$	energy sold in the electricity pool market in scenario ω, at hour i, on day j (MW-h)
$y^{buy}_{\omega ij}$	energy purchased from the electricity pool market in scenario ω, at hour i, on day j (MW-h)
x^{base}	baseline natural gas delivered at each hour (MBtu)
x^{intr}	intra-day natural gas delivered at each hour (MBtu)
$x^{buy}_{\omega ij}$	natural gas purchased from spot market in scenario ω, at hour i, on day j (MBtu)
$x^{sell}_{\omega ij}$	natural gas sold to spot market in scenario ω, at hour i, on day j (MBtu)
$x^{spot}_{\omega j}$	total spot market natural gas purchased or sold in scenario ω on day j (MBtu)
$x^{in}_{\omega ij}$	natural gas injected into storage facility in scenario ω, at hour i, on day j (MBtu)
$x^{out}_{\omega ij}$	natural gas withdrawn from storage facility in scenario ω, at hour i, on day j (MBtu)
$x^{gen}_{\omega kij}$	Natural gas used to generate electricity in scenario ω by generation unit k during hour i on day j (MBtu)
$S_{\omega ij}$	amount of natural gas in storage in scenario ω on day j at the beginning of hour i
z^{intr}	binary variable for intra-day natural gas, equal to one if intra-day natural gas is introduced and zero otherwise

Parameters

c^{opr}_k	operation cost of generation unit k (\$/MW-h)
$f^{\mathcal{HR}}_k$	heat rate function of generation unit k (MBtu/MW-h)
τ	duration of intra-day natural gas (h)
E_{ij}	contract electricity price at hour i, day j (\$/MW-h)
g^{base}	baseline natural gas price (\$/MBtu)
g^{intr}	intra-day natural gas price (\$/MBtu)
$g^{spot}_{\omega j}$	spot market natural gas price in scenario ω on day j (\$/MBtu)
D_{ij}	contracted energy for hour i on day j (MW-h)
c^{pump}	Storage facility pumping cost (\$/MBtu)
$p^{pool}_{\omega ij}$	pool market electricity price in scenario ω, at hour i, on day j (\$/MW-h)
ρ_ω	probability of scenario ω
$\overline{P}^{gen}_k$	maximum capacity of generation unit k (MW)
$\underline{P}^{gen}_k$	minimum capacity of generation unit k (MW)
$\overline{S}^{str}$	maximum capacity of natural gas storage facility (MBtu)
$\underline{S}^{str}$	minimum capacity of natural gas storage facility (MBtu)
$\overline{G}^{base}$	maximum baseline natural gas contract at each hour (MBtu)
$\overline{G}^{intr}$	maximum intra-day gas contract at each hour (MBtu)
$\underline{G}^{intr}$	minimum intra-day gas contract at each hour (MBtu)
$\overline{G}^{spot}$	maximum natural gas that can be purchased from spot market at each day (MBtu)
$\overline{G}^{pipe}$	maximum natural gas that can be delivered through pipeline per hour (MBtu)
$\overline{r}_k$	ramp-up factor of generation unit k
$\underline{r}_k$	ramp-down factor of generation unit k

allows the company to decrease its exposure to short-term natural gas price fluctuations. However, since these gas volumes will be constant for a 30-day period, there is a greater risk of having excess gas and not being able to store it. Trading in spot markets helps to adjust these risks. The company can also supply electricity through bilateral contracts with one or more customers.

We formulate a stochastic optimization model that enables the company to find optimal amounts of gas to be procured through contracts, an optimal trading strategy both in the electricity as in the natural gas spot markets, and an optimal strategy for managing gas storage. Uncertainty mainly comes from electricity and natural gas spot prices. We use autoregressive models to capture their behavior and generate scenarios. The model is formulated considering baseline and intra-day natural gas volumes as first stage decisions, and operation scheduling over the following four weeks as second stage decisions. In the second stage, every scenario corresponds to a 30-day realization of the electricity and natural gas spot price processes. Several instances of the problem are built in order to study the properties of optimal strategies. We want to assess the value of incorporating stochasticity in prices and maintaining natural gas storage capacity. We report results from numerical experiments for several different cases.

The rest of the paper is organized as follows. Section 2 contains a brief review of relevant literature. Section 3 lays out the problem description and discusses issues involving natural gas delivery terms, power generation units, electricity markets, and the value of the stochastic solution. In Section 4 we describe our model, where the natural gas supply and energy portfolio problems are combined and formulated as a stochastic mixed-integer linear programming (SMILP) model. Section 5 presents a numerical study and discusses computational experiences. Section 6 presents our conclusions and outlines directions for future research.

2. Literature review

The literature can be broadly categorized into two streams of research: natural gas supply and energy portfolio management. The first stream focuses on the optimal procurement of natural gas, as well as management of natural gas storage (if such is available). It is possible to distinguish contributions according to the nature of the organization considered, which can be either a natural gas distributor or a generation company. Guldmann [1] investigated the sourcing problem of a natural gas distributor and analyzed the trade-off among supply, storage, and service reliability. Bopp et al. [2] further examined this problem considering a minimum expected-cost model, taking into consideration the uncertainty in price and demand. A generation company that owns gas-fired plants is faced with several decisions regarding natural gas supply. Chen and Baldick [3] proposed an optimization model for short-term natural gas contract selection. At the beginning of each planning horizon, the company enters into natural gas futures contracts with different delivery terms. Since we take a similar point of view, these delivery terms are explained in Section 3, where we discuss the framework of our model. They incorporated the financial risks due to the stochastic natural gas spot price and demand, and the risk preferences of the utility companies, into their cost minimization model.

A substantial amount of work has been done in the second stream of research, and a common approach to model energy portfolio optimization problems is using the SMILP framework. In this