



Two-Stage Stochastic Day-Ahead Market Clearing in Gas and Power Networks Integrated with Wind Energy

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ABSTRACT

The significant penetration rate of wind turbines in power systems has caused a number of challenges in the operation of systems such as large-scale power fluctuations induced by wind farms. Gas-fired plants with fast starting ability and high ramping can handle natural uncertainties of wind power better than any other traditional plants. Therefore, the integration of electrical and natural gas systems has great potential of enhancing the flexibility of power systems to incorporate more renewable power sources such as wind turbines. In this area, the uncertainty associated with wind speed has a meaningful impact on the optimal management of the generation units in power grids. In classic models, the operation of gas and power networks is studied independently, which does not ensure the global optimality of the networks due to the mutual dependency of such networks. Accordingly, the interconnected operation of the combined power and gas systems has been considered as an important research topic in recent years. This study proposes a stochastic market-based model for clearing of energy in interconnected power and gas systems through the integration of wind power. Stochastic programming is developed for studying the uncertainty of wind power production using a normal distribution function in a two-stage model. It should be remarked that the proposed two-stage model covers the uncertainty of wind power generation and load demand in real-time dispatch, determining the hourly scheduling of units in the first stage. It is expected that the operation cost of the integrated networks, local marginal pricing of the gas and power, and the load shedding will be increased by an increase in the residential gas load. The investigations showed a 4.2 % increase in total operation costs of the integrated power and gas system by a 5 % increase in the residential gas load.

1. INTRODUCTION

In recent decades, due to environmental issues, the reduction of fossil fuels, and overwhelming growth of energy consumption, renewable energy productions, such as wind power plants, are becoming an optimal and practical choice for power generation in electricity grids [1, 2]. Statistics show that high penetration of wind turbines in the power network could supply a large part of electricity load at a lower cost and decrease the emission of pollutant gases due to conventional fossil-fired generation plants [3, 4]. According to the reports provided by the International Energy Agency (IEA), wind turbines will supply 2182 TWh in the year 2030 annually, which is seven times more than that reported in 2009 [5, 6]. The role of wind turbines (WT) and photovoltaic (PV) systems has increased in power networks, which take advantages of both environmental and economic aspects. The uncertain nature of power output of WTs in power systems, especially in high penetration rates, creates some new issues in operation of such systems. Additional operational flexibility is required to decrease the effect of uncertain wind power output in power systems [7, 8]. The uncertainties associated with renewable energy sources are necessary to be investigated to make the protection of electrical energy

networks possible considering sudden changes in wind power or PV output [9].

Power production technologies can be classified into base load production, peaking production, and load following production based on flexibility viewpoint. Gas-fired power plants are deemed as load following production units due to their fast response and high flexibility levels in production. Furthermore, the main advantages of gas-fired power plants are twofold: a start-up time lower than 1 hour and a ramp rate greater than 50 MW/min. On the other hand, the start-up time and ramp-rate of coal-fired power generation units are between 4 to 8 hours and almost 1 MW/min, respectively [10]. The gas-fired power plants are not only beneficial in terms of technical aspects, but also effective in reducing pollutant gas emissions. Such plants can reduce the emission of CO₂ by 60 % in comparison with coal-fired power production units [11]. Moreover, gas-fired power plants generate no SO₂ gases and insignificant NO_x. According to the reports published in 2014, natural gas-fired power plants allocate 16 % of the whole electricity generation of the United States [12]. The rapid interconnectivity between power and gas systems makes new issues in the operation of both systems. The unpredictability of gas prices and pressure loss in gas systems nodes and pipelines play a considerable role in dispatch and security of power systems [13].

The interconnectivity between gas and power organizations has been investigated in recent studies from different

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viewpoints. The authors have studied the security-constrained scheme for the management of interconnected power and gas systems by focusing on power losses and disruptions in the gas network in [14]. The energy flow investigations of integrated power and gas networks by implementing the Newton-Raphson technique were proposed in [15]. In [16], a robust framework was presented for interconnected gas and power networks, considering the uncertain parameters of both systems. The authors proposed a multi-objective problem in [17] for dealing with power and gas systems to determine the minimum operation cost of the whole network and emission of pollutant gases. In [18], a bi-level approach was introduced for interconnected energy systems through the instrumentality of power to gas technology to handle the expansion planning and optimal dispatch at upper and lower levels, respectively. The authors studied the influence of gas network constraints on the optimal management of power systems in [19] by employing an hourly demand response program. A stochastic model for scheduling of reserve and energy in interconnected energy networks was studied in [20], where the authors studied the influence of gas system limitations on market clearing of power system considering energy storage technology and reserve markets. However, the authors did not investigate the role of simultaneous market clearing of integrated energy networks in this research.

This study proposes a stochastic market-based framework for energy market clearing of interconnected power and gas networks with a high penetration rate of WTs. Four types of method for coordinated electricity and gas systems have been studied in the literature to address interdependency between both systems: 1) including the gas system limits into power system optimization problem (i.e., network-constrained unit commitment), 2) incorporating dynamic gas consumptions of the electric power system into natural gas system optimization models, 3) sequential optimization of the electricity grid and the natural gas network, and 4) integrated co-optimization of the power and gas systems. This paper focuses on co-optimization of both systems under a market clearing problem, while, in [7, 20], the first method was used. The uncertainty associated with WT power output is studied using stochastic programming based on the normal distribution function. A two-stage strategy is developed for solving the proposed problem, which handles the uncertainty of WT power production and demand in real-time dispatch obtaining the day-ahead operation in the first stage. The proposed model has been applied to a six-bus power network with a six-node gas delivery system for performing numerical analysis and proving the impact of the introduced framework. The influence of natural gas system constraints on operation cost of stochastic day-ahead energy scheduling is investigated based on numerical analysis. The results confirm the optimal operation of the interconnected system, considering high penetration of WTs and constraints of the gas system. The introduced two-stage stochastic model is demonstrated in Figure 1.

The rest of this paper is structured as follows: Section II provides the problem formulation of the introduced two-stage market clearing problem. The case study and simulation results are prepared in Section III. Finally, the study is concluded in Section IV.

2. PROBLEM FORMULATION

2.1. Objective function

The objective function of the suggested two-stage model is presented in this sub-section. The main objective of the introduced scheme is to minimize the operation cost of the whole interconnected power and gas network. The first term of the objective function (1) represents the minimum power supply cost of the non-gas fired plants. The second term of (1) is an approximated power production function of the plants. The gas supply cost of the gas system residential demands and gas-fired power production units are considered by the third term of (1). It should be noted that the proposed market model in this paper is a perfect competitive market, where plants bid their own marginal cost to the market operator. Accordingly, the price bidding of gas-fired plants to the market is considered in operation cost of the gas suppliers. The real-time operation cost of the non-gas fired power plants and gas supply cost of the whole network are noted by terms 4 and 5, respectively. The wind curtailment and value of lost load are considered by terms 6 and 7 of the objective function (1), respectively.

$$\begin{aligned} \min & \sum_{t=1}^{NT} \sum_{i=1}^{NP} \left[MC_{i,t} V_{i,t} + \sum_{s=1}^{NS} C_{i,t,s}^E P_{i,t,s} \right] \\ & + \sum_{t=1}^{NT} \sum_{ga=1}^{NGA} \left[C^G GA_{ga,t} \right] + \\ & \left[\sum_{i=1}^{NU} \left(C_{i,t,s}^E P_{i,t,s,w} - C_{i,t,s}^E P_{i,t,s} \right) + \right. \\ & \left. \sum_{t=1}^{NT} \sum_{w=1}^{NW} P_w \sum_{ga=1}^{NGA} \left(C_{ga,t,w}^{G-Up} GA_{ga,t,w}^{Up} - C_{ga,t,w}^{G-Dn} GA_{ga,t,w}^{Dn} \right) \right. \\ & \left. + \sum_{r=1}^{NR} C_{r,t}^{Curt} P_{r,t}^{Curt} + \sum_{j=1}^{NJ} voll_{j,t} Lshed_{j,t,w} \right] \quad (1) \end{aligned}$$

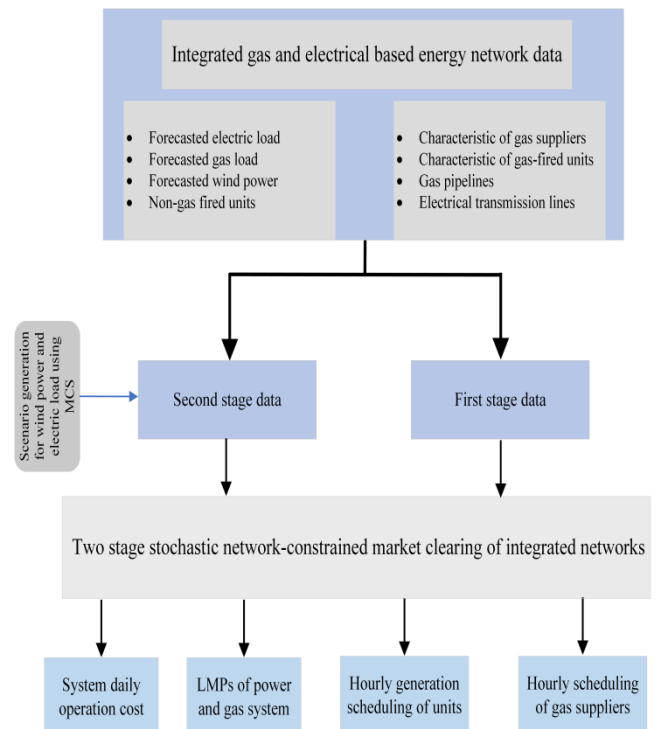


Figure 1. The proposed two-stage stochastic framework.

2.2. First-stage constraints

The total power production of each power plant is the sum of the power generation at each level of the linearized operation cost as noted by the objective function, which is considered by (2). The minimum and maximum power productions of each plants should be considered for each level of the linearized operation cost of power units as (3). Equations (4) and (5) denote the up/down ramp rate limitations of each power plant. The minimum up-time and maximum down-time of each power unit are mentioned by (6) and (7), respectively. The power balance constraint of the system is mentioned in (8) for satisfying power load by power production of plants and WTs. The power flow constraints and their limitation are represented by (9) and (10), respectively. The gas flow constraints for the gas network pipelines without compressor based on gas pressures at each node can be presented as (11) and (12). The gas flow of each gas pipeline with compressor is considered as (13). The gas consumption of each gas-fuelled power plant is considered as a linearized function, which is stated as (14). The limitations of gas pressure at each node and gas supply are represented by (15) and (16), respectively. The gas balance between gas supply and gas demand is considered by (17) [1, 20].

$$P_{i,t} = \sum_{s=1}^{NS} P_{i,t,s} \quad (2)$$

$$P_{i,s}^{\min} V_{i,t} \leq P_{i,t,s} \leq P_{i,s}^{\max} V_{i,t} \quad (3)$$

$$P_{i,t} - P_{i,t-1} \leq [1 - V_{i,t}(1 - V_{i,t-1})] R_i^{up} + V_{i,t}(1 - V_{i,t-1}) P_i^{\min} \quad (4)$$

$$P_{i,t-1} - P_{i,t} \leq [1 - V_{i,t-1}(1 - V_{i,t})] R_i^{dn} + V_{i,t-1}(1 - V_{i,t}) P_i^{\min} \quad (5)$$

$$(H_{i,t-1}^{up} - T_i^{up})(V_{i,t-1} - V_{i,t}) \geq 0 \quad (6)$$

$$(H_{i,t-1}^{dn} - T_i^{dn})(V_{i,t-1} - V_{i,t}) \geq 0 \quad (7)$$

$$\sum_{i=1}^{NU_b} P_{i,t} + \sum_{r=1}^{NR_b} P_{r,t} - \sum_{j=1}^{SJ_b} Load_{j,t} = \sum_{L=1}^{SL_b} PF_{L,t} \quad (8)$$

$$PF_{L,t} = \frac{\theta_{b,t} - \theta_{b',t}}{X_L} \quad (9)$$

$$-PF_L^{\max} \leq PF_{L,t} \leq PF_L^{\max} \quad (10)$$

$$GF_{pl,t} = \text{sgn}(\pi r_{m,t}, \pi r_{n,t}) K_{m,n} \sqrt{|\pi r_{m,t}^2 - \pi r_{n,t}^2|} \quad (11)$$

$$\text{sgn}(\pi r_{m,t}, \pi r_{n,t}) = \begin{cases} 1 & \pi r_{m,t} \geq \pi r_{n,t} \\ -1 & \pi r_{m,t} < \pi r_{n,t} \end{cases} \quad (12)$$

$$GF_{pl,t} \geq \text{sgn}(\pi r_{m,t}, \pi r_{n,t}) K_{m,n} \sqrt{|\pi r_{m,t}^2 - \pi r_{n,t}^2|} \quad (13)$$

$$GL_{gl,t} = MC_{i,t} V_{i,t} + \sum_{s=1}^{NS} \phi_{i,t,s}^E P_{i,t,s} \quad \forall gl = i, \dots, NG \quad (14)$$

$$\pi r_m^{\min} \leq \pi r_{m,t} \leq \pi r_m^{\max} \quad (15)$$

$$GA_{ga}^{\min} \leq GA_{ga,t} \leq GA_{ga}^{\max} \quad (16)$$

$$\sum_{ga=1}^{NGA_m} GA_{ga,t} - \sum_{gl=1}^{NGL_m} GL_{gl,t} = \sum_{pl=1}^{NPL_m} GF_{pl,t} \quad (17)$$

2.3. Second-stage constraints

The second-stage constraints include the constraints of power network and gas system, which are stated by (18)-(33). Equation (18) states the power generation in real-time dispatch. The relation between total power productions of each plant with linear piece in real-time dispatch is defined by (19). Equation (20) denotes the power production limitation of each plant in each linear piece. The ramp up/down in each scenario can be defined by (21) and (22). The power balance in real-time dispatch is considered by (23). Curtailed wind power in each scenario should not exceed the real-time wind power output, which is defined by (24). In some hours and scenarios in the real-time stage, it will be economical for the network operator to curtail load instead of using expensive power plants. The load shedding should be lower than the predicted load demand at each hour and each scenario, which is restricted by (25). The DC power flow and power transmission between power lines are represented by (26) and (27), respectively. The natural gas flow through each gas pipeline with and without compressor at each hour and in each scenario is defined by (28)-(30). The gas pressure limitation in the real-time stage is limited by (31). The gas supply in the real-time dispatch and its limitation are defined by (32) and (33). The gas supply and demand balance in the real-time stage is represented by (34). Finally, (35) presents the gas consumption of gas-fuelled power plants at real-time dispatch [1, 20].

$$P_{i,t,w} = P_{i,t} + r_{i,t,w}^{E-Up} - r_{i,t,w}^{E-Dn} \quad (18)$$

$$P_{i,t,w} = \sum_{s=1}^{NS} P_{i,t,s,w} \quad (19)$$

$$P_{i,s}^{\min} V_{i,t} \leq P_{i,t,s,w} \leq P_{i,s}^{\max} V_{i,t} \quad (20)$$

$$P_{i,t,w} - P_{i,t-1,w} \leq [1 - V_{i,t}(1 - V_{i,t-1})] R_i^{up} + V_{i,t}(1 - V_{i,t-1}) P_i^{\min} \quad (21)$$

$$P_{i,t-1,w} - P_{i,t,w} \leq [1 - V_{i,t-1}(1 - V_{i,t})] R_i^{dn} + V_{i,t-1}(1 - V_{i,t}) P_i^{\min} \quad (22)$$

$$\sum_{i=1}^{NU_b} (P_{i,t} + r_{i,t,w}^{E-Up} - r_{i,t,w}^{E-Dn}) + \sum_{r=1}^{NR_b} (P_{r,t,w} - P_{r,t,w}^{curtail}) - \sum_{j=1}^{NJ_b} (Load_{j,t,w} - Lshed_{j,t,w}) = \sum_{L=1}^{SL_b} PF_{L,t,w} \quad (23)$$

$$0 \leq P_{r,t,w}^{curtail} \leq P_{r,t,w} \quad (24)$$

$$0 \leq L_{shed,j,t,w} \leq Load_{j,t,w} \quad (25)$$

$$PF_{L,t,w} = \frac{\theta_{b,t,w} - \theta_{b',t,w}}{X_L} \quad (26)$$

$$-PF_L^{\max} \leq PF_{L,t,w} \leq PF_L^{\max} \quad (27)$$

$$GF_{pl,t,w} = \text{sgn}(\pi r_{m,t,w}, \pi r_{n,t,w}) \times K_{m,n} \sqrt{|\pi r_{m,t,w}^2 - \pi r_{n,t,w}^2|} \quad (28)$$

$$\text{sgn}(\pi r_{m,t,w}, \pi r_{n,t,w}) = \begin{cases} 1 & \pi r_{m,t,w} \geq \pi r_{n,t,w} \\ -1 & \pi r_{m,t,w} < \pi r_{n,t,w} \end{cases} \quad (29)$$

$$GF_{pl,t,w} \geq \text{sgn}(\pi r_{m,t,w}, \pi r_{n,t,w}) \times K_{m,n} \sqrt{|\pi r_{m,t,w}^2 - \pi r_{n,t,w}^2|} \quad (30)$$

$$\pi r_m^{\min} \leq \pi r_{m,t,w} \leq \pi r_m^{\max} \quad (31)$$

$$GA_{ga,t,w} = GA_{ga,t} + GA_{ga,t,w}^{Up} - GA_{ga,t,w}^{Dn} \quad (32)$$

$$GA_{ga}^{\min} \leq GA_{ga,t,w} \leq GA_{ga}^{\max} \quad (33)$$

$$\sum_{ga=1}^{NGA_m} (GA_{ga,t} + GA_{ga,t,w}^{Up} - GA_{ga,t,w}^{Dn}) - \sum_{gl=1}^{NGL_m} GL_{gl,t,w} = \sum_{pl=1}^{NPL_m} GF_{pl,t,w} \quad (34)$$

$$GL_{gl,t,w} = MC_{i,t} V_{i,t} + \sum_{s=1}^{NS} \varphi_{i,t,s}^E P_{i,t,s,w} \quad \forall gl = i, \dots, NG \quad (35)$$

Prediction error of power output of WTs and prediction error of the load demand follow a normal distribution function with standard variations of 10 % and 5 %, respectively [21, 22]. The load shedding cost and curtailment of wind power are considered as 400 \$/MW and 50 \$/MW, respectively. The introduced two-stage scheme is employed in GAMS software, which is solved by performing DICOPT solver. The studied 6-bus power network includes two gas-fuelled power plants: one non-gas fired power plant, seven power transmission lines, and three power load demands [19]. Additionally, a 6-node gas system consists of 5 pipes, one compressor, two suppliers, and 5 natural gas demands [20]. The forecasted wind power in the scheduling time horizon is demonstrated in Figure 3.

Table 1. The reduced scenarios.

| Scenarios | 1 | 2 | 3 | 4 | 5 |
|-------------|------|------|------|------|------|
| Probability | 0.26 | 0.12 | 0.08 | 0.05 | 0.16 |
| Scenarios | 6 | 7 | 8 | 9 | 10 |
| Probability | 0.09 | 0.03 | 0.06 | 0.07 | 0.08 |

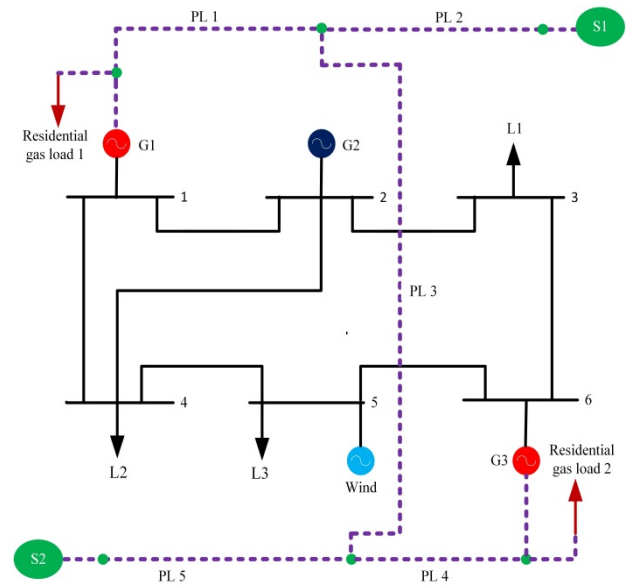


Figure 2. The studied integrated gas and power system.

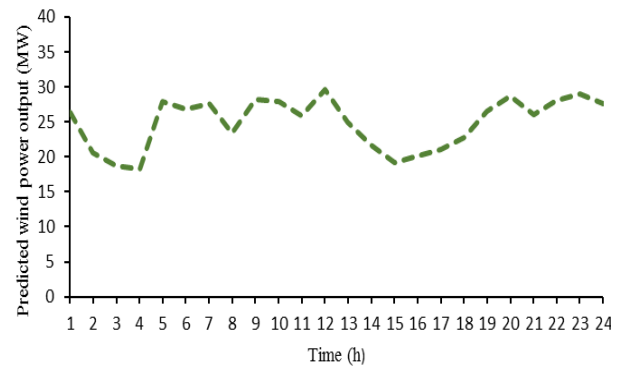


Figure 3. Forecasted wind power.

3. CASE STUDY AND SIMULATION RESULTS

The introduced two-stage stochastic framework is tested on a six-bus power network interconnected with a six-node gas system for obtaining numerical analysis and confirming the performance of the presented model. The studied test system is shown in Figure 2. 100 scenarios are generated for wind power output and load demand of the system using the Monte-Carlo simulation method. The generated scenarios are reduced to 10 scenarios using SCENRED tool, which are mentioned in Table 1. Such a tool includes two reduction methods: The backward and forward approaches. The first one has the best-expected response time-based performance. Additionally, the obtained results of the forward strategy are more detailed than those of the backward method; however, the forward approach needs longer calculation time. SCENRED can select the desired number of preserved scenarios, called Red-num-leaves. Moreover, red-percentage is an option of SCENRED, which acts based on the relative distance between the initial and reduced scenarios. This paper has applied fast backward reduction strategy according to the running time and performance certainty with the red-num-leaves factor of 10.

To assess the introduced model, it is implemented to determine values of residential gas load demand in the first step. The hourly dispatch of plants under such a condition is shown in Figure 4. As can be obtained from this figure, the

gas-fired unit G1 is incorporated in all of time intervals in demand-supply. The plant G1 cannot cooperate in power supply with its maximum capacity due to the gas supply limitation to that unit. The gas-fired plant G3 is incorporated as an expensive plant at medium and on-peak hours. The expensive non-gas fired plant G2 cooperates in power demand-supply at on-peak hours. At some time intervals, it is economical for the network operator to curtail the load demand in some scenarios instead of power dispatch of expensive gas-fired plants. Accordingly, at some time intervals and in scenarios, load shedding occurs. Total load shedding under such a condition is equal to 0.651 MWh. The total operation cost in this condition is equal to \$138055.786, which includes \$9841.994 power system cost and \$128213.792 gas network cost.

to the participant of expensive non-gas fired unit G2 in this period of time.

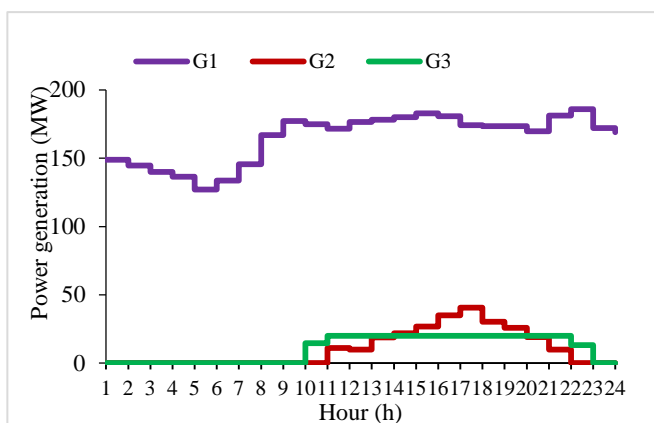


Figure 4. Hourly dispatch of generation plants.

Figure 5 shows the effect of a 5 % increase of residential natural gas demand with respect to the predicted value on the power dispatch of plants. As it can be seen in this figure, the power plant G3 has made its contribution for more than one hour in this condition with respect to the previous one due to an increase in fuel limits transferred to the power plant G1. In this condition, the hourly participations of the plants G1 and G2 are similar to those of the previous one with one difference. The power dispatch of plant G1 decreases between $t=9$ to $t=23$ h due to the limited fuel supply, which can be seen in Figure 6. Such power dispatch decrement has led to the power supply of the expensive plant G2. Additionally, total load shedding is increased under such a condition to 1.166 MWh according to the elimination of expensive plant G2 power dispatch. The total operation cost under a 5 % increase in natural gas residential demand is \$14,383,214, which is increased with respect to the previous condition. In addition, Table 2 shows the influence of an increase in natural gas load on the cost of the whole integrated network. The cost of both systems has increased as compared to the previous condition, which indicates the dependence of the grid on natural gas and the need for the implementation of an integrated market. In addition, the increasing residential gas load also causes an increase in the power system's average locational marginal price (LMP). For comparison, the average LMP profile of the 6-buses is given in Figure 7. As can be seen, by raising the gas load, LMP has increased during hours 9 and 21 due to the dispatch of the expensive unit resulting from gas fuel limit delivered to the low-cost unit. Figure 8 presents the average LMP of the gas system for Case 2. As shown in this figure, LMP spikes during hours between 11 and 21 that corresponds

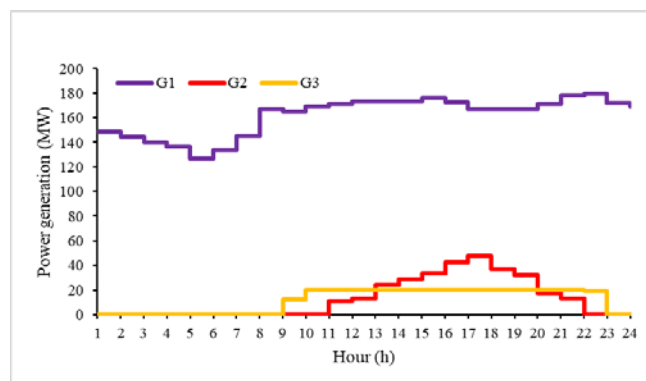


Figure 5. Power dispatch of plants under 5 % increase of gas load.

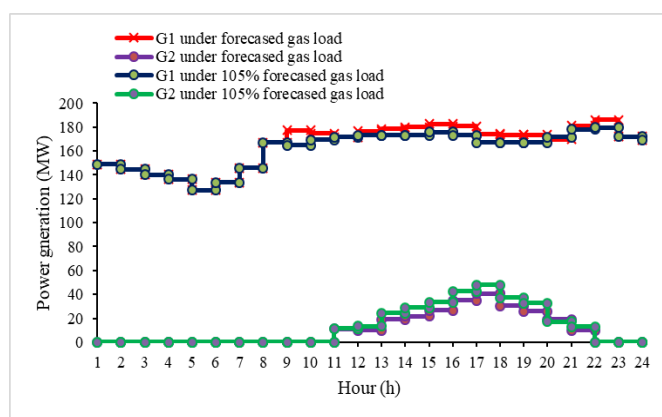


Figure 6. The impact of fuel limits on dispatch of G1 and G2.

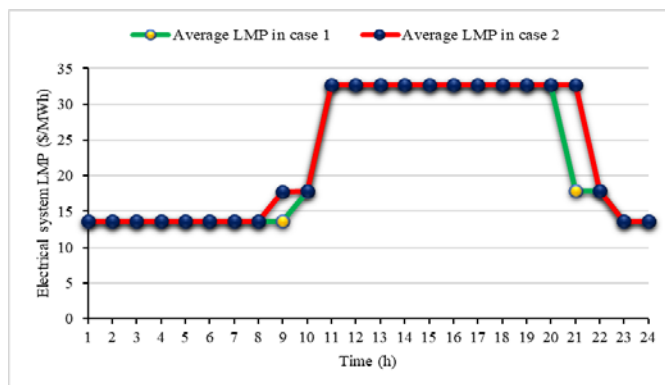


Figure 7. The impact of fuel limits on system average LMP.

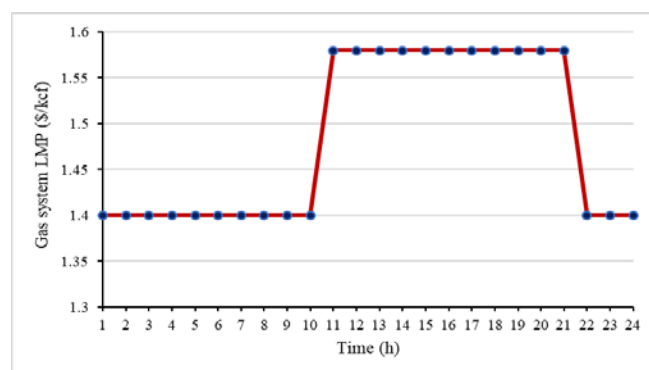


Figure 8. The gas system average LMP in case 2.

Table 2. The influence of gas demand variations on total cost.

| | 100% forecasted gas load | 105% forecasted gas load |
|----------------------------------|--------------------------|--------------------------|
| Total operation cost (\$) | 138055.786 | 143834.214 |
| Gas system operation cost (\$) | 128213.792 | 131791.014 |
| Power system operation cost (\$) | 9841.994 | 12043.200 |

4. CONCLUSIONS

This paper proposed a stochastic energy market clearing pattern for integrated gas and electricity networks including a wait and see in the first phase and here and now in the second one. The introduced model simulates both real-time and energy markets. For modeling the uncertainties of electric load and wind production, the Monte-Carlo simulation was used. The consideration of such uncertain parameters had a significant effect on the dispatch of gas-fuelled units and, accordingly, the distribution of gas suppliers. Moreover, the constraints of gas supplement from gas suppliers to gas consumers were considered that are effective in attaining a more realistic method for interconnected gas and power networks. Moreover, in order to show the effect of the connection of the power systems on the gas network and the need to consider an integrated energy market, the impact of natural gas demand variations on the operation cost of the coordinated network and load shedding was examined. Moreover, the results showed that the operation cost of the electrical network, gas and power LMPs, and the curtailed load were increased by an increase in the natural gas load. The investigations of the obtained operation cost of the whole integrated power and gas system showed a 4.2 % increase with a 5 % increase in the residential gas load. Therefore, the obtained results indicated the dependence of the power grid on the natural gas system and the need for the implementation of an integrated market. The role of wind energy in different buses of the power system and cost-effective analysis of integration of wind turbine in Iran can be considered in planning problem of integrated power and gas systems, where the main objective is to study long-term analysis of the systems as future trends.

5. ACKNOWLEDGEMENT

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