Chapter 3
Hourly price-based demand response for optimal scheduling of integrated gas and power networks considering compressed air energy storage

Mohammad Amin Mirzaei[1], Morteza Nazari-Heris[1], Behnam Mohammadi-Ivatloo[1], Kazem Zare[1], Mousa Marzband[2] and Amjad Anvari-Moghaddam[3]

[1)] Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran, mm.mirzaei@tabrizu.ac.ir, mnazari@tabrizu.ac.ir, bmohammadi@tabrizu.ac.ir

[2)] Department of Mathematics, Physics and Electrical Engineering, Northumbria University, Newcastle, England, mousa.marzband@northumbria.ac.uk

[3)] Department of Energy Technology, Aalborg University, Aalborg, Denmark, aam@et.aau.dk

Abstract: Gas-fired plants are becoming an optimal and practical choice for power generation in electricity grids due to high efficiency and less emissions. Such plants with fast start-up capability and high ramp-rate are flexible in response to stochastic load variations. Meanwhile, gas system constraints affect the flexibility and participation of such units in energy market. Compressed air energy storage (CAES) as a flexible source with high ramp-rate can be an alternative solution to reduce the impact of gas system constraints on operation cost of power system. In addition, demand response (DR) programs are expressed as practical approaches to overcome peak-demand challenges. This study introduces a stochastic unit commitment scheme for coordinated operation of gas and power systems with CAES technology as well as application of an hourly price-based DR. The introduced model is performed on a six-bus system with a six-node gas system to verify the satisfactory performance of the model.

Keywords: Stochastic unit commitment, network-constrained scheduling, compressed air energy storage, distributed generation, integrated systems, natural gas network.

NOMENCLATURE

Index:

t	Time interval
i	Power plants

l	Gas demand index
sp	Gas provider
pl	Gas pipeline
m, n	Gas system nodes
$b, b^{'}$	Power system buses
j	Power demand index
L	Power lines
s	Scenario index
Constants:	
NT	Sum of time intervals
NGL	Sum of gas demands
NU	Sum of power plants
NGS	Sum of gas suppliers
NB	Number of buses
NS	Number of scenarios
$\alpha_i, \beta_i, \gamma_i$	Fuel consumption coefficients of the power plant *i*
p_s	Probability of scenario *s*
$P_i^{\max}, P_i^{\min}$	Max/min capacity of power plant *i*
R_i^{up}, R_i^{dn}	Ramp up/down of power plant *i*
T_i^{On}, T_i^{Off}	Minimum up/down time of power plant *i*
$A_k^{\max} / A_k^{\min}$	Max/min air storage in the CAES
x_L	Reactance of line *L*
$PF_L^{\max}$	Capacity of line *L*
$DR_{j,t,s}$	Power demand
$C_{m,n}$	Constant of pipeline
$\pi_m^{\max}, \pi_m^{\min}$	Max/min pressure
$U_{sp}^{\max}, U_{sp}^{\min}$	Max/min natural gas injection
$DR_{j,t,s}$	Adjustable load *j* at time *t* in scenario *s*
$CBL_{j,t,s}$	Base value of demand *j* at time *t* in scenario *s*
$B_{n,j,t}$	Marginal benefit of price-responsive shiftable consumer *n* at time *t*
α_k^w	Conversion factor of the released air to the electric power

α_k^{ing}	Conversion factor of the electric power to the stored air
Variables:	
$F_{i,t}^C$	Operation cost of power plant *i* at time *t*
$SUC_{i,t,s}$ / $SDC_{i,t,s}$	Start-up and shut-down cost of power plant *i*
$F_{i,t,s}^{gasunit}$	Fuel function of plant *i* at time *t* in scenario *s*
$P_{i,t,s}$	Power supply of plant *i* at time *t* in scenario *s*
$I_{i,t,s}$	Binary on/off indicator of power plant *i* at time *t* in scenario *s*
$X_{i,t-1,s}^{on}, X_{i,t-1,s}^{off}$	On/Off time of power plant *i* at time *t* in scenario *s*
$\pi_{m,t,s}$	Pressure of gas node *m* at time *t* in scenario *s*
$U_{sp,t,s}$	Gas supply of provider *sp* at time *t* in scenario *s*
$F_{pl,t,s}$	Gas flow of pipeline *pl* at time *t* in scenario *s*
$L_{l,t,s}$	Gas demand *l* at time *t* in scenario *s*
$PF_{L,t}$	Power flow at line *L* at time *t*
$\delta_{b,t}$	Voltage angle of power system buses
$V_{k,t,s}^{W} / V_{k,t,s}^{ING}$	Release/store of compressed air in CAES at time *t* in scenario *s*
$A_{k,t,s}$	The stored air in CAES at time *t* in scenario *s*
$P_{k,t,s}^{DIS}$	The amount of generated power by the CAES
$P_{k,t,s}^{CH}$	The amount of stored power by the CAES
$I_{k,t,s}^{DIS} / I_{k,t,s}^{CH}$	Generation/storage mode of CAES

3.1 Introduction

The annual gas consumption for supplying electrical energy has been rapidly increased since 2007 [1]. Emission regulation and power system reliability improvements show a great importance in such research area. One fundamental approach for reliability improvement is to increase the flexibility in system operation. To enhance this flexibility in power networks, different approaches have been proposed such as the use of demand response programs [2], integration of energy storage system (ESS) in the model [3, 4] and the use of flexible gas-turbine power plants such as combined heat and power plants [5, 6]. Gas-fired units are more flexible compared to other types of plants with fast starting time (i.e., less than one hour) and ramp rate ability of more than 50 MW/minute, while coal-fueled and nuclear type have 4 up to 8 hours starting time and ramp rate of 1 MW/minute [7, 8]. From environmental perspective, gas turbine power plants produce 50% to 60% CO2 lesser than coal-fired plants, and insignificant SO2 [9]. Natural gas consumption makes gas-fired power generation plants more dependent on natural gas network, where the shortage pressure in gas transmission line or increase of prices of natural gas can increase power system operation cost.

Recently, according to some considerable improvements in the power industry, new options have appeared to be employed for energy management purposes. One of these options is demand side management service which itself includes various programs i.e. time-of-use program according to which some of load is shifted from peak time intervals into off-peak ones to make the operating system performance the most optimal [10]. Demand response (DR) program is defined as an efficient method to overcome the issues created in the electrical systems during on-peak hours. Recently, significant efforts have been made to apply DR programs in energy systems. In [11, 12], demand response services have been proposed for electrical consumers in multi-energy systems in which various energy couplings have been provided to make the system performance more flexible. Higher flexibilities of these energy systems can ease electricity consumer's participation in such proposed demand response services. In [4], the authors have considered DR programs in providing optimal energy management of micro-grids, where time-of-use (TOU) program is employed to shift power load demand from on-peak hours to off-peak hours. The profit of hydrogen storage system and demand response program (DR) on system operation cost in SCUC problem has been evaluated in [13]. The authors have proposed a novel electricity market model based on an agent-based DR program in [14] for managing air conditioning loads, where machine learning approach is employed. Demand response services can also enhance energy systems performances from viewpoint of various criteria such as reliability. As an example, in [15], demand response services have been proposed for energy consumers in distribution network to make the system performance more economic and enhance reliability of system through reducing the loss of load index. In [16], a day-ahead scheduling problem is proposed for price-based DR with hydrogen energy storage.

Compressed air energy storage (CAES) plant with compressing air via a compressor and storing it in underground storage cavern at low load hours is one possible solution for achieving higher system flexibility. Releasing the high pressure (i.e., over 100 psi) air at peak load hours enables power production utilizing less fuel. Two types of these plants are located in Huntorf, Germany with 290 MW facility in 1978, and McIntosh, Alabama with 110 MW capacity in 1991 [17, 18]. An in-hand CAES project with 317 MW capacity Texas, U.S.A would be ready to operate in 2019 [19]. In [20, 21], stochastic security-constrained unit commitment (SCUC) problems have been solved with the penetration of wind farms and CAES plants, while in [22], the authors have studied the influence of CAES on operation cost with the integration of wind farms. The authors have proposed a look-ahead operation model for CAES systems considering DR programs in [23]. In [24], the capability of producing both power and heat from CAES systems has been studied for increasing the efficiency of storing energy. In this reference, the optimal operation of the studied advanced adiabatic CAES system is examined in energy and reserve markets. The participation of CAES systems in real-time markets has been investigated in [25] considering fast ramping and fast response abilities of CAES. In [26]-a robust bidding strategy problem has been solved for participation of CAES in day-ahead market. This literature has modelled the uncertainty of power price under a robust approach. In [27], a stochastic unit commitment problem with CAES and DR program has been proposed. In this literature the constraints related to natural gas networks have been ignored. A conditional value at risk (CVaR)-based stochastic method for maximizing profit of a company consisting of thermal plants and CAES has been expressed in [28]. An economic assessment of the merit of employing CAES system to a renewable-based network as well as a financial analysis of the system have been accomplished in [29]. In [30], a non-dominated sorting genetic algorithm has been applied for solving a multi-objective problem in operation of CAES systems considering two conflicting objectives including round trip efficiency and annual total cost saving.

Recently, several research studies have been concentrated on integrated gas and electricity networks. In [23, 24], the dependency of power network to natural gas is analyzed. Day-ahead scheduling scheme using the stochastic model is proposed in [6], where the authors solved SCUC problem considering natural gas transmission limits. The stochastic model includes network load prediction error, line outage, and generation outage contingencies. Impact of hourly electricity demand responses on dependency reduction of electric system to gas has been studied in the stochastic day-ahead management of coordinated electricity and gas networks [2]. In [25], stochastic scheduling of coordinated electricity and gas systems has been performed to firm the variability of wind. The effect of the uncertainty of natural gas supplier and price changes is studied by solving a two-stage stochastic scheduling problem in [26]. Robust day-ahead management for coordinated gas and electricity system has been performed to facilitate volatile renewable generation via power-to-gas (P2G) [27]. In [28], the influence of distributed natural gas storage system on robust operation of the integrated electricity-natural gas system has been studied. In [29], a two-stage stochastic network constrained UC has been proposed for multi-carrier energy systems.

This study introduces a SCUC problem for integrated electricity and gas systems with the integration of CAES system and price-based DR program. The main features of the paper are as follows:

- CAES is utilized for reducing dependency of power system operation cost to constraints of the gas system.
- Influence of DR programs on operation cost of the integrated energy networks as well as load profile are investigated.

- Constraints of natural gas network have been included in day-ahead security-constrained scheduling of power system.
- The influence of gas system limits is studied on the hourly participants of gas-fired plants in the market and power system operation cost.

The rest of this chapter is organized as follows: the problem formulation and the corresponding concept is provided in Section 6.2. Section 6.3 provides a full description of modified six-bus system and the numerical results. The conclusions are provided in Section 6.4.

3.2 Problem formulation

The main objective of SCUC problem is providing an optimal scheduling of plants to maximize the social welfare. The proposed objective function considering CAES plant is given as (3.1). The first term in (3.1) corresponds to benefit of DR providers (DRPs). Second three terms include fuel cost of generation plants, start-up and shut-down costs, respectively. The last term corresponds to the fuel cost of CAES plant in generation mode.

$$\max \sum_{s=1}^{NS} P_s \left[\begin{array}{l} \sum_{n=1}^{NP} \sum_{t=1}^{NT} \sum_{j=1}^{NJ} B_{n,j,t}\, d_{n,j,t,s} \\ -\sum_{t=1}^{NT} \sum_{i=1}^{NU} \left[F_{i,t}^{C}(P_{i,t,s}) + SUC_{i,t,s} + SDC_{i,t,s} \right] \\ -\sum_{t=1}^{NT} \sum_{k=1}^{NK} F_{k,t}^{C}(P_{k,t,s}^{DIS}) \end{array} \right] \tag{3.1}$$

This maximization process is subjected to the following constraints.

A. **Electric network constraints**

Power generation limits of power plants is as given in (3.2).

$$P_i^{\min} I_{i,t,s} \leq P_{i,t,s} \leq P_i^{\max} I_{i,t,s} \tag{3.2}$$

Increase or decrement in power production of a plant at consecutive periods depend on up and down ramp-rate of the plant, which is shown in (3.3) and (3.4). R_i^{up} and R_i^{dn} are the ramp rate limits of plants.

$$P_{i,t,s} - P_{i,t-1,s} \leq R_i^{up} \tag{3.3}$$

$$P_{i,t-1,s} - P_{i,t,s} \leq R_i^{dn} \tag{3.4}$$

Minimum up/down time limits of plants are defined in (3.5) and (3.6).

$$(X_{i,t-1,s}^{on} - T_i^{on})(I_{i,t-1,s} - I_{i,t,s}) \geq 0 \quad (3.5)$$

$$(X_{i,t-1,s}^{off} - T_i^{off})(I_{i,t,s} - I_{i,t-1,s}) \geq 0 \quad (3.6)$$

Constraints corresponding to start-up and shut-down cost of plant *i* are expressed as (3.7) and (3.8).

$$SUC_{i,t,s} \geq SU_i \, (I_{i,t,s} - I_{i,t\text{-}1,s}) \quad (3.7)$$

$$SDC_{i,t,s} \geq SD_i \, (I_{i,t\text{-}1,s} - I_{i,t,s}) \quad (3.8)$$

Conversion of compressed air to electric power and vice versa in CAES system are mentioned by (3.9) and (3.10).

$$P_{k,t,s}^{DIS} = \alpha_k^w V_{k,t,s}^W \quad (3.9)$$

$$P_{k,t,s}^{CH} = \alpha_k^{ing} V_{k,t,s}^{ING} \quad (3.10)$$

Amount of injected air or released air from storage system depends on gate size and pressure limitations that are modeled as (3.11) and (3.12).

$$V_{k,\min}^W I_{k,t,s}^{DIS} \leq V_{k,t,s}^W \leq V_{k,\max}^W I_{k,t,s}^{DIS} \quad (3.11)$$

$$V_{k,\min}^{ING} I_{k,t,s}^{CH} \leq V_{k,t,s}^{ING} \leq V_{k,\max}^{ING} I_{k,t,s}^{CH} \quad (3.12)$$

CAES at each time can only operate in one of the three modes of generation, storage and no-load states, which is defined in (3.13).

$$I_{k,t,s}^{DIS} + I_{k,t,s}^{CH} \leq 1 \quad (3.13)$$

The following relations (3.14)-(3.16) model the capacity of CAES system. Equation (3.14) is related to the quantity of air stored in CAES system at time *t* and scenario *s,* which is limited to its maximum and minimum quantities as defined in (3.15). At each time period, CAES system has a specific initial capacity at time *t*=0 and final capacity at time *t=24* should be same as given by (3.16).

$$A_{k,t,s} = A_{k,t\text{-}1,s} + V^{ING}_{k,t,s} - V^{W}_{k,t,s} \tag{3.14}$$

$$A_k^{\min} \le A_{k,t,s} \le A_k^{\max} \tag{3.15}$$

$$A_{k,0,s} = A_{k,in,s} = A_{k,24,s} \tag{3.16}$$

Equation (3.17) shows the power balance in each bus. Power flow from bus b to b' is determined by (3.18) while constrained by (3.19).

$$\sum_{i=1}^{NU_b} P_{i,t,s} + \sum_{k=1}^{NK_b} P^{DIS}_{k,t,s} - \sum_{k=1}^{NK_b} P^{CH}_{k,t,s} - \sum_{j=1}^{NJ_b} d_{j,t,s} = \sum_{l=1}^{NL_b} PF_{L,t,s} \tag{3.17}$$

$$PF_{L,t,s} = \frac{\delta_{b,t,s} - \delta_{b',t,s}}{x_L} \tag{3.18}$$

$$-PF_L^{\max} \le PF_{L,t,s} \le PF_L^{\max} \tag{3.19}$$

The constraints related to the DR program are defined by (3.20)-(3.23). Equation (3.20) indicates the relation between blocks of DR demand and total load of the system. Moreover, the limitations of blocks of DR demand are defined by (3.21). The limitation of adjustable load demand is defined by (3.22), and (3.23) indicates that total curtailed load is shifted to another time interval [16]:

$$\sum_{n=1}^{NP} d_{n,j,t,s} = D_{j,t,s} - DR_{j,t,s} - CBL_{j,t,s} \tag{3.20}$$

$$0 \le d_{n,j,t,s} \le d^{\max}_{n,j,t,s} \tag{3.21}$$

$$\left| DR_{j,t,s} \right| \le DR^{\max}_{j,t,s} \tag{3.22}$$

$$\sum_{t=1}^{NT} DR_{j,t,s} = 0 \tag{3.23}$$

where, the number of levels of DR demand and the associated demand are defined by n and d. Moreover, DR and CBL indicate the adjustable load and base value. It is noticeable that base loads do not participate in DR program.

B. Gas network constraints

Natural gas transmission network is responsible for transmitting gas from suppliers to consumers. Any gas network includes several gas wells, gas storage systems, gas loads, pipelines, compressor, and other devices such as control taps and regulators. Gas flow within pipeline is a quadratic function of the end nodes pressure, and are defined by (3.24) and (3.25). The gas flow direction through the pipeline $F_{pl,t,s}$ is determined by ± 1, which is positive when gas pressure at node m is greater than the pressure at node n, and vice versa.

$$F_{pl,t,s} = \text{sgn}(\pi_{m,t,s}, \pi_{n,t,s}) C_{m,n} \sqrt{\left|\pi^2_{m,t,s} - \pi^2_{n,t,s}\right|} \tag{3.24}$$

$$\text{sgn}(\pi_{m,t,s}, \pi_{n,t,s}) = \begin{cases} 1 & \pi_{m,t,s} \geq \pi_{n,t,s} \\ -1 & \pi_{m,t,s} \leq \pi_{n,t,s} \end{cases} \tag{3.25}$$

where, $F_{pl,t,s}$ is natural gas flow through pipeline *pl* at time *t* and scenario *s*, $\pi_{m,t,s}$ and $\pi_{n,t,s}$ are natural gas pressure at nodes *m* and *n*. Also, $C_{m,n}$ determines pipeline constant in which its value depends on temperature, and diameter of pipeline, fraction and gas composites, natural gas pressure of each node, like the same as bus voltage limits in electric network, varies between upper-limit and lower limit as given in (3.26).

$$\pi^{\min}_{m} \leq \pi_{m,t,s} \leq \pi^{\max}_{m} \tag{3.26}$$

The delivered natural gas to corresponding nodes by suppliers is limited to maximum and minimum values as (3.27).

$$U^{\min}_{sp} \leq U_{sp,t,s} \leq U^{\max}_{sp} \tag{3.27}$$

In each node of gas network, amount of injected gas should be equal to consumed gas which is modeled as (3.28).

$$\sum_{sp=1}^{NGS_m} U_{sp,t,s} - \sum_{l=1}^{NGL_m} L_{l,t,s} = \sum_{pl=1}^{NPL_m} F_{pl,t,s} \tag{3.28}$$

Gas-fired plants and CAES system are the large consumers of gas which are connected to natural gas network considering (3.29) and (3.30). Amounts of gas fuel used by gas-fired power and CAES plants are indicated by (3.31) and (3.32).

$$L_{l,t,s} = F^{gasunit}_{i,t,s} \tag{3.29}$$

$$L_{l,t,s} = F^{CAES}_{k,t,s} \tag{3.30}$$

$$F^{gasunit}_{i,t,s} = \alpha_i + \beta_i P_{i,t,s} + \gamma_i P^2_{i,t,s} \tag{3.31}$$

$$F^{CAES}_{k,t,s} = HR_k \, P^{DIS}_{k,t,s} \tag{3.32}$$

where, α_i β_i and γ_i are gas-fueled plant coefficients, and HR_k declares heat rate of CAES system.

3.3 Simulation results

For studying the performance of the introduced model, it is applied and tested on a six-bus power system [30] integration with six-node gas network. A day-ahead stochastic-based SCUC model is performed on the test system taking into account gas system constraints and CAES plant. Six-bus network consists of 3 gas-fired plants, one CAES plant and 2 loads of different types. The characteristics of gas network are also given in [9]. Data for the generation plants, the transmission lines of power system, the pipelines of gas system and gas load table, characteristics of the nodes in gas pipelines, characteristics of the gas pipelines and hourly residential gas load have been reported in Tables 3.1.-3.6. The SCUC problem is solved for four different cases.

TABLE 3.1. CHARACTERISTICS OF THE GENERATION PLANTS

Unit	α (MBtu/h)	β (MBtu/MWh)	c (MBtu/MWh)	Pmax	Pmin	Initial Status (h)	Min Down (h)	Min Up (h)	Ramp (MW/h)
G1	176.95	13.51	0.0004	220	100	4	4	4	55
G2	129.97	32.63	0.001	100	10	-3	3	2	50
G3	137.41	17.7	0.005	20	10	-1	1	1	20

TABLE 3.2. CHARACTERISTICS OF THE TRANSMISSION LINES OF POWER SYSTEM

Branch	From Bus	To Bus	X (p.u.)	Flow Limit (MW)
Line 1	1	2	0.17	200
Line 2	1	4	0.258	100
Line 3	2	3	0.197	100
Line 4	2	4	0.140	100
Line 5	3	6	0.037	100
Line 6	4	5	0.037	100
Line 7	5	6	0.018	100

TABLE 3.3. CHARACTERISTICS OF THE PIPELINES OF GAS SYSTEM AND GAS LOAD

Index	From Node	To Node	C (kcf/Psig)	Load No.	Node No.	Load type

Pipe 1	1	2	50.6	1	1	G1
Pipe 2	2	4	50.1	2	1	Residentioal gas load
Pipe 3	2	5	37.5	3	3	G3
Pipe 4	3	5	43.5	4	3	Residentioal gas load
Pipe 5	5	6	45.3	5	2	G2

TABLE 3.4. CHARACTERISTICS OF THE NODES IN GAS PIPELINES

Node No.	Min-Pressure (Psig)	Max-Pressure (Psig)
1	105	120
2	120	135
3	125	140
4	130	155
5	140	155
6	150	175

TABLE 3.5. CHARACTERISTICS OF THE GAS PIPELINES

Supplier No.	Node No.	Min-Outpout (kcf/h)	Max-Outpout (kcf/h)
1	4	1500	5000
2	6	2000	6000

TABLE 3.6. HOURLY RESIDENTIAL GAS LOAD

Time (h)	Residenatial gas load	Time (h)	Residenatial gas load (kcf)	Time (h)	Residenatial gas load (kcf)	Time (h)	Residenatial gas load (kcf)
1	2439.196	7	2607.496	13	2803.68	19	3055.97
2	2298.944	8	2831.73	14	2663.43	20	3168
3	2186.746	9	2887.83	15	2691.48	21	3112.07
4	2214.96	10	2962.576	16	2747.58	22	3055.97
5	1915.814	11	2859.78	17	2831.73	23	2831.73
6	2635.05	12	2859.78	18	2915.88	24	2579.446

A. Solving deterministic SCUC (case 1)

Figure 3.1 shows hourly production dispatch of three gas-fueled plants. The cheapest plant G1 is committed at the whole scheduling item, while the expensive plant G2 is committed between $t=11$ and $t=22$. Also, plant G3, as the second expensive plant, is dispatched during hours $t=10$ to $t=22$. Total operation cost in case 1 is equal to $83,242.6.

B. SCUC considering gas system constraints (case 2)

The comparison of the hourly dispatch of plants G1 and G2 with case 1 is demonstrated in Fig. 3.2. As shown in this figure, the limited capacity of gas transmission lines enforces some limitations on gas consumption of generation plant G1which results in a reduction in its power generation. Consequently, the power generation of plants G2 and G3 are increased. The total operation cost, in this case, is equal to $86,644.5, which shows $3401.9 increase in cost.

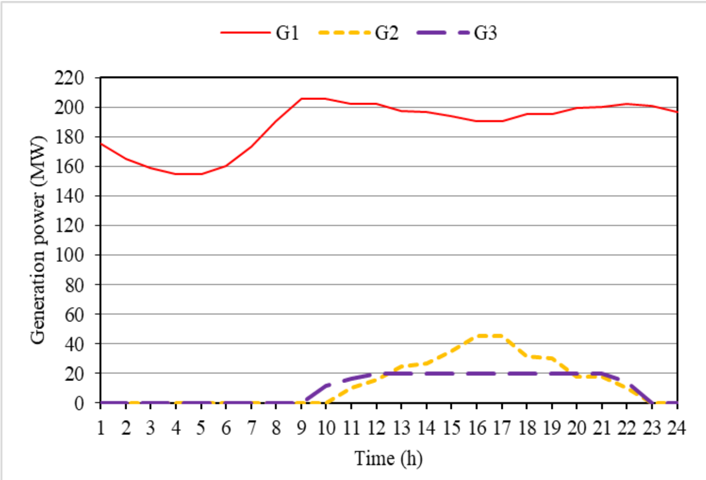

Fig. 3.1. Hourly generation dispatch of gas-fueled power plants

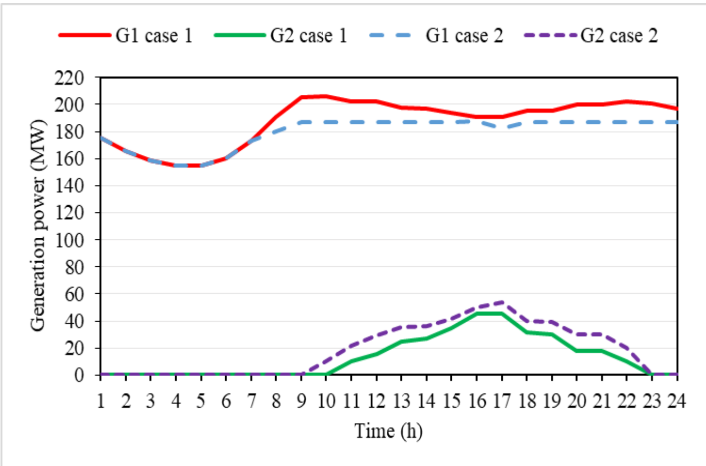

Fig. 3.2. Comparison of hourly generation dispatch of gas-fired power plants in case 1 and 2.

C. Case 2 with CAES (case 3)

In this case, a CAES with the capacity of 30 MW is located at bus 5. Table 3.7. shows the characteristics of CAES system. Based on [19], coefficient α_k^w and

α_k^{ing} are assigned as 0.9. Initial capacity of CAES is assumed as 50% of its maximum capacity. It is obvious from Figs. 3.3 and 3.4 that CAES system is in generation mode during off-peak time periods. In these periods, plant G1 produces more power than case 2, but at other periods specifically at peak hours (i.e., *t=15, 16* and *17*), power injection by CAES to the network causes some reduction in power generation of plant G2 with respect to case 2. This results in daily generation cost reduction. In this case, the total system operation cost is reduced to $83,276.4.

TABLE 3.7. CHARACTERISTICS OF CAES SYSTEM

$A_{k,t}^{max}$	$A_{k,t}^{min}$	$V_{k,max}^{W}$	$V_{k,min}^{W}$	$V_{k,max}^{ING}$	$V_{k,min}^{ING}$
180	40	30	5	30	5

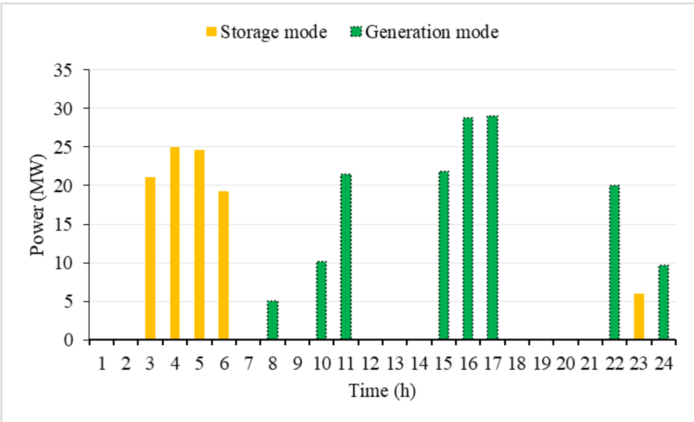

Fig. 3.3. Generated and stored power by CAES system

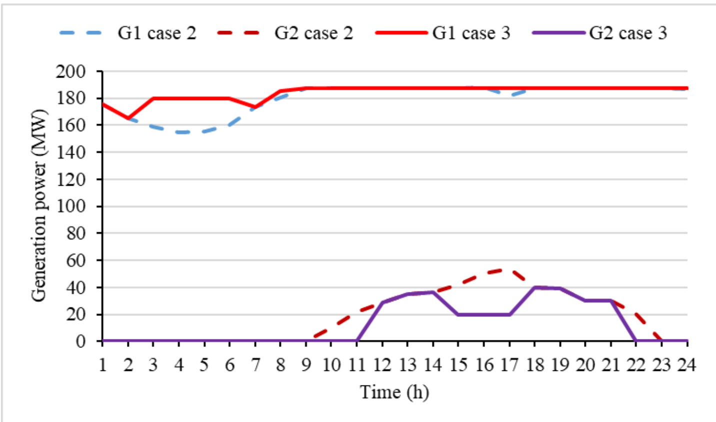

Fig. 4.3. Comparison of hourly generation dispatch of gas-fueled power plants in case 2 and 3

D. Case 3 with DR program (case 4)

In this case, the effect of DR as well as the CAES is investigated on the operation cost of the network. The DR includes a demand block with a marginal profit of 45 $/MWh. It is assumed that 10% of the load participate in price-based DR program. Figure 3.5 demonstrates the load profile after application of DR program. As it is seen in this figure, the load has been shifted from peak hours to off-peak hours, which reduces the participation of expensive power plants. The cost of the system in this case is $79,153.52, which is reduced with respect to Case 3.

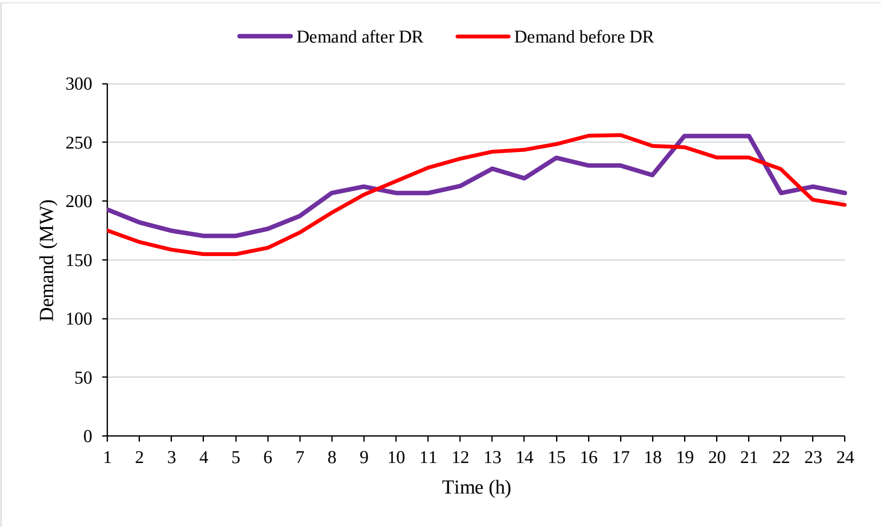

Fig. 3.5. The role of DR on load demand profile of the system

E. Solving Stochastic SCUC (case 5)

In this case, network electric load uncertainty is modeled utilizing Monte Carlo simulation approach. The load prediction error follows a normal distribution function with a mean value that is equal to the load prediction and a standard deviation of 5% of the mean value. The initial scenario set generated by Monte Carlo (which represents 1000 loading conditions) is then decreased to 5 suitable scenarios utilizing the SCENRED. Such tool includes two reduction methods: The backward approach and forward approach. The first one takes advantages of the best expected response time-based performance. Additionally, the obtained results of the forward approach are more accurate than the backward approach; however, the forward approach requires higher computation time. SCENRED has the capability of selecting desired number of preserved scenarios, which is called *Red_num_leaves.* In addition, *red_percentage* is an option of SCENRED, which works based on the relative distance between the initial and reduced scenarios. This chapter has used fast backward reduction approach according to the running time and performance accuracy with *red_num_leaves* factor of 5.

The power generation of power plants G1-G3 for different scenarios have been reported in Tables 3.8-3.10. In addition, Tables 3.11 and 3.12 reports the optimal charge/discharge of the CAES system in different scenarios. Daily operation cost in different scenarios is shown in Table 3.13. As shown in Table 3.13, scenarios 2 and 3 result more operation cost with respect to deterministic case (i.e., case 4). Total operation cost is equal to $79076.3, which is less than case 4.

TABLE 3.8. DAILY POWER GENERATION OF G1 IN DIFFERENT SCENARIOS

Time	S_1	S_2	S_3	S_4	S_5	Time	S_1	S_2	S_3	S_4	S_5
1	187.091	187.091	187.091	187.091	187.091	13	188.921	188.921	188.921	188.921	188.921
2	176.745	169.317	174.65	175.412	173.27	14	188.921	188.921	188.921	188.921	188.921
3	176.745	169.317	174.65	175.412	173.27	15	188.921	188.921	188.921	188.921	188.921
4	176.745	169.317	174.65	175.412	173.27	16	188.921	188.921	188.921	188.921	188.921
5	176.745	169.317	174.65	175.412	173.27	17	188.921	188.921	188.921	188.921	188.921
6	176.745	169.317	174.65	175.412	173.27	18	188.921	188.921	188.921	188.921	188.921
7	176.745	169.317	174.65	175.412	173.27	19	188.921	188.921	188.921	188.921	188.921
8	188.921	185.45	188.921	188.921	188.921	20	188.921	188.921	188.921	188.921	188.921
9	188.921	188.921	188.921	188.921	188.921	21	188.921	188.921	188.921	188.921	188.921
10	188.921	188.921	188.921	188.921	188.921	22	188.921	188.921	188.921	188.921	188.921
11	188.921	188.921	188.921	188.921	188.921	23	188.921	188.921	188.921	188.921	188.921
12	188.921	188.921	188.921	188.921	188.921	24	188.921	188.921	188.921	188.921	188.921

TABLE 3.9. DAILY POWER GENERATION OF G2 IN DIFFERENT SCENARIOS

Time	S_1	S_2	S_3	S_4	S_5	Time	S_1	S_2	S_3	S_4	S_5
1	0	0	0	0	0	13	25.254	15.699	22.559	23.539	20.869
2	0	0	0	0	0	14	25.254	15.699	22.559	23.539	20.869
3	0	0	0	0	0	15	25.254	15.699	22.559	23.539	20.869
4	0	0	0	0	0	16	25.254	15.699	22.559	23.539	20.869
5	0	0	0	0	0	17	25.254	15.699	22.559	23.539	20.869
6	0	0	0	0	0	18	25.254	15.699	22.559	23.539	20.869
7	0	0	0	0	0	19	25.254	15.699	22.559	23.539	20.869
8	0	0	0	0	0	20	25.254	15.699	22.559	23.539	20.869
9	0	0	0	0	0	21	25.254	15.699	22.559	23.539	20.869
10	10	10	10	10	10	22	21.172	12.313	18.673	19.582	17.106
11	22.661	13.745	20.146	21.061	18.569	23	188.921	188.921	188.921	188.921	188.921
12	25.254	15.699	22.559	23.539	20.869	24	188.921	188.921	188.921	188.921	188.921

TABLE 3.10. DAILY POWER GENERATION OF G3 IN DIFFERENT SCENARIOS

Time	S_1	S_2	S_3	S_4	S_5	Time	S_1	S_2	S_3	S_4	S_5

1	0	0	0	0	0	13	20	20	20	20	20
2	0	0	0	0	0	14	20	20	20	20	20
3	0	0	0	0	0	15	20	20	20	20	20
4	0	0	0	0	0	16	20	20	20	20	20
5	0	0	0	0	0	17	20	20	20	20	20
6	0	0	0	0	0	18	20	20	20	20	20
7	0	0	0	0	0	19	20	20	20	20	20
8	0	0	0	0	0	20	20	20	20	20	20
9	0	0	0	0	0	21	20	20	20	20	20
10	20	20	20	20	20	22	20	20	20	20	20
11	20	20	20	20	20	23	14.743	16.902	12.531	13.335	11.144
12	20	20	20	20	20	24	12.387	14.713	10.422	11.009	10.865

TABLE 3.11. DAILY POWER CHARGE OF CAES IN DIFFERENT SCENARIOS

Time	S_1	S_2	S_3	S_4	S_5	Time	S_1	S_2	S_3	S_4	S_5
1	9.624	16.456	11.551	10.85	12.76	13	0	0	0	0	0
2	9.448	8.461	9.17	9.271	8.929	14	0	0	0	0	0
3	15.976	14.738	15.627	15.754	15.341	15	0	0	0	0	0
4	20.004	18.61	19.611	19.753	19.696	16	0	0	0	0	0
5	19.669	18.289	19.28	19.421	18.969	17	0	0	0	0	0
6	14.179	13.01	13.849	13.969	13.576	18	0	0	0	0	0
7	0	0	0	0	0	19	0	0	0	0	0
8	0	0	0	0	0	20	0	0	0	0	0
9	0	0	0	0	0	21	0	0	0	0	0
10	0	0	0	0	0	22	0	0	0	0	0
11	0	0	0	0	0	23	0	0	0	0	0
12	0	0	0	0	0	24	0	0	0	0	0

TABLE 3.12. DAILY POWER DISCHARGE OF CAES IN DIFFERENT SCENARIOS

Time	S_1	S_2	S_3	S_4	S_5	Time	S_1	S_2	S_3	S_4	S_5
1	0	0	0	0	0	13	11.153	11.263	11.184	11.173	11.204
2	0	0	0	0	0	14	12.592	12.646	12.607	12.602	12.617
3	0	0	0	0	0	15	17.92	17.769	17.878	17.893	17.851
4	0	0	0	0	0	16	24.94	24.519	24.822	24.865	24.747
5	0	0	0	0	0	17	25.153	24.724	25.032	25.076	24.956
6	0	0	0	0	0	18	15.773	15.704	15.753	15.76	15.741
7	0	0	0	0	0	19	14.993	14.955	14.982	14.986	14.975
8	0	0	0	0	0	20	6.261	6.559	6.345	6.314	6.397
9	0	0	0	0	0	21	6.22	6.52	6.305	6.274	6.358
10	0	0	0	0	0	22	0	0	0	0	0

11	0	0	0	0	0	23	0	0	0	0	0
12	5.994	5.341	5.092	5.057	5.154	24	0	0	0	0	0

TABLE 3.13. DAILY OPERATION COST IN DIFFERENT SCENARIOS

Scenario	S_1	S_2	S_3	S_4	S_5
Daily operation cost ($)	75780.3	82708.4	81620.9	76209.9	78865.1

3.4 Conclusions

This paper solved a stochastic-based SCUC with CAES plant. Moreover, gas delivery to gas-fueled power plants and CAES plant is modeled. Considering gas system model could result in dispatch of more expensive plants in energy provision process and therefore imposes higher daily operation costs. The impact of CAES plant as a flexible source with high ramp-rate on electric network dependency to natural gas fuel reduction has been studied. Also, its impact on the reduction of expensive unit commitment and power system operation cost has been investigated. In addition, the role of DR program in optimal scheduling of integrated energy networks is studied, and the effect of such programs is investigated on the operation cost of the system, which shows reduction in such index. Moreover, the influence of DR on load demand profile shows that such programs are effective in shifting demand from on-peak hours to off-peak hours. The numerical results proved the effectiveness of the introduced concept.

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