Economic-environmental effect of power to gas technology in coupled electricity and gas systems with price-responsive shiftable loads

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Abstract—Integration of renewable energy sources in electrical energy networks, is significantly increased due to economic and environmental issues in recent years and has appeared new challenges in the operation of power systems. Additionally, the power to gas (P2G) technology is a practical solution for accommodating the variability of the power output of wind energy sources, which are effective in reducing pollutant gas emissions considering their gas or power injection to the network at on-peak time intervals. Moreover, natural gas (NG)-fired generation plants can be introduced as practical solutions for decreasing power output variations of renewable sources due to their high ramp rates and quick response. This study proposes a multi-objective two-stage stochastic unit commitment scheme for integrated gas and electricity networks taking into account novel flexible energy sources such as P2G technology and demand response (DR) programs as well as high penetration of wind turbines. In this paper, P2G technology is introduced as a promising option for increasing the wind power dispatch in power systems. In addition, DR program as a cost-environmental effective method is modeled as a price-responsive bidding mechanism that is influential in decreasing the operation cost of the integrated network by shifting load from on-peak time intervals to off-peak time intervals. The introduced scheme has been implemented on an integrated 6-bus power system with 6-node gas networks by analyzing the performance of the framework in terms of operation cost and release of environmental pollutant gases. The results show that the simultaneous consideration of power-to-gas technology and demand response program reduces environmental pollution in addition to reducing costs. The investigation of the operation cost of the whole integrated system shows that application of both P2G and DR is beneficial in decreasing cost by 2.42% and 1.78% with respect to consideration of each of the P2G and DR, respectively.

Index Terms—Power to gas technology; pollutant gas emission; wind energy; two-stage multi-objective unit commitment; coupled power and gas systems; demand side management.

Index:

t	Time Period
i	Thermal unit
g	NG load
r	Wind power plant
w	Scenario
sp	NG suppliers
pl	NG pipeline
m,n	Nodes in the NG network
st	NG storage system
pg	P2G technology
p	PRSLs bidding block
$b,b^{'}$	Power system bus
k	Power load

L	Power transmission line

Constants:

NT	Sum of time periods
NP	Number of PRSLs bidding blocks
NK	Number of power loads
NC	Number of non-gas-fired plants
NGU	Number of gas-fired plants
NG	Sum of residential gas loads
NU	Sum of thermal units
NSP	Sum of NG suppliers
NST	Number of NG storage systems
NPG	Number of P2G systems
NR	Sum of wind farms
NB	Sum of buses
$\alpha_i, \beta_i, \gamma_i$	Coefficient of gas-fired plant *i*
$P_i^{\max}, P_i^{\min}$	Min/Max generation of thermal unit *i*
R_i^{up}, R_i^{dn}	Ramp up/down thermal unit *i*
T_i^{up}, T_i^{down}	Minimum up/down-time of unit *i*
$STUC_i, SHDC_i$	Start-up/shut-down costs of non-gas-fired plant *i*
$SUG_i, SHDG_i$	Start-up/shut-down NG consumption of gas-fired plant *i*
$q_{n,k,t}^{\max}$	Limitation of load at each bidding block of the PRLSs at time *t*
$\Delta d_k^{up}, \Delta d_k^{dn}$	Ramp-up/down of power loads
X_L	The reactance of line *L*
$PF_L^{\max}$	Maximum capacity of line *L*
$D_{k,t}$	Expected demand at time *t*
$BL_{k,t}$	Base load of the power system at time *t*
γ	Shiftable power load
$R_{m,n}$	Constant of pipeline *pl*

$RG_{g,t}$	Residential gas load *g* at time *t*
$PR_m^{\max}, PR_m^{\min}$	Max/min pressure
$G_{sp}^{\max}, G_{sp}^{\min}$	Max/min NG injection of supplied *sp*
$G_{st,\max}^{out}, G_{st,\max}^{in}$	Max releasing/storing capacity of NG storage system *st*
$\eta_{st}^{in}, \eta_{st}^{out}$	Storing/releasing efficiency of NG storage system *st*
$ST_{st}^{\max}, ST_{st}^{\min}$	Max/min NG stored in NG storage system *st*
η_{pg}^{p2g}	The efficiency of P2G technology
ER	Elimination of CO2 from the environment by the P2G technology
C^{sp}	The operation cost of NG supplier
C^{st}	The operation cost of NG storage system
ρ_w	Scenario probability

Variables:

F_i^C	Cost function of thermal unit *i*
F_i^E	Emission function of plant *i*
$F_{i,t}^{gas}$	Fuel function of NG-fired unit *i* at time *t*
$P_{i,t}$	Dispatch of unit *i* at time *t*
$Z_{i,t}$	Binary on/off status of unit *i* at time *t*
$M_{i,t-1}^{up}, M_{i,t-1}^{down}$	Up/down-time of unit *i*
$D_{k,t}^r$	Power load after application of DR at time *t*
$DR_{k,t}$	Adjustable power load at time *t*
$q_{n,k,t}$	Power load at each bidding block of the PRLSs at time *t*
$P_{r,t}$	Wind power dispatch at time *t*
$P_{pg,t}^{p2g}$	Power consumption of the P2G technology at time *t*
$PF_{L,t}$	Power flow through power transmission line *L* at time *t*
$G_{st,t}^{out}, G_{st,t}^{in}$	Discharge /charge of the NG storage *st*

$ST_{st,t}$	Energy stored in the storage system at time *t*
$PR_{m,t}$	NG pressure at each node of the gas system at time *t*
$F_{pl,t}$	NG flow through each line of the gas system at time *t*
$U_{pg,t}^{p2g}$	NG generated by the P2G technology at time *t*
$G_{sp,t}$	NG supplied by the supplier *sp* at time *t*
$LG_{m,t}$	NG load connected to node *m* at time *t*
$\Delta P_{i,t,w}$	The power output of plant *i* at time *t* in scenario *w*
$\Delta G_{st,t,w}^{out}$	NG release from the storage *st* at time *t* in scenario *w*
$\Delta G_{st,t,w}^{in}$	NG charge of the storage *st* at time *t* in scenario *w*
$\Delta P_{pg,t,w}^{p2g}$	Power consumption of P2G technology at time *t* in scenario *w*
$PR_{m,t,w}$	NG pressure at each node of the gas system at time *t* in scenario *w*
$F_{pl,t,w}$	NG flow through the gas system at time *t* in scenario *w*
$D_{k,t,w}^{r}$	Power load after application of DR at time *t* in scenario *w*
$DR_{k,t,w}$	Adjustable power load at time *t* in scenario *w*
$\delta_{b,t,w}$	Voltage angle of each power system bus at time *t* in scenario *w*
$ST_{st,t,w}$	Energy stored in the storage system at time *t* in scenario *w*
$P_{r,t,w}$	Wind power dispatch at time *t* in scenario *w*

1. Introduction

1.1. Motivation

Global economic and environmental challenges of fossil-fueled electrical energy production technologies have resulted in enhancing the penetration of renewable resources in recent years (Heydarian-Forushani, Ehsan et al., 2017; Madadi et al., 2019). The urban energy usage and emissions of carbon have been increased considering the continuous growth of the urban population and economy (Wei et al., 2017a; Wei et al., 2018). The emission of environmental pollutant gases is of great importance considering the current issues against climate revisions (Wei et al., 2017b). Considering the statistics of the International Energy Agency (IEA), an annual wind production of 2182 TWh estimated by 2030. Although the current energy system handles 320 GW generated power from renewable sources, this value will grow to 536 GW by 2020 (Jorge and Hertwich, 2014). However, the uncertainties associated with the generation of electrical energy by wind turbines and photovoltaic systems as the most known renewable energies as well as uncertain system load demands require practical solutions. NG-fired power plants can be defined as an appropriate solution for the above-mentioned issue with capabilities of high ramp-rates and fast start-up and decrement of gas emissions up to 60% with respect to coal-fired generation units (Heinen et al., 2017). Moreover, the gas price has decreased in recent years due to shale gas generation technology in the U.S.A, which was impactful in extending gas combined-cycle units (Alabdulwahab et al., 2015). The utilization of NG for producing electrical energy has reached 39% in 2012 in U.S.A (He et al., 2018). It should be noted the priority of non-power gas loads is higher than power gas loads, which leads to pressure drop in gas networks during the winter season due to an increment of non-power gas loads. This event is effective in the delivery of NG to NG-fired power units, which highlights the importance of gas and electricity system interdependency. Power to gas (P2G) technology, which is introduced as an innovative concept for storing energy, can play an essential role in electrical energy networks for accommodating the variability of renewable energy generation (Clegg and Mancarella, 2015; Mirzaei et al., 2019a). The P2G technology converts the extra energy of renewable energy resources such as wind turbines and photovoltaic cells to syntenic natural gas (SNG) by a chemical process considering fluctuating nature of the renewable energy resources. Accordingly, the integration of P2G technology in energy systems is of the great importance in minimizing the operation cost and emission of pollutant gases by generation of SNG, which is known as environmentally friendly energy carrier (Man et al., 2018; Zeng et al., 2019). The interconnectivity of electrical energy and NG networks has been increased considering the penetration of gas-fueled generation plants and P2G technology (Leonzio, 2017). Demand response (DR) programs, which are defined as the capability of electricity consumers to change their consumption patterns according to the load profile of the power network, are effective in dealing with the variability of renewable energy generation (Nazari-Heris et al., 2017). On the other hand, such programs can be defined as an appropriate choice when providing NG for gas-fired plants encounters with limitation in critical conditions. Therefore, in this paper, the effects of economic and environmental of P2G technology and DR program in a coordinated gas and power market is evaluated as a multi-objective two-stage stochastic optimization problem.

1.2. Literature review

Recently, several research studies have been published in the area of combined electricity and gas networks. Dependency on gas and electricity networks taking deterministic renewable energy generation into account has been addressed in (Li et al., 2008). Different models have been proposed for relaxing coupling constraints of such integrated networks such as augmented Lagrangian relaxation (Liu et al., 2010), Benders decomposition (Liu et al., 2009), and alternating direction method of multipliers (Wen et al., 2018). The authors have studied the consequences of coupled power and gas systems in (Erdener et al., 2014), where a security-constrained model has been introduced studying disruptions in gas pipelines and losses of power transmission. In (Cui et al., 2016), a bi-level scheme is introduced to solve the co-optimization of combined power and gas systems, where the objectives include minimization of the integrated network operation cost and maximization of the private owner's profit. A bi-level framework for such integrated networks is presented in (Wang et al., 2017) dealing with electricity network operation in upper-level and supplying the gas network in lower-level. The effect of participation of gas-fueled units in security-constrained unit commitment problem in an energy market has been investigated by incorporating a gas network in (Zhang et al., 2015). The authors have proposed a two-stage stochastic framework for market-clearing of interconnected gas and power systems considering network constraints and energy and reserve products in the existence of compressed air energy storage technology in (Mirzaei et al., 2019b).

P2G technology has been studied as a promising system in integrated gas and electrical networks to accommodate the variability of wind power supply. Such technology is effective in storing the extra power output of wind turbines as a gas at off-peak hours and supply the NG consumption of NG-fired plants by the stored gas at on-peak hours. A robust scheme is presented in (He et al., 2017) for determining optimal scheduling of coupled power and gas networks in the existence of P2G technology. The authors have proposed an operational analysis for integration of P2G in operation of interconnected power and gas for Great Britain's system in (Clegg and Mancarella, 2015). In this reference, the possibility of transforming extra wind output to various gas types by P2G is evaluated, and a CO_2 emission reduction model is introduced to analyze the environmental effects of P2G in the whole network. In (Jentsch et al., 2014), an optimal P2G capacity determination method in line with an optimal spatial P2G distribution is proposed for an 85% renewable energy scenario in Germany. The authors have investigated the capability of P2G in integrated networks in minimizing the cost of supplying the gas and power loads with both analyses of low and high power load in Great Britain in (Qadrdan et al., 2015), where high penetration of wind turbines is considered. The authors have assessed the capability of P2G in couple with gas storage to generate gas from renewable sources and its effect of NG prices in

[25]. In [26], a steady-state investigation of coupled power and NG networks in the existence of P2G is accomplished by employing a unified energy flow model for describing the nodal balance and branch flow in both networks.

Demand response (DR) programs, which are defined as the capability of electricity consumers to change their consumption patterns according to the load profile of the power network, are effective in dealing with the variability of renewable energy generation (Nazari-Heris et al., 2017). On the other hand, such programs can be defined as an appropriate choice when providing NG for gas-fired plants that encounters with limitation in critical conditions. The effect of cooperation of DR programs in day-ahead energy and reserve markets is analyzed in (Liu and Tomsovic, 2014) maximizing the expected social welfare. The impact of emerging flexible resources such as DR, bulk energy storage, and electric vehicle parking lots in the network-constrained joint market-clearing of energy and reserve is investigated in (Heydarian-Forushani, E et al., 2017). In (Wu et al., 2015), the impact of DR programs in the ramp costs of generation plants has been investigated in two-stage security-constrained scheduling in the existence of renewable resources. The authors have investigated the impact of price-based DR on decreasing the dependency of the electricity system on the gas network in (Zhang et al., 2016b). Coordinated operation of NG and power systems have been studied considering DR programs in (Zhang et al., 2016a), where the impact of DR has been analyzed on the reduction of flexible ramping and energy cost. It is notable that application of DR programs in electrical energy networks is effective in reducing the emission of pollutant gases because shifting load demands from on-peak hours to off-peak hours decreases the requirement for the development of new power generation plants to meet on-peak loads that are big sources of environmental gas pollutions. The role of DR programs on environmental issues has not been discussed in the literature, which is taken into account in this study as an objective.

1.3. Contribution

To the best knowledge of authors, simultaneous consideration of P2G technology and DR program has not been addressed in recent studies. In addition, it is worth to note that the literature has only concentrated on cost evaluations of P2G technology in power systems; however, the P2G technology is beneficial in terms of environmental issues by satisfying the on-peak load demands and eliminating the construction of pollutant power plants. This study aims to investigate the scheduling of combined NG and power networks considering both P2G technology and DR program. P2G technology is considered as a promising option which converts the excess wind power to SNG and stores it in the NG storage system and then injects the stored gas into electricity grid when it is required. In addition, the DR program is introduced as a practical option to reduce the operation cost of the integrated electricity network and NG systems. Moreover, such programs are effective in reducing the emission of pollutant gases considering the shift of load demands from on-peak time intervals to off-peak time intervals and lesser gas emissions of pollutant power generation plants on on-peak hours. The proposed framework is a two-stage multi-objective stochastic programming model that accomplishes the here and now decision in the first stage and performs the wait and see decision in the second stage considering network constraints of the gas and power systems. The main contributions of this study in comparison with the literature can be highlighted as follows:

- Solving a multi-objective two-stage stochastic problem for integrated power and gas systems with high integration of wind energy studying the uncertainties of both systems (i.e., electric and gas load and wind power). The main objectives of the proposed scheme include operation cost of the power and gas systems and cost of emission of environmental pollutant gases. Consideration of the cost emission of pollutants as a separate objective function in the day-ahead scheduling of the integrated power and gas systems has a significant influence on the operation cost of the integrated power and NG systems.

- Integrating a price-based DR program into the proposed multi-objective two-stage stochastic scheduling problem, where a price-responsive shiftable load (PRSL) model is developed as a DR program. In the presented DR program, load aggregator as consumers representative sends the demand as well as the price offer to the market operator. The participation of these consumers as PRSLs in the power market play a remarkable role in the operation cost and pollutant gas emissions.
- Considering P2G technology as an effective tool for decreasing the operation cost of the integrated power and gas systems and emissions of pollutants as well as more efficient use of wind power generation.

1.4. Organization of paper

The remainder of this study is as follows: Section 2 provides a problem formulation of the proposed framework. The case study and simulation results are included in Section 3. Finally, the paper has been concluded in Section 4.

2. Problem formulation

The proposed framework in this study aims at minimizing the operation cost of the whole integrated network and emission of pollutant gases for satisfying power and gas demands in the presence of P2G technology and DR programs. In this section, the objective function of the proposed framework as well as operational and technical constraints of the problem are introduced.

2.1.Objective function

In a restructured system, agents such as load-serving entity (LSE) or distribution companies can take part in the energy market as representatives of price-responsive shiftable load (PRSLs), and they offer their price and consumption to the power system operator. It is worth to mention that the offered price to market shows the sensitivity of consumers to the market price. This study introduces a co-optimization scheme for interconnected electrical and NG networks, which is demonstrated in Fig. 1. In the proposed model, power system operator and gas system operator under a coordinated approach solves a market-clearing problem for both systems in order to maximize the social welfare.

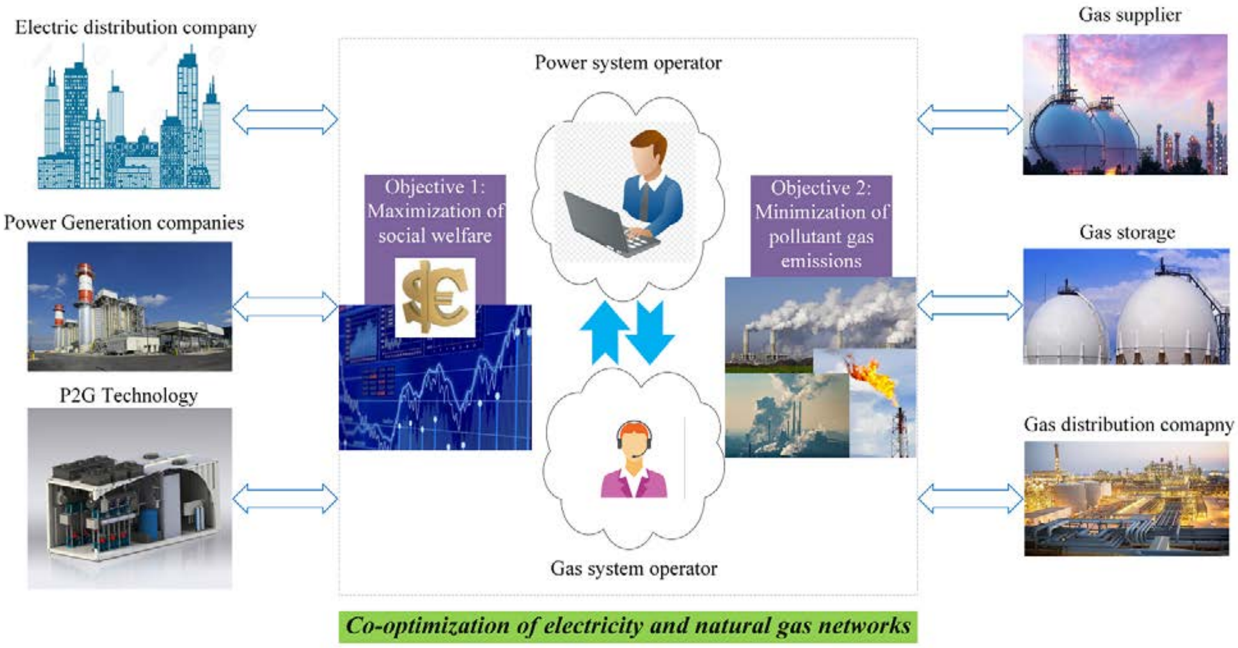

Fig. 1. A simple diagram for the proposed co-optimization of gas and power systems

The introduced framework is a multi-objective two-stage stochastic problem, for which the first objective function is defined as (1) that includes marginal benefits of the DR providers in the first term and the whole operation cost of electrical and NG networks in the second term. It should be noted that only the power consumers are considered as price-responsive loads. Accordingly, gas consumers do not offer price for their consumption to the network operator. Equation (2) includes the operation cost of non-gas-fired power plants, the cost of gas suppliers and the cost of gas storage in the first and second stages. The second objective function is also defined in (3), which includes the emission of pollutant gases by the power generation plants and the reduced CO2 gas emissions from the surrounding atmosphere due to the production of SNG by P2G technology in the first and second stages. It is notable that *ER* is 61.15 Kg/kcf (Clegg and Mancarella, 2015).

$$OF_1 = \max \sum_{p=1}^{NP} \sum_{t=1}^{NT} \sum_{k=1}^{NK} b_{n,k,t}\, q_{n,k,t} - \mathrm{TOC} \tag{1}$$

$$\begin{aligned} \mathrm{TOC} = {} & \sum_{t}^{NT} \sum_{i}^{NC} \left[F_i^C (P_{i,t}) + STU_{i,t} + STD_{i,t} \right] + \sum_{t}^{NT} \sum_{sp}^{NSP} C^{sp} G_{sp,t} + \sum_{t}^{NT} \sum_{st}^{NST} C^{st}\, G_{st,t}^{out} \\ & + \sum_{w=1}^{NW} \rho_w \left[\sum_{t}^{NT} \sum_{i}^{NC} \left[F_i^C (\Delta P_{i,t,w}) \right] + \sum_{t}^{NT} \sum_{sp}^{NSP} C^{sp} \Delta U_{sp,t,w} + \sum_{t}^{NT} \sum_{st}^{NST} C^{st}\, \Delta U_{s,t,w}^{out} \right] \end{aligned} \tag{2}$$

$$\begin{aligned} OF_2 = {} & \sum_{t=1}^{NT} \sum_{i=1}^{NU} \left[F_i^E (P_{i,t}) + STU_{i,t}^E + STD_{i,t}^E \right] - \sum_{pg=1}^{NPG} ER\, U_{pg,t}^{p2g} \\ & + \sum_{w=1}^{NW} \sum_{t=1}^{NT} \sum_{i=1}^{NU} \rho_w \left[F_i^E (\Delta P_{i,t,w}) \right] - \sum_{w=1}^{NW} \sum_{t=1}^{NT} \sum_{i=1}^{NU} \rho_w \left[U_{pg,t,w}^{p2g} - U_{pg,t}^{p2g} \right] \end{aligned} \tag{3}$$

2.2.First stage

The constraints of the first stage are introduced and described in the following.

2.3. Unit commitment constraints

The power generation of the plants should be limited to their lower and upper bounds as (4). The ramp-up and ramp-down rates of unit *i* should be considered as inequality constraints as mentioned by (5)-(8). Equations (9) and (10) define the start-up/shut-down cost of non-gas fired plants, and (11) and (12) provide the formulation of NG consumption of the gas-fired plants (Nazari-Heris et al., 2019b; ReddyK et al., 2018).

$$P_i^{\min} Z_{i,t} \le P_{i,t} \le P_i^{\max} Z_{i,t} \tag{4}$$

$$P_{i,t} - P_{i,t-1} \le \left[1 - Z_{i,t}(1 - Z_{i,t-1})\right] R_i^{up} + I_{i,t}(1 - Z_{i,t-1}) P_i^{\min} \tag{5}$$

$$P_{i,t-1} - P_{i,t} \le \left[1 - Z_{i,t-1}(1 - Z_{i,t})\right] R_i^{dn} + I_{i,t-1}(1 - I_{i,t}) P_i^{\min} \tag{6}$$

$$(M_{i,t-1}^{up} - T_i^{up})(Z_{i,t-1} - Z_{i,t}) \ge 0 \tag{7}$$

$$(M_{i,t-1}^{down} - T_i^{down})(Z_{i,t} - Z_{i,t-1}) \ge 0 \tag{8}$$

$$\begin{aligned} &STU_{i,t} \ge STUC_i\,(Z_{i,t} - Z_{i,t\text{-}1}) \\ &STU_{i,t} \ge 0 \qquad\qquad i \in TP \end{aligned} \tag{9}$$

$$\begin{aligned} &STD_{i,t} \ge SD_i\,(Z_{i,t\text{-}1} - Z_{i,t}) \\ &STD_{i,t} \ge 0 \qquad\qquad i \in TP \end{aligned} \tag{10}$$

$$\begin{aligned} &STUG_{i,t} \ge SUG_i\,(Z_{i,t} - Z_{i,t\text{-}1}) \\ &STUG_{i,t} \ge 0 \qquad\qquad i \in GP \end{aligned} \tag{11}$$

$$\begin{aligned} &STDG_{i,t} \ge SDG_i\,(Z_{i,t\text{-}1} - Z_{i,t}) \\ &STDG_{i,t} \ge 0 \qquad\qquad i \in GP \end{aligned} \tag{12}$$

2.4. Demand response program constraints

In this paper, the DR program is studied as a price-responsive shiftable scheme, which is demonstrated in Fig. 2. LSE or distribution companies as representatives of PRSLs offers demand blocks with their bid prices to the power market, and ISO as a joint operator of the NG and power systems solves the market-clearing problem to increase the social welfare. Then, the hourly scheduling of PRSLs is determined. PRSLs can be shifted from on-peak time intervals to off-peak time intervals to attain economic advantages. The correlation between PRSLs blocks and the whole load demand is provided by (13) and (14). In addition, (15) limits the mentioned correlation. The limitation of the value of adjustable load demand at each time and the scenario is provided by (16). Equation (17) and (18) determine the limitations of variation rates for PRSLs at each time interval. It should be mentioned that the total shifted load during the day is zero that can be stated as (19).

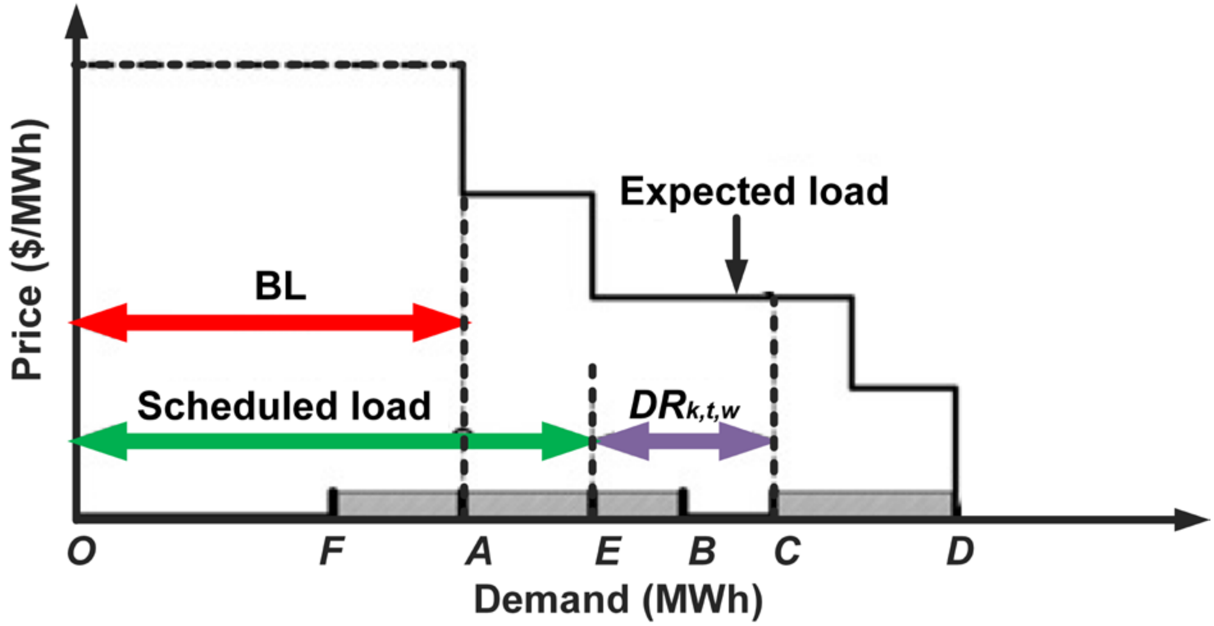

Fig. 2. Bidding mechanism for PRSLs

$$D_{k,t}^{r} = D_{k,t} - DR_{k,t} - BL_{k,t} \tag{13}$$

$$\sum_{n=1}^{NP} q_{n,k,t} = D_{k,t}^{r} \tag{14}$$

$$0 \le q_{n,k,t} \le q_{n,k,t}^{\max} \tag{15}$$

$$\begin{cases} 0 \le DR_{k,t} \le \gamma D_{k,t}, & if \;\; DR_{k,t} \ge 0 \\ DR_{k,t} \ge D_{k,t} - (1+\gamma) D_{k,t}, & else \end{cases} \tag{16}$$

$$D_{k,t}^{r} - D_{k,t-1}^{r} \le \Delta d_{k}^{up} \tag{17}$$

$$D_{k,t-1}^{r} - D_{k,t}^{r} \le \Delta d_{k}^{dn} \tag{18}$$

$$\sum_{t=1}^{NT} DR_{j,t} = 0 \tag{19}$$

2.5. *Electricity network constraints*

The power balance at each bus of the network should be satisfied using (20). Equation (21) formulates the power transmission between buses of the network. In addition, the power transmission is limited by (22).

$$\sum_{i=1}^{NU_b} P_{i,t} + \sum_{r=1}^{NR_b} P_{r,t} - \sum_{pg=1}^{NPG_b} P_{pg,t}^{p2g} - \sum_{k=1}^{Nk_b} (D_{k,t} - DR_{k,t}) = \sum_{l=1}^{NL_b} PF_{L,t} \tag{20}$$

$$PF_{L,t} = \frac{\delta_{b,t} - \delta_{b',t}}{x_L} \tag{21}$$

$$-PF_{L}^{\max} \le PF_{L,t} \le PF_{L}^{\max} \tag{22}$$

2.6. *Gas storage system constraint*

NG system can be used to flatten the gas load profile. Also, such technology is effective when the capacity of gas supplier or capacity of the gas transmission pipeline cannot satisfy the gas load demand. The storage and release capacity of the gas storage is limited using (23) and (24), respectively. Equations (25) and (26) formulate the storage balance and capacity limitation, respectively. The equality of initial and final condition of the NG storage system is mentioned by (27).

$$0 \leq G_{st,t}^{in} \leq G_{st,\max}^{in} \tag{23}$$

$$0 \leq G_{st,t}^{out} \leq G_{st,\max}^{out} \tag{24}$$

$$ST_{st,t} = ST_{st,t\text{-}1} + \eta_{st}^{in} G_{st,t}^{in} - \frac{G_{st,t}^{out}}{\eta_{st}^{out}} \tag{25}$$

$$ST_{st}^{\min} \leq ST_{st,t} \leq ST_{st}^{\max} \tag{26}$$

$$ST_{st,0} = ST_{st,NT} \tag{27}$$

2.7.Natural gas network constraints

The NG flow of a gas pipeline is a quadratic function of initial and end pressure of the gas node, which is defined by (28) and (29). The NG flow considering compressor is defined by (30). The connection of the residential NG loads and gas-fired plants to the node *m* of NG system is provided by (31). The natural-gas consumption of the gas-fired units considering the NG storage connected to the plant is defined by (32). P2G technology is considered as NG supplier as mentioned in (33). The gas supplier limitation and pressure limitation of the nodes are provided by (34) and (35). Equation (36) defines the NG balance in each node of the NG system.

$$F_{pl,t} = \operatorname{sgn}(PR_{m,t}, PR_{n,t})\, R_{m,n} \sqrt{\left| PR_{m,t}^{2} - PR_{n,t}^{2} \right|} \tag{28}$$

$$\operatorname{sgn}(PR_{m,t}, PR_{n,t}) = \begin{cases} 1 & PR_{m,t} \geq PR_{n,t} \\ -1 & PR_{m,t} < PR_{n,t} \end{cases} \tag{29}$$

$$F_{pl,t} \geq \mathrm{sgn}(PR_{m,t}, PR_{n,t})\, R_{m,n} \sqrt{\left| PR_{m,t}^{2} - PR_{n,t}^{2} \right|} \tag{30}$$

$$LG_{m,t} = \sum_{g=1}^{NG_m} RG_{g,t} + \sum_{i=1}^{NGU_m} F_{i,t}^{gas} \tag{31}$$

$$F_{i,t}^{gas} = \alpha_i + \beta_i P_{i,t} + \gamma_i P_{i,t}^{2} + SU_{i,t} + SD_{i,t} + \sum_{s=1}^{NS_i} (U_{s,t}^{in} - U_{s,t}^{out}) \qquad i \in NGU \tag{32}$$

$$U_{pg}^{p2g} = \varphi P_{pg,t}^{p2g}\, \eta_{pg}^{p2g} \tag{33}$$

$$PR_{m}^{\min} \leq PR_{m,t} \leq PR_{m}^{\max} \tag{34}$$

$$G_{sp}^{\min} \leq G_{sp,t} \leq G_{sp}^{\max} \tag{35}$$

$$\sum_{sp=1}^{NGS_m} G_{sp,t} - LG_{m,t} + \sum_{k=1}^{Nk_m} U_{pg}^{p2g} = \sum_{pl=1}^{NPL_m} F_{pl,t} \tag{36}$$

2.8.Second stage

Constraints of the second stage in this section. Equations (37)-(40) are related to the limitation of distributed power, power variation limit in the continues load in each scenario. Equations (41)-(48) refer to the DR at each time interval and each scenario. Equations (19)-(51) relate to power balance, DC power flow, and power transmission limits of each line in each scenario. Equations (52)-(56) are related to the constraints of the natural storage system in each scenario. Equations (57)-(65) are related to NG flow from each pipeline with and without compressor, the gas consumed by NG-fired plants, NG supply of the P2G, the limitation of the NG pressure, the limits of NG supply and gas balance in each scenario.

$$-R_{i}^{dn} \leq \Delta P_{i,t,w} \leq R_{i}^{up} \tag{37}$$

$$P_i^{\min} Z_{i,t} \le P_{i,t} + \Delta P_{i,t,w} \le P_i^{\max} Z_{i,t} \tag{38}$$

$$P_{i,t} + \Delta P_{i,t,w} - P_{i,t\text{-}1} - \Delta P_{i,t-1,w} \le \left[1\text{-} Z_{i,t}(1 - Z_{i,t-1})\right] R_i^{up} + I_{i,t}(1 - I_{i,t-1}) P_i^{\min} \tag{39}$$

$$P_{i,t-1} + \Delta P_{i,t-1,w} - P_{i,t} - \Delta P_{i,t,w}) \le \left[1\text{-} I_{i,t-1}(1 - I_{i,t})\right] R_i^{dn} + I_{i,t-1}(1 - I_{i,t}) P_i^{\min} \tag{40}$$

$$D^r_{k,t,w} = D_{k,t,w} - DR_{k,t,w} - BL_{k,t,w} \tag{41}$$

$$\sum_{n=1}^{NP} q_{n,k,t,w} = D^r_{k,t,w} \tag{42}$$

$$0 \le q_{n,k,t,w} \le q^{\max}_{n,k,t} \tag{43}$$

$$\begin{cases} 0 \le DR_{k,t,w} \le \gamma D_{k,t}, & if\ DR_{k,t,w} \ge 0 \\ DR_{k,t,w} \ge D_{k,t} - (1+\gamma) D_{k,t}, & else \end{cases} \tag{44}$$

$$D^r_{k,t,w} - D^r_{k,t-1,w} \le \Delta d_k^{up} \tag{45}$$

$$D^r_{k,t-1,w} - D^r_{k,t,w} \le \Delta d_k^{dn} \tag{46}$$

$$\sum_{t=1}^{NT} DR_{k,t,w} = 0 \tag{47}$$

$$\begin{cases} 0 \le DR_{k,t,w} \le \gamma D_{k,t}, & if\ DR_{k,t,w} \ge 0 \\ DR_{k,t,w} \ge D_{k,t} - (1+\gamma) D_{k,t}, & else \end{cases} \tag{48}$$

$$\sum_{i=1}^{NU_b} (P_{i,t} + \Delta P_{i,t,w}) + \sum_{r=1}^{NR_b} P_{r,t,w} - \sum_{pg=1}^{NPG_b} (P^{p2g}_{pg,t} + \Delta P^{p2g}_{pg,t,w}) - \sum_{k=1}^{Nk_b} (D_{k,t,w} - DR_{k,t,w}) = \sum_{l=1}^{NL_b} PF_{L,t,w} \tag{49}$$

$$PF_{L,t,w} = \frac{\delta_{b,t,w} - \delta_{b',t,w}}{x_L} \tag{50}$$

$$-PF_L^{\max} \le PF_{L,t,w} \le PF_L^{\max} \tag{51}$$

$$0 \le G^{out}_{st,t} + \Delta G^{out}_{st,t,w} \le G^{out}_{st,\max} \tag{52}$$

$$0 \le G_{st,t}^{in} + \Delta G_{st,t,w}^{in} \le G_{st,\max}^{in} \tag{53}$$

$$ST_{st,t,w} = ST_{st,t\text{-}1,w} + \eta_{st}^{in}(G_{st,t}^{in} + \Delta G_{st,t,w}^{in}) - \frac{(G_{st,t}^{out} + \Delta G_{st,t,w}^{out})}{\eta_{st}^{out}} \tag{54}$$

$$ST_{st}^{\min} \le ST_{st,t,w} \le ST_{st}^{\max} \tag{55}$$

$$ST_{st,0,w} = ST_{st,NT,w} \tag{56}$$

$$F_{pl,t,w} = \mathrm{sgn}(PR_{m,t,w}, PR_{n,t,w})\, R_{m,n} \sqrt{\left| PR_{m,t,w}^{2} \text{ - } PR_{n,t,w}^{2} \right|} \tag{57}$$

$$\mathrm{sgn}(PR_{m,t,w}, PR_{n,t,w}) = \begin{cases} 1 & PR_{m,t,w} \ge PR_{n,t,w} \\ \text{-}1 & PR_{m,t,w} < PR_{n,t,w} \end{cases} \tag{58}$$

$$F_{pl,t,w} \ge \mathrm{sgn}(PR_{m,t,w}, PR_{n,t,w})\, R_{m,n} \sqrt{\left| PR_{m,t,w}^{2} \text{ - } PR_{n,t,w}^{2} \right|} \tag{59}$$

$$L_{m,t,w} = \sum_{g=1}^{NG_m} RG_{g,t} + \sum_{i=1}^{NGU_m} F_{i,t,w}^{gas} \tag{60}$$

$$\begin{aligned} F_{i,t,w}^{gas} &= \alpha_i + \beta_i (P_{i,t} + \Delta P_{i,t}) + \gamma_i (P_{i,t} + \Delta P_{i,t,w})^2 + SU_{i,t} + SD_{i,t} \\ &+ \sum_{st=1}^{NST_i} (G_{st,t}^{in} + \Delta G_{st,t,w}^{in} - G_{st,t}^{out} - \Delta G_{st,t,w}^{out}) \qquad i \in NGU \end{aligned} \tag{61}$$

$$U_{pg,t,w}^{p2g} = \varphi(P_{pg,t}^{p2g} + \Delta P_{pg,t,w}^{p2g})\, \eta_{pg}^{p2g} \tag{62}$$

$$PR_m^{\min} \le PR_{m,t} \le PR_m^{\max} \tag{63}$$

$$G_{sp}^{\min} \le G_{sp,t} \le G_{sp}^{\max} \tag{64}$$

$$\sum_{sp=1}^{NGS_m} G_{sp,t,s} - LG_{m,t,s} + \sum_{pg=1}^{Nk_m} U_{pg,t,s}^{p2g} = \sum_{pl=1}^{NPL_m} F_{pl,t,s} \tag{65}$$

2.9.The ε-constraint method

The ε-constraint method is known as a practical solution for dealing with multi-objective problems. An optimization problem such as (33) with *z* objectives can be handled by using the ε-constraint technique (Nazari-Heris et al., 2019a).

$$\begin{aligned} &\max \quad (f_1(x), f_2(x), \ldots, f_z(x)) \\ &\text{s.t.} \\ &\qquad x \in A \end{aligned} \tag{66}$$

Where, *x* and *A* define the decision variables and feasible zone of variables, respectively.

The ε-constraint approach deal with multi-objective problems by optimizing one of the objective function, where the other objective function is considered as a constraint of the problem. The above-mentioned *z*-objective problem is transformed into the following single-objective problem by applying the ε-constraint approach.

$$\begin{aligned} &\max \quad f_1(x) \\ &\text{s.t.} \\ &\qquad f_2(x) \geq \varepsilon_2, \\ &\qquad f_3(x) \geq \varepsilon_3, \\ &\qquad \ldots \\ &\qquad f_z(x) \geq \varepsilon_z, \\ &\qquad x \in A \end{aligned} \tag{67}$$

The parameters of the ε-constraint method $(\varepsilon_2, \varepsilon_3, \ldots, \varepsilon_k)$ are altered parametrically to determine the optimal solution of the problem. The values of parameters are based on the range of $z-1$ objective functions.

The best solution can be selected from the produced Pareto optimal set by employing fuzzy decision-making process. This method allocates a fuzzy membership value in [0, 1] for all of the solutions in the Pareto set. The fuzzy membership for each of the objective functions of the problem can be attained as follows:

$$\hat{f}_z = \left\{ \begin{array}{ll} 1 & f_z \le f_z^L \\ \dfrac{f_z^{\max} - f_z}{f_z^{\max} - f_z^{\min}} & f_z^L \le f_z \le f_z^U \\ 0 & f_z \ge f_z^U \end{array} \right\} \tag{68}$$

The min-max approach is applied for determining the best compromise solution among all of the obtained optimal solutions, which is based on providing the minimum amounts of f_1 and f_2, and selecting the best solution as the maximum value of min $(\hat{f}_1, \hat{f}_2)$.

3. Case study and simulation results

The proposed framework has been implemented on a six-bus power system, which is a standard system, integrated with a six-node gas system considering real data to evaluate the performance and practicality of the model. The studied network is depicted in Fig. 3 including three generation plant, wind farm, NG storage, gas suppliers, P2G and power and gas load demands. The proposed model has been solved using generalized algebraic modeling systems (GAMS) software under DICOPT solver. The studied six-node gas network contains five pipelines, two NG suppliers and four gas loads including two gas-fired plants and two residential gas demands. Data utilized in this research has been adapted from (Alabdulwahab et al., 2017). The P2G technology with a capacity of 100 MW is connected to bus 5 of the electric network and node 5 of the gas system. In addition, the NG storage unit is located at node 1, which has characteristics of respective maximum inflow and outflow, and capacity of 600, 600, and 1000 kcf. The NG fuel price is 2 $/kcf. The operation cost of NG storage unit has been considered in this study, which is equal to 0.5 $/kcf (Chuan et al., 2017). Data for the emission of generation plants have been adapted from (Nazari-Heris et al., 2017).

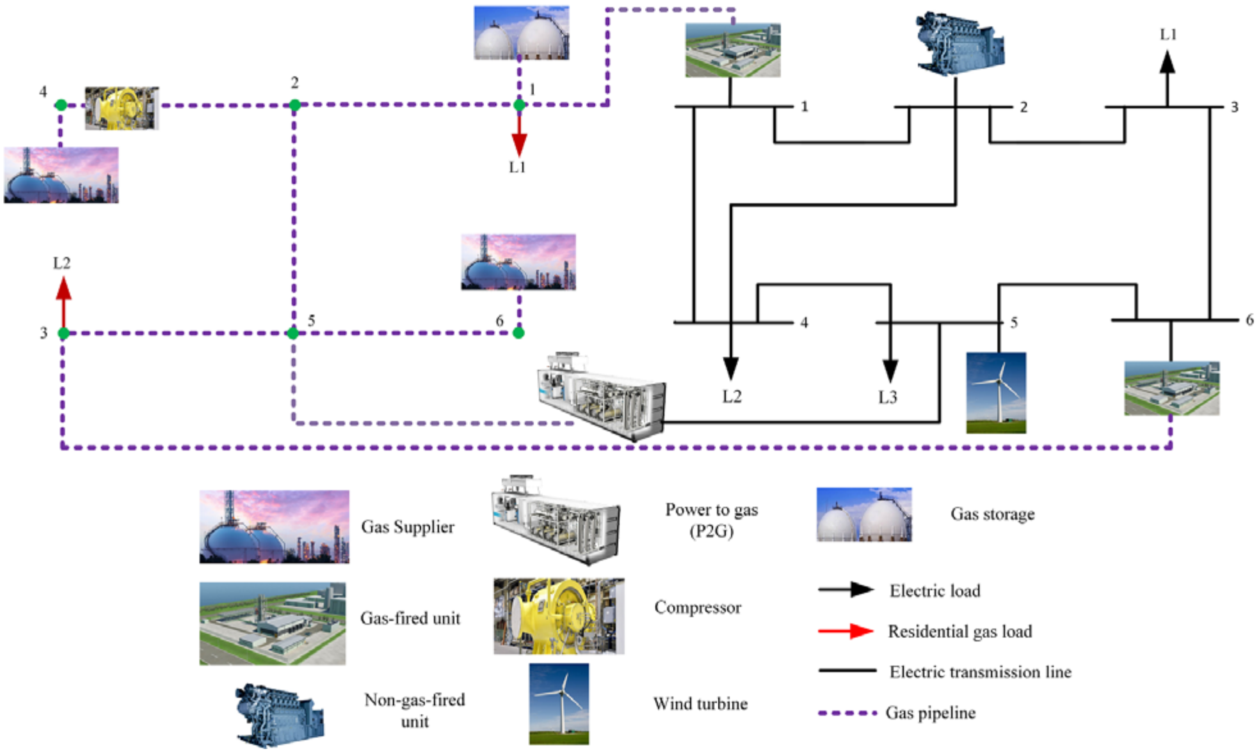

Fig. 3. The studied test system

Four cases have been taken into account to ensure the effectiveness and practicality of the proposed model as follows:

3.1. Case 1: Deterministic UC without P2G and DR

In this case, P2G technology and DR program have not been considered. The optimal power generation scheduling of plants is shown in Fig. 4. As it can be observed from this figure, G1 as the cheapest plant has participated in supplying load during the whole time interval. At on-peak hours, when the net load of the system (i.e., load demand minus wind power generation) is maximum, G1 cannot produce at its upper bound (220 MW) due to power transmission limitation of the network. Accordingly, a part of the required system load demand is satisfied using expensive plants G2 and G3. In addition, Fig. 5 defines the relation between NG storage level and wind power generation. As it is obvious in this figure, the gas storage operates in charge status when the power output of wind turbine is high, and it injects the stored gas to the gas system when the wind power generation decreases. In this way, the gas storage provides required fuel of the gas-fired plant G1 when a shortage of gas pressure limits the gas transmission to this generation plants. In other words, the gas storage supports fuel of the gas-fired plant G1. The operation cost of the system, in this case, is equal to $133,549.1.

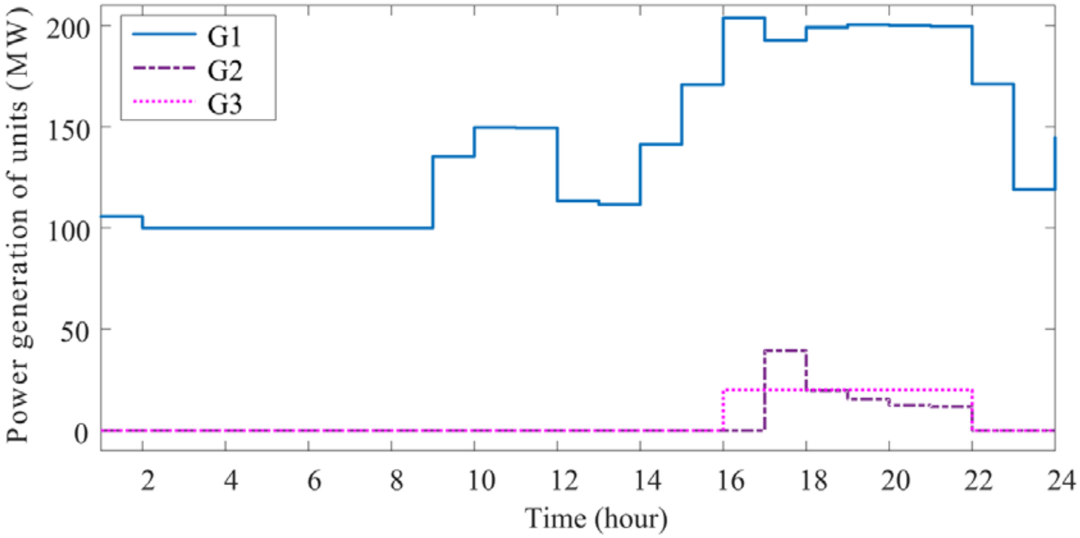

Fig. 4. Optimal scheduling of plants in case 1

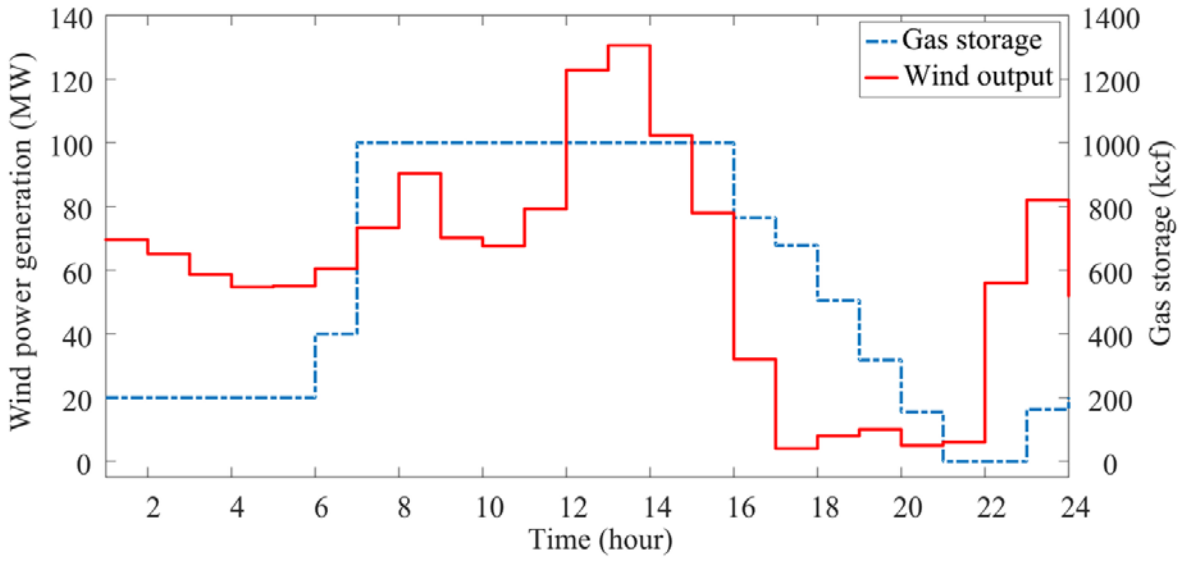

Fig. 5. The relation between NG storage level and power generated by wind turbine

3.2. Case 2: Deterministic UC with P2G

In this case, P2G technology has been considered in scheduling problem of power and gas systems. The impact of P2G technology on wind power dispatch has been shown in Fig. 6. As it can be observed in this figure, P2G technology converts the extra wind power generation to NG at off-peak hours. Accordingly, dispatched wind power is increased using the P2G technology. Considering that the gas supplied by the extra wind power, which is otherwise assumed to be spilled, the generated gas is stored in the NG storage unit to be injected to the gas-fired plant G1 at on-peak hours. This is effective in reducing the operation cost of the system, which is reduced to $132,696.5 in this case.

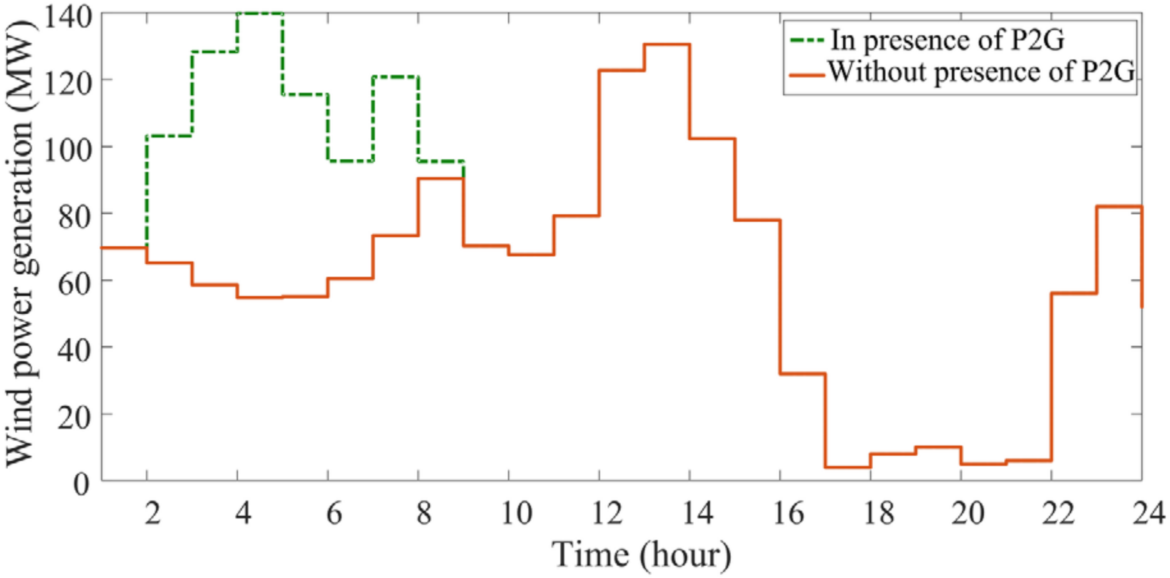

Fig. 6. The effect of P2G technology on wind power dispatch

3.3.Case 3: Deterministic UC with P2G and DR

The effect of DR program as well as P2G technology on scheduling problem and operation cost of NG and power networks. DR program is applied in all buses of the electric network, where the maximum shiftable load is considered as 5% of the forecasted load value at each time. A single energy block is included in the PRSL bid with a marginal benefit of 45 $/MWh. Figure 7 shows the impact of hourly DR on the electrical load demand of the network. As seen in this figure, the load has been shifted from on-peak hours (i.e., *t*=15 to *t*=23 h) to the off-peak hours (i.e., *t*=1 to *t*=9 h). Also, taking into consideration the increment of load demand and reduction of wind power production at *t*=10 and 11 h, the load demand has been shifted to other time intervals. In addition, considering the increment of wind power dispatch at *t*=12 to 14 h, load consumption is increased. Figure 8 exhibits the effect of the application of DR program on power dispatch of the wind turbines. As can be seen in this figure, the participation and power production of the expensive plant G2 has been decreased by applying for the DR program. Accordingly, the system operation cost has been decreased. The operation cost and wind power curtailment for case studies 1-3 are reported in Table 1. As it can be observed from this figure, operation cost and wind power curtailment in this case, which is equal to 130,319.17 and 0, is decreased with respect to the previous case studies 1 and 2. Decrement of operation cost in case 3 is as a result of load shift from on-peak hours to off-peak hours.

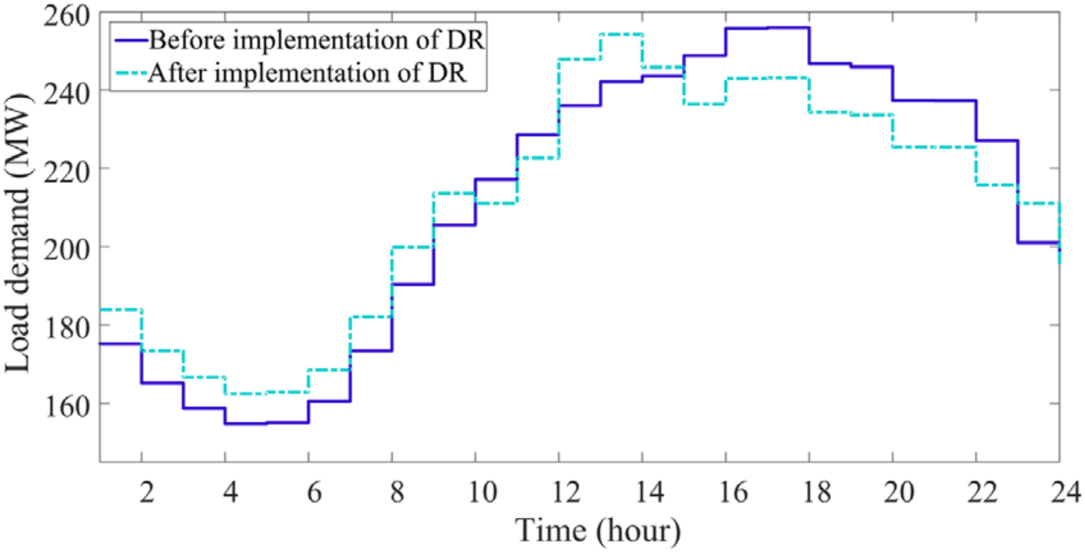

Fig. 7. The effect of hourly DR program on the electrical load demand

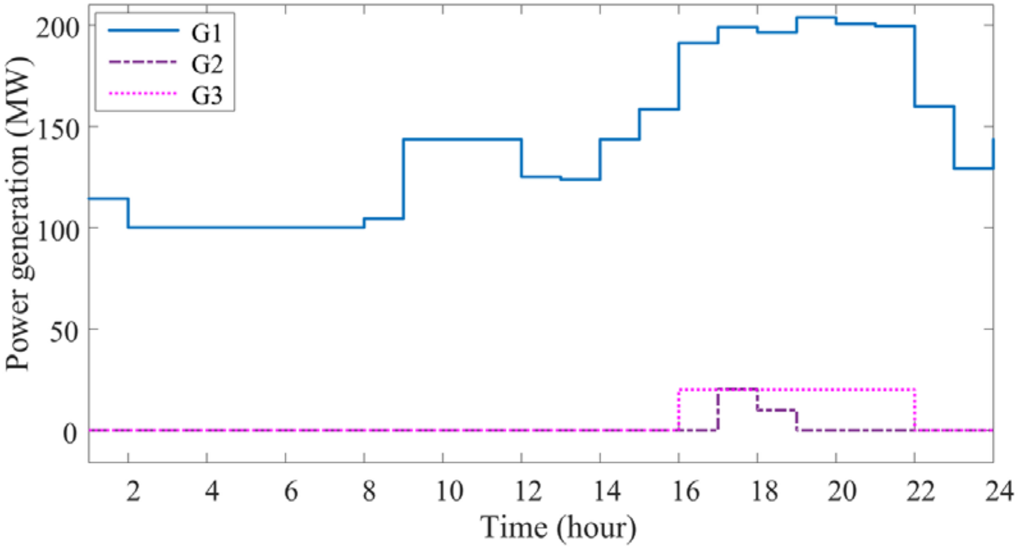

Fig. 8. The effect of the application of DR program on power dispatch of the plants

Table 1. Comparison of operation cost and wind power curtailment in case studies 1-3

	Case 1	Case 2	Case 3
Total operation cost ($)	133549.075	132696.525	130319.17
Electrical operation cost ($)	4493.686	4493.686	1749.334
NG operation cost ($)	128555.390	127702.840	128082.256
Curtailed wind power	341.02	0	0

3.4. Case 4: Multi-objective two-stage stochastic UC for cases 1-3

In this case, a multi-objective two-stage stochastic problem is introduced. In order to model the wind power uncertainty, electric demand and NG load, Monte Carlo simulation has been applied. Wind power, electric demand, and NG load follow a normal distribution function with a deviation of 10%, 5% and 3%, respectively. The predicted operation cost for cases 1-3, without consideration of the emission of pollutants, are reported in Table 2. As can be seen, the predicted operation cost with the uncertainty of the system in case 3 (with the presence of DR and P2G) is lower. In order to analyze the influence of P2G technology and price-responsive demand on emissions of pollutants, a multi-objective two-stage stochastic problem is solved. The results of the Pareto optimal solutions of the multi-objective problem for cases 1-3 are presented in Tables 3-5. The best compromise solution among optimal Pareto sets for case studies 1-3 are defined in Tables 3-5. As it is obvious in these tables, the emission of air pollutant gases is significantly decreased in the presence of P2G technology with respect to case 1. In fact, the maximum CO2 produced in the optimal Pareto sets in case 2 is less than the minimum CO2 produced in the Pareto optimal sets in case 1. However, the operation cost is increased due to the considerable influence of P2G on the emission of air pollutant gases. It should be noted that the first optimal Pareto solution considering the P2G technology provides better economic and environmental conditions than all of the Pareto optimal solutions in comparison with all of the optimal solutions without the presence of P2G technology. Therefore, taking P2G technology into account allows the operator to achieve a more desirable operation cost under the more appropriate environmental condition of case 1. In addition, as it can be seen in Table 5, the simultaneous presence of the P2G technology and DR obtained the best compromise optimal solution in terms of economic and environmental issues among all of the case studies. It is worth to mention for this case that the first Pareto optimal solution in case 3, which generates the highest carbon emissions, is less than the minimum carbon gas produced in case 1. This fact shows that the consideration of flexible resources such as DR and P2G technology, not only provides a highly desirable environmental condition but also benefits the operator in terms of economic viewpoints.

Table 2. The predicted operation cost considering the uncertainties of a system for cases 1-3

	Case 1	Case 2	Case 3
Total operation cost ($)	133896.166	133089.486	129468.902
Electrical operation cost ($)	5083.630	5083.630	4162.816
NG operation cost ($)	128812.536	128005.856	125306.086

Table 3. Pareto optimal solutions without P2G technology and DR

Solution	Total cost ($)	Gas cost ($)	Power cost ($)	Emission (Kg/day)	Ψ_1 (p.u.)	Ψ_2 (p.u.)
1	133896.166	128812.536	5083.63	290848.298	0.999	0
2	133941.399	128760.748	5180.652	289217.201	0.980	0.0499
3	133986.675	128709.003	5277.672	287586.320	0.960	0.099
4	134031.991	128657.293	5374.698	285955.688	0.940	0.149
5	134122.727	128553.955	5568.771	282693.504	0.900	0.249

6	134168.143	128502.315	5665.828	281062.610	0.880	0.299
7	134213.622	128450.694	5762.928	279431.205	0.860	0.349
8	134291.883	128374.017	5917.866	277800.299	0.826	0.399
9	134621.033	127973.405	6647.628	276169.351	0.682	0.449
10	**134710.818**	**127870.648**	**6840.170**	**272907.154**	**0.642**	**0.549**
11	135020.697	127485.318	7535.379	271276.159	0.507	0.599
12	135096.432	127418.452	7677.980	269645.454	0.473	0.649
13	135535.521	127508.087	8027.435	259859.321	0.281	0.949
14	136027.755	126948.851	9078.903	258869.120	0.065	0.980

Table 4. Pareto optimal solutions with P2G technology

Solution	Total cost ($)	Gas cost ($)	Power cost ($)	Emission (Kg/day)	Ψ_1 (p.u.)	Ψ_2 (p.u.)
1	133089.486	128812.536	5083.63	255999.736	0.999	0
2	133785.138	127185.238	6599.899	240128.730	0.948	0.155
3	134920.294	126512.877	8407.417	220325.641	0.863	0.350
4	135966.837	126816.315	9150.522	205850.657	0.785	0.492
5	136988.472	127837.950	9150.522	200753.759	0.709	0.542
6	**138010.841**	**128860.319**	**9150.522**	**195803.233**	**0.632**	**0.591**
7	139033.863	129883.341	9150.522	190957.572	0.556	0.639
8	140057.473	130906.951	9150.522	185964.620	0.480	0.688
9	141081.604	131931.082	9150.522	180864.598	0.404	0.73
10	142106.224	132955.702	9150.522	175843.931	0.327	0.787

11	143131.308	133980.786	9150.522	170903.362	0.251	0.836
12	144156.830	135006.308	9150.522	165405.734	0.174	0.890
13	145182.771	136032.249	9150.522	160994.731	0.098	0.933
14	146209.118	137058.596	9150.522	155869.795	0.021	0.983

Table 5. Pareto optimal solutions with P2G technology and DR

Solution	Total cost ($)	Gas cost ($)	Power cost ($)	Emission (Kg/day)	Ψ_1 (p.u.)	Ψ_2 (p.u.)
1	129468.902	125306.086	4162.816	203373.935	0.999	0
2	129607.757	124587.348	5020.408	189569.729	0.988	0.147
3	130408.652	123877.398	6531.254	165701.850	0.924	0.399
4	131370.650	124839.396	6531.254	160992.641	0.848	0.449
5	132333.241	125801.987	6531.254	156283.635	0.771	0.499
6	133296.371	126765.117	6531.254	151574.852	0.694	0.549
7	**134259.977**	**127728.723**	**6531.254**	**146865.931**	**0.617**	**0.599**
8	135224.025	128692.771	6531.254	142156.510	0.540	0.649
9	136188.492	129657.238	6531.254	137447.777	0.463	0.698
10	137153.358	130622.104	6531.254	132738.893	0.386	0.748
11	138118.602	131587.348	6531.254	128029.955	0.309	0.798
12	139084.209	132552.955	6531.254	123320.931	0.232	0.848
13	140050.176	133518.922	6531.254	118611.833	0.155	0.898
14	141983.181	135451.927	6531.254	109193.546	0.001	0.997

4. Conclusions

This study proposed a co-optimization framework for electrical and gas networks considering a security-constrained framework for both networks in high penetration of wind turbines. The proposed model is a multi-objective two-stage stochastic problem, which considers uncertainties associated with wind power output, power demand, and NG load. In addition, P2G technology has been introduced as an appropriate solution for decreasing wind curtailment and operation cost of the integrated networks. In fact, this advantage is attained by storing the extra power of the wind power generation as gas in NG storage at off-peak hours and injecting the stored gas to the gas-fired units at on-peak hours. The presence of P2G technology was effective both on decreasing the operation cost of the integrated power and gas system as well as reducing the emission of environmental pollutant gases. Moreover, DR program has been defined as a price-responsive bidding mechanism, which shifts the load demand from on-peak time intervals to off-peak time intervals to increase the social welfare and decrease the operation cost of the integrated electricity and gas network. To summarize, the most findings of this paper is as follows: 1. The role of P2G technology and demand response programs are evaluated on the operation of the integrated system, which are effective in increasing the wind power dispatch and reducing the operation cost of the integrated system and environmental pollution. 2. The simultaneous consideration of P2G technology and demand response programs are more likely to reduce operation costs, and environmental pollution with response to the condition that only one of these technologies are studied. 3. The effect of P2G technology and demand response program are evaluated in managing the uncertain nature of power and gas systems under a multi-objective two-stage framework. The future trend will be focused on the integration of flexible technologies such as multi-carrier energy storage and integrated demand response programs in combined power, gas and district heating networks as a robust multi-objective problem.

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