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The operational economics of compressed air energy storage systems under uncertainty

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ABSTRACT

A Compressed Air Energy Storage System is a means of storing energy which can then be used when the demand for energy increases. In this system, air is compressed in a cavern when power prices are low, and this air is used to run a natural gas-fired turbine to generate power when prices go up, with the aim of profiting from the price difference. This type of system can independently compress air, generate electricity, or do both. However, the prices of electricity and natural gas fluctuate, which directly impacts the amount of revenue that can be made, and this requires the calculating of estimates to optimize operation strategies and maximize profit. For these reasons, this is a crucial energy storage technology that requires economic analyses to justify investment decisions in power markets. In this paper, a mixed integer programming method is developed to schedule the operation of the system for forward market prices that are estimated using a markov-based probabilistic model. Then an algorithm that includes two separate modules in a simulation is employed to optimize the annual operation of the system. The paper presents a case study for Turkey as well as economic analyses based on probabilistic forward prices and the profits obtained from the optimization module.

Contents

1. Introduction

Compressed Air Energy Storage (CAES) is an integrated system that is used to store potential energy during off-peak times which can then be used when energy is needed during peak times. The CAES system can be thought of as a modification to a Natural Gas Turbine (NGT) in which the generation turbine is connected to an air compressor. When natural gas is combusted in the turbine to generate electricity, the compressed air drives the combustion process. In such a system, the compressor usually consumes two-thirds of the electric power generated in the gas turbine and thus only one-third of the power output is actually transmitted to the power grid. The CAES system makes it possible to separate the combustion and compression processes, thus resulting in three times more power output in terms of energy input. Currently, there are two CAES plants in operation, one of which is the Huntorf Plant which began operations in 1978 as the world's first CAES [1]. The plant provides peak shaving, spinning reserves and support for the power market with a capacity of 290 MW. The total volume of the reservoir, which is composed of two underground salt caverns

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Notation

t	hour index in the year
n	year index
$G_{n,t}$	1 if the unit generates in hour t of year n, 0 otherwise
$P_{n,t}$	1 if the compressor runs in hour t of year n, 0 otherwise
$U^c_{n,t}$	1 if the compressor is started up in hour t of year n, 0 otherwise
$U^g_{n,t}$	1 if the generator is started up in hour t of year n, 0 otherwise
$I_{n,t}$	inventory of the compressed air in hour t of year n (generation hours)
$I_{n,f}$	inventory of the compressed air at the beginning of year n (generation rs)
$I_{n,l}$	inventory of the compressed air at the end of year n (generation hours)
Q_G	the capacity of the generating unit (MW)
Q_C	the capacity of the compressor (MW)
Q_{CT}	the capacity of the gas cycle turbine (MW)
$MP_{n,t}$	market price for power in hour t of year n ($/MWh)
$N_{n,t}$	the gas price in hour t of year n ($/mmBTU)
H_{CT}	the heat rate of the gas cycle turbine (mmBTU/MWh)
VOM^g_n	the variable operation maintenance cost for generator in year n ($/MWh)
VOM^C_n	the variable operation maintenance cost for compressor in year n ($/MWh)
S^c_n	start-up cost of the compressor in year n ($/start-up)
S^g_n	start-up cost of the generator in year n ($/start-up)
κ	the number of compression hours consumed by each generating hour
B	the number of generating hours possible for each compression hour
θ	the capacity of the facility in total compression hours
η_c	efficiency of the compressor
η_g	efficiency of generation turbine
$r(n)$	the change in power price in year n compared to year $n-1$ (%)
$s(n)$	the change in natural gas price in year n compared to year $n-1$ (%)
P_r	transition probability matrix for $r(n)$
A_n	DTMC states for power price changes
q_n	the steady state probabilities for annual change in power prices
$F_r()$	the cumulative distribution function of the percentage changes in power prices
$s(n)$	the change in natural gas price in year n compared to $n-1$ (%)
T_r	transition probability matrix for $s(n)$
B_n	DTMC states for natural gas price changes
ν_n	the steady state probabilities for annual change in natural gas prices
$H_r()$	the cumulative distribution function of the percentage changes in natural gas prices
Rv_n	operation revenue of the CAES in year n (Objective function value)
y	number of replications in the multi-year analysis
f	discount rate for the forward revenues
CC_O	the total initial cost of CAES system ($)

located 2100–2600 feet below the surface, is 11 million cubic feet, and these hold up to 1000 psi of compressed air. The system fully recharges 12 h of off-peak power, and the system can run at full output capacity for up to 4 h. The other CAES plant is the McIntosh facility which was built in 1991 and is currently owned by the Alabama Electric Power Company. It is run from a cylindrical salt cavern, which at 300 m deep and 80 m wide contains a volume of 5.32 million m^3. The plant has a capacity of 110 MW and can supply power for 26 h with a start-up of 9–13 min. A typical CAES consists of a serial system that includes a compressor, storage, expander and generator, as illustrated in Fig. 1 [2]. Air is injected into a secure storage area via a compressor which consumes off-peak power, which is generally cheaper. This air is then cooled and stored in a leak-proof subsurface reservoir, typically a natural cavern, salt cavity or aquifer. When electricity is in demand, the air is channeled into a conventional gas turbine expander to be used in the combustion of fuel for the generator.

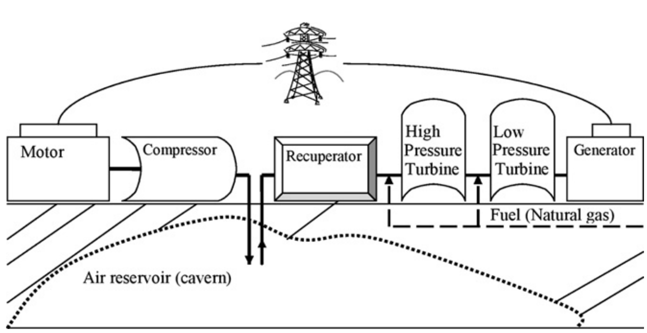

Fig. 1. Operation of a CAES system.

The amount of volume required for a reservoir is related to the desired capacity of a power plant; naturally, a larger reservoir makes it possible to compress more air and hence generate more power. While such a system is optimal at large scales with higher storage and production capacities (around 50–400 MW), it is important that the reservoir volume and plant capacity are properly configured for maximum efficiency. The compressed air can be stored for up to one year, depending on the quality of the seal of the reservoir. Conventional NGTs require 20–30 min for a normal start-up, and this is one of the fastest start-up times compared to other thermal power plants. CAES, on the other hand, can have an emergency start-up time of around 10 min and a normal start-up of 12 min, and this makes it possible for such a system to be used as an alternative power source for load changes or drops in power generation. Since the system is underground, it is not visible, and it also produces lower emissions, which is also advantageous [3].

Energy storage allows for more efficient usage of baseload generation as it significantly decreases the requirements of extra power and reserve levels for peak demand hours. As such it is an economically viable option and has the potential to play a vital role in deregulated power markets. Since the direct storage of electricity is quite expensive, power is stored in other forms, and when electricity is needed, the stored form of power is then transformed into electricity. In deregulated power markets, the supply and demand of electric power determines the hourly market clearing price. Lower demand for electricity drives prices down, while increased demand pushes prices up. Demand usually displays a cyclic pattern in which demand increases during the day and decreases to a minimum at night, and this pattern is reflected in the price of power during a 24-hour period. When prices are low and there is space is available, the system