Scheduling Compressed Air Energy Storage Systems

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Abstract: A Compressed Air Energy Storage System (CAES) is a way to store energy to be used when the demand for energy is high. In this system, the air is pumped into a cavern when the power price is low and the air is used in a natural gas fired turbine to generate power when the price is high aiming to make profit from this price difference. The system can pump or generate or do both. Typically the power price is low at nights and high during the daytime. However, the power and natural gas price along with the heat rate of the turbine should be included to the model to determine when the air should be pumped and when the power should be generated to maximize the revenue. In this research, a mixed integer programming method is developed to determine a pumping-generation schedule for the CAES given that market and natural gas price for each hour can be forecasted. Appropriate forecasting methods are used to forecast the power and natural gas prices for the analysis. The model is coded in General Algebraic Modeling System (GAMS) and a case study is presented to validate the model.

Keywords: *CAES, power price, natural gas, energy storage, optimization, scheduling*

Nomenclature (Optional)

G_t *1 if the unit generates in hour t, 0 otherwise……………………………......*
P_t *1 if the pumping unit works in hour t, 0 otherwise………………………....*
U_t^c *If compressor started up at hour t…………………………………………......*
U_t^g *If generator is started up at hour t……………………………………………….*
I_t *Inventory of the compressed air in hour t…………………………………hours*
I_b *The inventory of compressed air at the beginning……………………….hours*
I_e *The inventory of compressed air at the end…………………………….hours*
Q_G *The capacity of the generating unit………………………………………..Mw*
Q_G *The capacity of the pumping unit…………………………………………..Mw*
QC_T *The capacity of the gas cycle turbine……………………………………...Mw*
LMP_t *Locational marginal price at the pumped air station bus……………….TL/MWh*
H_{CT} *The heat rate of the gas cycle turbine……………………………………mmBTU/Mwh*
N_t *The gas price in hour t……………………………………………………..$/mmBTU*
VOM_G *The variable operation maintenance generation cost…………………$/Mwh*
S_t^c *Start- up cost of compressor……………………………………………. $/start-up*
S_t^g *Start- up cost of generator…………………………………………………..$/start-up*
κ *The number of pumping hours consumed by each generating hour…....hours*
B *The number of generating hours possible for each pumping hour…......hours*
Θ *The capacity of the facility in total pumping hours………………………..hours*
η_c *Efficiency of compressor…………………………………………………………*
η_t *Turbine efficiency……………………………………………………………….*

1. Introduction

Compressed air energy storage (CAES) is a hybrid generation or storage technology that is used to store the potential power in a cavern when the electricity is not demanded and used to generate electricity when the electricity is highly demanded. The technology allows air to be injected at high pressure into natural caverns. The underground reservoirs can be salt cavern, abandoned hard rock mine, or aquifer [1]. This compressed air assists the operation of natural gas-fired turbines at the times when there is an increased need for electricity. For generating electricity; the compressed air allows the turbine to generate electricity using less natural gas [2], [3]. Load-leveling is adopted via CAES because CAES is created in capacities of a few hundred MW and can be started up quickly over long (4-24 hours) periods of time and can have a fast ramp-up rate. In this technology, the low-cost power from an off-peak baseload facility is replaced for the more expensive gas turbine-produced power to compress the air for combustion. Nearly two thirds of the energy produced is used to pressurize the air in a gas turbine.

In CAES systems, if the energy is available, the air will run the air compressors. Then the compressors will pump the air into the storage cavern. When the electricity is demanded, it is expanded via conventional gas turbine expanders. Huntorf Plant is the world's first compressed air storage power station. In 1978, the Huntorf Plant which is located in Bremen, Germany began operation. The capacity of the plant was 290 MW. The plant used to provide peak shaving, spinning reserves and support for the power market. Total volume of the plant is 11 million cubic feet. This plant has two underground salt caverns which is pressures up to 1000 psi inside and also situated 2100-2600 feet below the surface. The system is fully recharging 12 hours of off-peak power, and the delivering full output capacity of the system for up to 4 hours [1].

A CAES system has a compressor section which pumps air into cavern and an expander section which transmits air to a combined cycle natural gas fired turbine to generate power. Conventional gas turbine has a two-stage expander section [4]. The first expander section is usually committed to running the two-stage compressor and no energy goes to generating electricity at this stage. The quantity of the mechanical energy which used to run the compressor sections of the turbine is nearly 2/3. The expander does not drive the compressor when CAES system is used as the air is already compressed. As a result, the net yield of the expander increased by 3 times because there will not be waste of energy to expand the air to combined cycle turbine. Decreasing of the amount of gas required during expansion is another issue proposed by different concepts. Waste heat from the compression cycles is recovered in the McIntosh Plant. The McIntosh Plant is reducing natural gas more than the Huntorf Plant.

Energy storage is an economic decision. In the deregulated power markets, energy storage has vitally important role. The direct storage of electricity is very expensive so the electricity is stored in other forms. If the electricity is needed, the system will transform the electricity from the stored form to the real power. The cost of power is cheap at night so the system is storing power at night. Integrating the existing segments and creating a more responsive market is the critical issues for Electric power market. Storage will improve the reliability of electricity supply. Also, increasing the productivity of existing power plants and transmission facilities can be done with storage. Electricity storage can be beneficial to reduce the investment necessary in these facilities [5].

To generate power, the system releases during peak daytime hours to power a turbine or generator. However, the price of power and natural gas change each hour and the CAES system will run only if it is economic. There are start-up costs for compressor and expander section each time they start working. The problem becomes when to run the compressor and when to run the expander given a set of forecasted power and natural gas prices over the year in order to maximize the profit. The next section provides the problem formulation and model details.

2. Problem formulation

CAES has a fairly low capital cost compared to other energy storage technologies. The CAES unit can pump or generate in any hour. In such systems, the most important issue is to decide when is the best time for pumping the air or generating the electricity while releasing the air. One should know the market prices or at least can forecast the possible market prices in order to schedule a CAES system. Another important issue is the price of natural gas that is used in the CAES system as it directly affects the profit and cost hence it becomes an issue for scheduling. The CAES system has an air inventory that is filled while pumping and emptied while generating electricity as the air is used in turbine to generate electricity. The hourly profit is the revenue which is gained when the power is sold to the market, minus the cost which is the variable and operating cost, natural gas cost, and sum of start-up costs. The sum of hourly profits over the year can give us the total profit of the corresponding year. The capacity of the compressed air storage facility is important for CAES analysis. We assume that the facility starts with a full inventory of compressed air and finishes with a full inventory of compressed air. The problem then becomes to use the air inventory efficiently to maximize the profit. The schedule of pumping and generation depends only on the relative prices and the capacity of the storage facility. In other words, the generation will be scheduled when the hourly power prices are high enough that will cover the cost of natural gas and operating costs and make profit. The pumping will be scheduled when the power prices are too low that will give the minimum cost so that the power can be sold later for profit. We did not include fixed costs to the model as they do not affect the scheduling. The model is given as follows:

$$Max \sum_{t=1}^{T}\left[G_t(Q_G(LMP_t - VOM_G) - Q_{CT}H_{CT}N_t) - \frac{(LMP_t + VOM_C)Q_C P_t}{\eta_t \eta_C} - S_t^C U_t^C - S_t^g U_t^g \right] \quad (1)$$

s.t

$$I_{t+1} - I_t + \kappa G_{t+1} - P_{t+1} = 0 \quad (2)$$

$$G_{t+1} \le \beta I_t \quad (3)$$

$$I_f = I_l = \theta \quad (4)$$

$$U_t^C \ge P_t - P_{t-1} \quad (5)$$

$$U_t^g \ge G_t - G_{t-1} \quad (6)$$

$$0 \le P_t \le 1 \quad (7)$$

$$0 \le G_t \le 1 \quad (8)$$

$$U_t^C, U_t^g \in \{0,1\} \quad (9)$$

The objective function Eq. (1) is the revenue minus cost of natural gas, variable operating cost and startup costs. The first part in the parenthesis represents the differences between the locational market price at the pumped air station bus and the variable operational maintenance generation cost at hour *t*. At the first part of the equation; the net market price at hour *t* is multiplied with the MW rating of the generating unit to calculate the revenue at hour. In the next part; the cost of gas at hour *t* is calculated. At this part the rating of the gas cycle turbine multiplied with the heat rate of the gas turbine and it is multiplied with the gas price in hour *t*. In this part the system calculates the gas turbine‘s cost at hour *t*. Then at the last parenthesis equation the function calculates the total pumping cost of the system.

The locational market price at hour *t* plus the variable operational maintenance pumping cost at hour *t* gives the total cost of the pumping station. The efficiency of the compressor and turbine are also included. Then the pumping cost at hour *t* is multiplied with the MW Rating of the pumping unit for total pumping cost. The last part of the objective function has two binary equations. If the compressor is started up at hour *t*, the start up cost of compressor will be included. If the compressor is not started up at hour *t*, the started up cost of compressor will not be included at hour *t*. If the generator is started up at hour *t*, the start up cost of the generator will be included at hour t. If the generator is not started up at hour *t*, the started up cost of generator will not be included.

In the constraint section Eq. (2) shows the change in the air inventory. The inventory is measured in units of generation hours that can be gained from the stored air in the inventory. The air inventory at time *t+1* is equal to air that was available at time *t* plus injected air and minus used air for generation. Eq. (3) gives the relationship between the air inventory and possible generation hour. The unit generation in hour *t+1* should be less or equal to possible number of generating hours for each pumping hour. Eq. (4) states that the air inventory starts with a full level and ends with a full inventory. Eq. (5) and (6) are the binary constraints to ensure the start-up times for compressor and expander. The start-up points directly affect the start-up costs so it becomes very important to determine the right start-up point. Eq. (7) and (8) represent the binary equations meaning that it the system is pumping or generating the value will be 1 otherwise it will be represented with 0. Eq. (9) ensures the binary conditions.

To optimize the scheduling of the facility, one needs to know the forward electric prices, forward natural gas prices and the value of CAES air inventory. The market price for electricity and natural are stochastic and the value of air inventory depend on the market prices for both. In order to schedule a CAES system, we should first determine the hourly price scenarios and natural gas scenarios.

3. Numerical Analysis

We develop a numerical analysis to validate our model. The base for the analysis is the CAES system given in [2]. The system has a turbine capacity of 360 MW, compressor capacity of 216 MW and a storage capacity of 1478 GW capacity which is equal to 68 hours of generating capacity. The details are given in Table 1. The model is implemented in General Algebraic Modeling System (GAMS) which is one of the high-level modeling system for mathematical programming problems.

Table 1. Details of the CAES system

Compressor	Capacity	216 MW
	Efficiency	0.691
Storage	Capacity	1478 MW
Turbine	Capacity	360 MW
	Efficiency	2.44
	Fuel Ratio	1.15
Investment	Costs	411.750.000 TL
	Life Time	30 Years
	Interest Rate	8%
Operation Costs	Fixed Costs	10.633.104 TL/Year
	Variable Compressor	5.135.563 TL/MWh
	Variable Turbine	6.040.508 TL/MWh

The power price is a stochastic decision variable which depends on the load, temperature, unit breakdowns, workdays etc. The hourly price in a day has cyclic with random deviations which need to be estimated. The model takes the hourly power price as the input for the scheduling. Figure 1 shows the hourly power price for 2010 in Turkish power market.

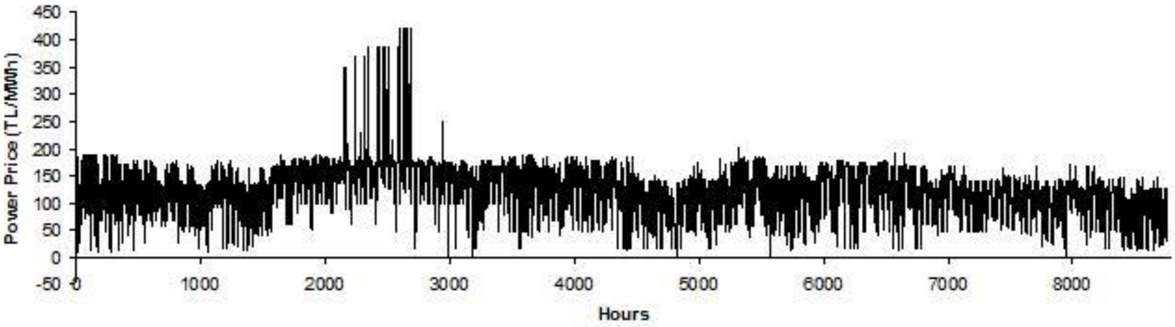

Fig. 1. Hourly Electric power price in Turkish Power Market, 2010

Another input to the scheduling model is the hourly natural gas price. The natural gas price depends on the supply demand of the wholesale market which is highly related with the international politics, market conditions and supply stability. Figure 2 shows the natural has price for 2010.

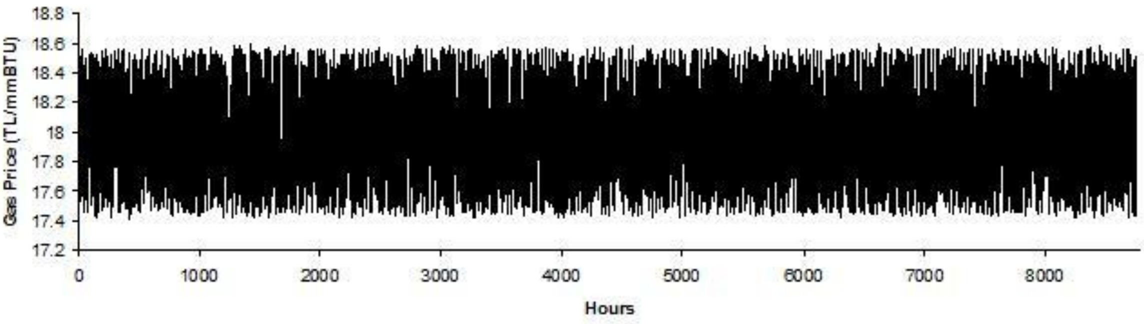

Fig. 2. Hourly Natural Gas price in Turkey, 2010

The model gives a schedule of pumping and generation based on the market price and natural gas price of which market price determines the revenue and natural gas price determines the cost. Figure 3 shows the pumping and generation schedule for 1 week period. Notice that pumping and generation can occur on the same time.

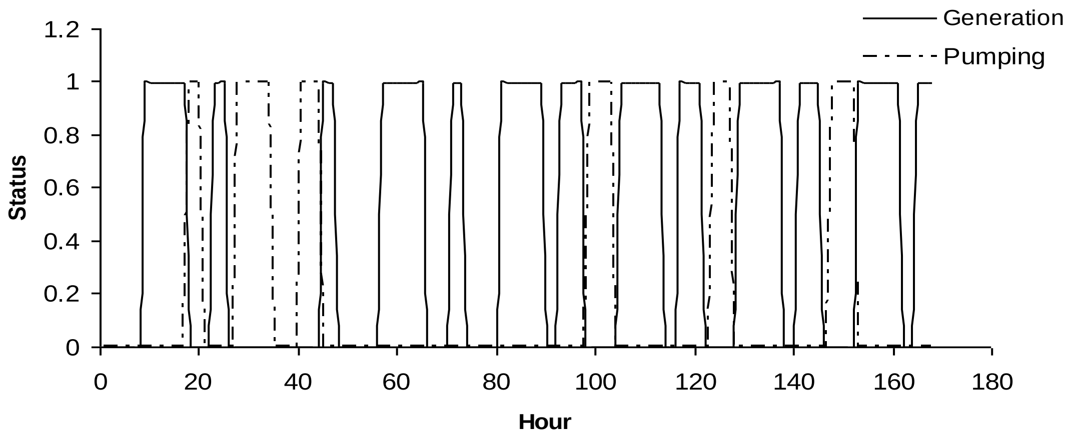

Fig. 3. Generation-Pumping schedule for the CAES system

The level of air inventory in the air storage shows gradual changes over the year. Figure 4 shows the air inventory (in terms of generation hours) over the year. When the power price is too low the system will pump the air into the inventory. This air is used when the power is too expensive or when the demand is too high.

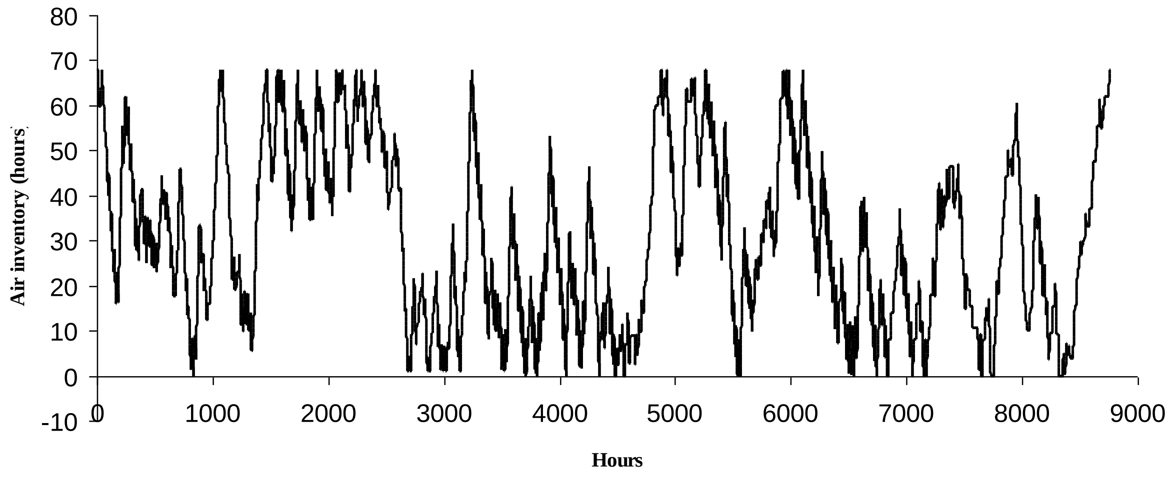

Fig. 4. Air inventory in CAES system

The objective of the model is to maximize the profit which is revenue from power sales minus the cost of the power and natural gas that are used. The profit of the year is 36,670,354 TL. The inventory starts with a full level and end-up with a full inventory. It is reasonably as the power demand will be similar each year at the same time.

4. Conclusion

The importance of energy storage systems is increasing as it can be used to balance the load deviations, to cover the thermal unit breakdowns, and to efficiently use the power resources. CAES is one of the most important storage technology and the scheduling this critical resource is an important task. The electric power price and natural gas price are two important issues that need to be considered when scheduling the CAES systems. In this paper, we have showed that it is possible to optimize the operation of the CAES generation and pumping schedule given that there are estimated hour power and natural gas prices.

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