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Expansion Planning of Integrated Energy Systems with Flexible Demand-Side Resources

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Abstract— **The main purpose of this paper is to study the effect of responsive electrical loads on gas and electricity networks expansion planning problem. A centralized approach performs the expansion planning of the integrated gas and electricity networks. An incentive-based demand response (DR) is incorporated so that electricity network operator pays the consumers for participating in DR program. In this planning model for an integrated gas-electricity network, both supply and demand sides are matched together to guarantee the adequacy of fuel for gas consuming units (GCU). To illustrate the effectiveness of the proposed method Khorasan province of Iran is considered as a case study which has a high penetration level of GCUs.**

Keywords—Gas; Electricity; Expansion Planning; Demand Response; Optimization; MINLP.

NOMENCLATURE

Indices and Sets

i,j	Indices of gas nodes
m,n	Indices of electricity nodes
t	index for load period (off-peak, mid load, and peak)
d	Index of days
y	Index of years
g	Index of generation units
T	Planning period
N^{Gas}, N^{Elec}	Sets of nodes in gas and electricity networks
$\mathcal{TL}$	Set of transmission lines
$\mathcal{PL}, \mathcal{PL}^{Active}$, $\mathcal{PL}^{passive}$	Sets of pipelines, active pipelines and passive pipelines
GU, GU^{gas}	Sets of power plants and GFPPs

Variables

S_{iyd}^{Gas}	Gas production in node *i* on day *d* of year *y*
OC_{ydt}	Fuel cost of electricity network
C_{yd}^{Elec}	Operation cost of electricity network
C_{yd}^{Gas}	Operation cost of gas network
$\mathrm{\theta_{mydt}}$	Voltage angle of bus m
$\mathrm{f_{ijyd}^{Gas}\theta_{mydp}}$	Gas flow through pipeline *ij* on day *d* of year *y*
$\mathrm{s_{iyd}^{l}}$	Gas load at node *i* on day *d* of year *y*
pr_{iyd}^{g}	Gas pressure at node *i* on day *d* of year *y*
PF_{mnyd}	Power flow through line *m-n* on day *d* of year *y*
X_{mgyd}^{Elec}	Gas consumption of power plants on day *d* of year *y* in electricity network
X_{iyd}^{gas}	Gas consumption of power plants on day *d* of year *y* in gas network
p_{mgydt}^{Gen}	Power generation of unit g of bus *m* at period *t* of day *d* of year *y*
θ_{mydt}	Voltage angle at period *t* of day day *d* of year *y*
bin_{ij}^{Pipe} $/ bin_{mn}^{Trans}$ $/ bin_{mg}^{Gen}$	Binary variable indicating existence of pipeline/transmission line/generation
$P_{mydt}^{E\_load}$	Effective load of bus *m*
$P_{DR_{mydt}}^{-}$ $/ P_{DR_{mydt}}^{+}$	Decrement/increment of demanded load in bus *m*
$u_{DR_{mydt}}^{-}$ $/ u_{DR_{mydt}}^{+}$	Binary variable indicating decrement/increment of demanded load in bus *m*

Parameters

$\mathrm{K_{ij}^{pipe}}$	Weymouth constant
λ_{iyd}^{Gas}	Gas price in gas network
L_{ij}^{Pipe}	Length of pipeline
A_{ij}^{Pipe}	Diameter of pipeline
P_{mg}^{rated}	Power plant rated power
$\mathrm{p_{mydp}^{load} p_b}$	Load in electricity network
$\mathrm{\lambda_{m}^{X}}$	Fuel price
λ_{mydt}^{DR}	DR price
$\mathrm{y_{mn}}$	Per unit admittance
p_b	Base MW
GHV_h	Gross heating value of fuel
$cost_{ij}^{Pipe}$ $/ cost_{mn}^{trans}$ $/ cost_{mg}^{Gen}$	Construction cost of pipeline/ transmission line/generation unit
r	Interest rate

I. INTRODUCTION

Gas-fired power plants (GFPP) and other types of gas consuming units (GCU) are joint points of gas and electricity networks in an integrated energy system [1]. GFPPs are environmentally friendly because of their high efficiency rates and low CO_2 emissions. Also GFPPs can easily be fired up in just a few minutes, far more quickly than coal-fired power plants. Hence they are ideally suited to mitigate renewable fluctuations and that's why GFPPs will play a crucial role in future of electricity network [2]. In the literature, gas-electricity expansion planning problem has been carried out in [3-6]. A model that integrates electricity distribution and natural gas networks is presented in [3]. This model is proper for utilities that own both electricity and natural gas networks and could reduce their investment costs via electricity or gas tariffs. Proposed model in [4] simultaneously minimizes the total operational and expansion costs of gas and electricity networks. Additionally it determines the optimal location of the planned power generating units. In [5] a robust model proposes an integrated electricity and natural gas planning with the grid resilience considered as a set of constraints. An iterative process between gas and electricity networks in a combined market is illustrated in [6]. Obtained model minimizes the total investment and operational cost of a gas-electricity expansion problem.

Literature about integrating DR into investment planning is studied in [7-13].The impact of short-term DR on long-term generation expansion planning is studied in [7]. Presented work in [8] introduces an integrated methodology for planning distribution networks in which the operation of distributed generators and cross-connections is optimally planned. The impact of DR on generation and transmission network expansion planning is modeled in [9] with a probabilistic multi-objective function. Proposed models in [10] present a bi-level model for distribution network and renewable energy expansion planning under a DR framework. The proposed transmission expansion model in [11] can find the optimal trade-off between transmission investment and demand response expenses. Effect of DR and distributed generation on transmission expansion panning is studied in [12] through a probabilistic multi-objective function. Authors in [13] present a nonlinear economic model of responsive loads and provide an analytical framework to incorporate DR in transmission expansion planning.

In this paper a centralized approach to co-expansion of gas-electricity planning problem is introduced. A central entity as Ministry of Energy performs the coordinated expansion planning of gas and electricity networks. DR cost is integrated with operation and investment cost of electricity network so as to find a flexible expansion plan of electricity system coordinated with gas system expansion plan. With an incentive-based DR, electricity network operator pays the consumers for participating in DR program. By the proposed assumptions, DR program models load shifting to study the effects of flexible loads on integrated energy system expansion plan. In electricity network level both transmission and generation expansion opportunities are optimized. Generation expansion determines the size and location of new units and transmission expansion ensures a feasible power delivery. On the other hand, in gas network appropriate decisions regarding the pipeline expansions are made.

In the following sections, firstly expansion planning of integrated energy system is modeled. Then, the proposed incentive based DR is described and its effectiveness is demonstrated within a case study on Khorasan province of Iran which has a high penetration level of GCUs. Finally, a brief discussion is presented over the results.

II. EXPANSION PLANNING PROBLEM FORMULATION

A. Integrated expansion model

The main objective of the integrated expansion planning is to supply the loads with minimum total cost which includes both operation and investment costs [14]. In this way supplying new loads in gas network could be achieved by adding new pipelines if needed. New pipelines should be located in the gas network in a way to guarantee the feasible performance and operating point. This optimization process is subjected to the Weymouth equations [15] and some other technical constraints of gas network. Electricity network operator also aims at keeping a feasible and economic operation profile while making an expansion planning for the electricity network. To simplify the load flow studies while checking the feasibility of solutions in terms of meeting the technical constraints, DC power-flow is incorporated in the planning loop [16]. Proposed formulation performs both generation and transmission expansion planning in which location and size of new generation units is determined and on the other hand new transmission lines are located to have a reliable network. Hence the objective function of integrated energy network is to minimize the cost of investment and the net present value (NPV) of operation cost during the planning period. Expansion planning model of integrated energy network could be written as:

$$\begin{aligned} Min\ C^{ISO} = &\sum_{mn}\left(bin_{mn}^{trans} cost_{mn}^{trans}\right) \\ &+ \sum_{mh}\left(bin_{m,h}^{gen} P_{s_{mh}}^{rated} cost_{mh}^{gen}\right) \\ &+ \sum_{ij} bin_{ij}^{Pipe}\, L_{ij}^{Pipe}\, A_{ij}^{Pipe} cost_{ij}^{Pipe} \\ &+ \sum_{y=1}^{T}(1+r)^{-(y-1)} \sum_{d}\left(C_{yd}^{Gas} \right. \\ &\left. + C_{yd}^{Elec}\right) \end{aligned} \tag{1}$$

$s.t.$

$$C_{yd}^{Gas} = \sum_{i} S_{iyd}^{Gas} \lambda_{i}^{Gas} \tag{2}$$

$$C_{yd}^{Elec} = \sum\nolimits_{t} OC_{yd} + \sum\nolimits_{tm} \lambda_{mydt}^{DR} P_{DR_{mydt}}^{-} \tag{3}$$

$$\underline{f_{ij}^{Gas}} \le f_{ijyd}^{Gas} \le \overline{f_{ij}^{Gas}} \qquad \forall\, ij \in \mathcal{PL}^{passive} \tag{4}$$

$$sign\left(f_{ijyd}^{Gas}\right){f_{ijyd}^{Gas}}^{2} = {K_{ij}^{pipe}}^{2}\left({pr_{iyd}^{g}}^{2} - {pr_{jyd}^{g}}^{2}\right) \qquad \forall\, ij \in \mathcal{PL}^{passive} \tag{5}$$

$$sign\left(f_{ijyd}^{Gas}\right){f_{ijyd}^{Gas}}^{2} \ge {K_{ij}^{pipe}}^{2}\left({pr_{iyd}^{g}}^{2} - {pr_{jyd}^{g}}^{2}\right) \qquad \forall\, ij \in \mathcal{PL}^{Active} \tag{6}$$

$$0 \le f_{ijyd}^{Gas} \le \overline{f_{ij}^{Gas}} \qquad \forall\, ij \in \mathcal{PL}^{Active} \tag{7}$$

$$\underline{S_{i}^{Gas}} \le S_{iyd}^{Gas} \le \overline{S_{i}^{Gas}} \qquad \forall\, i \in N^{Gas} \tag{8}$$

$$\underline{pr_{i}^{g}} \le pr_{iyd}^{g} \le \overline{pr_{i}^{g}} \qquad \forall\, i \in N^{Gas} \tag{9}$$

$$S_{iyd}^{Gas} = \sum_{j} bin_{ij}^{Pipe} f_{ijyd}^{Gas} + \left(X_{iyd}^{Gas} + s_{iyd}^{l}\right) \qquad \forall\, i \in N^{Gas} \tag{10}$$

$$OC_{yd} = \sum_{mg} \lambda_{m}^{X} X_{mgyd}^{Elec} bin_{mg}^{Gen} \qquad \forall m \in N^{Elec},\ g \in GU \tag{11}$$

$$\sum_{g} bin_{mg}^{Gen} p_{mgydt}^{Gen} = \sum_{n} bin_{mn}^{Trans} PF_{mnydt} + p_{mydt}^{E\_load} \qquad \forall m \in N^{Elec} \tag{12}$$

$$PF_{mnydt} = p_{b} \times \sum_{n} y_{mn}\left(\theta_{mydt} - \theta_{nydt}\right) \qquad \forall\, m \in N^{Elec} \tag{13}$$

$$\theta_{ref} = 0 \tag{14}$$

$$\underline{p_{mg}^{Gen}} \le p_{mgydt}^{Gen} \le \overline{p_{mg}^{Gen}} \qquad \forall m \in N^{Elec},\ g \in GU \tag{15}$$

$$-\overline{PF_{mn}} \le PF_{mnyd} \le \overline{PF_{mn}} \qquad \forall m \in N^{Elec},\ mn \in TL \tag{16}$$

$$X_{mgyd}^{Elec} = \sum_{t} \frac{T_{t}}{GHV_{g}}\left(\alpha_{mg} + \beta_{mg} p_{mgydt}^{Gen} + \gamma_{mg} {p_{mgydt}^{Gen}}^{2}\right) \qquad \forall\, m \in N^{Elec},\ g \in GU \tag{17}$$

In which constraints (2) and (3) represent gas and electricity networks operation cost, respectively. Constraint (4) shows limitations on gas flow in passive pipelines without compressor pipelines. Constraints (5)-(6) are Weymouth equations of gas network which relate the gas flow to the pressure difference in passive and active pipelines with compressor pipelines, respectively [15]. Gas flow in active pipelines is limited by (7). Constraint (8) indicates supply bounds in different nodes. Constraint (9) determines gas pressure limits at each node. Node balance of gas network is defined by (10).

Constraint (11) defines operation cost of generation units in each day of a year. Node balance of electricity network is indicated by (12). Power flow in transmission lines is obtained using (13). Based on DC load flow reference bus angle is fixed to zero by (14) [16]. Generation units' bounds are defined by (15). Constraint (16) determines the limitations in transmission lines. Fuel consumption of generating units is obtained by their Gross heating value using (17).

B. *DR model*

In this paper, DR cost is integrated with operation and investment cost to find a flexible expansion plan of integrated energy system. Proposed DR is an incentive-based DR that electricity operator pays to the consumers for participating in DR program [17]. Value of DR bid is assumed to be higher than the electricity consumption cost [11]. By the proposed assumptions, DR models load shifting to study the effects of electricity flexible loads on integrated energy network expansion plan. Proposed DR program can be modeled as follows.

$$P_{mydt}^{E\_load} = P_{mydt}^{load} - P_{DR_{mydt}}^{-} + P_{DR_{mydt}}^{+} \qquad \forall\, t \in \mathcal{T}, m \in \mathcal{B} \tag{18}$$

$$\sum_{t}\left(P_{DR_{mydt}}^{+} - P_{DR_{mydt}}^{-}\right) = 0 \qquad \forall m \in \mathcal{B} \tag{19}$$

$$0 \le P_{DR_{mydt}}^{-} \le u_{DR_{mydt}}^{-} \overline{P_{DR_{mydt}}^{-}} \qquad \forall\, t \in \mathcal{T}, m \in \mathcal{B} \tag{20}$$

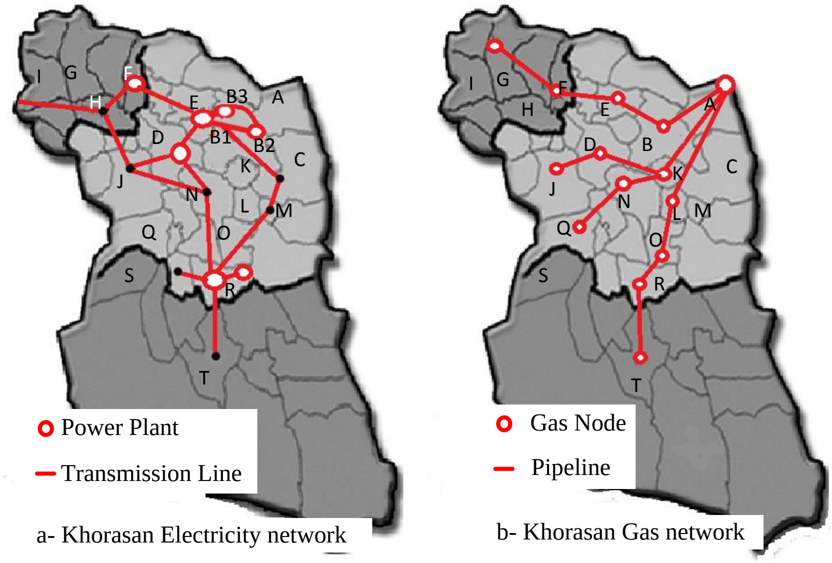
$$0 \le P_{DR_{mydt}}^{+} \le u_{DR_{mydt}}^{+} \overline{P_{DR_{mydt}}^{+}} \qquad \forall\, t \in \mathcal{T}, m \in \mathcal{B} \tag{21}$$

$$u_{DR_{mydt}}^{+} + u_{DR_{mydt}}^{-} \le 1 \qquad \forall\, t \in \mathcal{T}, m \in \mathcal{B} \tag{22}$$

Expected load according to the DR is defined by (18). Shift-able load is ensured by (19). DR limitations is indicated by (20) and (21) for load decrement and increment opportunities respectively. DR penetration level is also determined by the upper level of DR used in (20) and (21). Constraint (22) ensures that only one of the either load increment or decrement opportunities of DR program can be considered in a time period. This is accomplished by binary variables used in (20)-(22).

III. SIMULATION RESULTS

The test system used to apply the proposed methodology is the Khorasan province of Iran gas and electricity networks. The 400 KV electricity system includes 18 transmission lines and 15 buses in which 33 gas consuming units are dispatched among 7 buses. In gas network, there are 14 nodes that are connected together through 13 pipelines. Supplementary data of the proposed electricity and gas networks are given in [18] and [19], respectively. We suppose a planning period of 15 years with annual load growth of 3% in both gas and electricity networks. The current demand in electricity network is 3129 MW while a maximum generation of 3880 MW is available. In gas network there is a consumption rate of 39.133 million standard cubic meters per day (MSCMD) demanded by other parties than GCUs such as residential sector. Existing pipelines, transmission lines, and generating



a- Khorasan Electricity network

b- Khorasan Gas network

Fig. 1. Khorasan Electricity (A) And Gas (B) Networks

units and their candidates for expansion planning are depicted in Fig. 1. Expansion candidates of both gas and electricity networks and their investment cost are given in TABLE I [19].

TABLE 1 EXPANSION CANDIDATES AND THEIR INVESTMENT COSTS

Pipe.	Cost (k$/inch-km)	Trans.	Cost (k$/km)	Gen.	Cost (k$/MW)
A-B3	40	S-Q	240	C	900
A-L	40	K-C	240	S	900
A-K	60	B-C	360	Q	900
F-D	60	K-D	480	L	900
G-J	60	R-Q	480	F	900
		R-T	480	I	900
		R-S	480	T	1170
				B	1440
				R	1080

In integrated method a single entity is responsible for expansion of both gas and electricity networks [14]. Numerical results show that without DR program, electricity network intends to add new capacity of 1000 MW in J and increase the capacity of B3 by 600 MW. Additionally new transmission lines in F-H, B1-C and K-N must be installed. In gas network a capacity increment in pipelines A-B and A-K is needed. Results are summarized in TABLE 2. Obtained results shows a total cost of 23.72 billion dollars for gas network. It is noteworthy that all reported costs are net present values.

Effect of electricity network DR program on system performance is studied in TABLE 2. By this method, total expansion cost of gas network is 22.64 billion dollars which is relatively lower than the cost estimated by the proposed integrated approach. Results demonstrate that the total cost of investment and operation in integrated method with DR program is 26.24 billion dollar which is less than the results of integrated method without DR implementation. The reason for this is that with DR program there is no need to add new capacity in J. In gas network, J is supplied by A-K pipeline. So to supply the new capacity in J, in the proposed integrated method without DR program, it was necessary to increase the capacity of A-K pipeline. Whereas with omitting the new capacity in J, there is no need to increase the capacity of A-K pipeline anymore.

TABLE II RESULTS OF PROPOSED METHODOLOGY

case	Without DR		With DR	
	Electricity	Gas	Electricity	Gas
Investment Cost (10^6\$)	846.31	1063	523.39	25
Generation Cost (10^9\$)	3.11	22.65	3.07	22.62
DR Cost (10^6\$)	-	-	0.64	-
Total Cost (10^9\$)	3.96	23.72	3.6	22.64
Generation Candidates	J,B3	-	B3	-
Transmission/Pipeline Candidates	F-H, B1-C, K-N	A-B.A-K	F-H,B1-C,K-N	A-B
Total Integrated System Cost (10^9\$)	27.68		26.24	

Expansion planning results for possible generation and pipeline facilities are shown in Fig. 2.

Expansion planning decisions of generation opportunity show that DR can reduce new generation installations. By peak shaving and load shifting actions, the need for new installations could also be reduced. In this regard effect of different DR penetration level on electricity network expansion cost is studied in Fig. 3. To better investigate the DR effect, results of generation cost, expansion cost, DR cost, expansion candidates of generation and total amount of electricity network generation and expansion costs are summarized in table III.

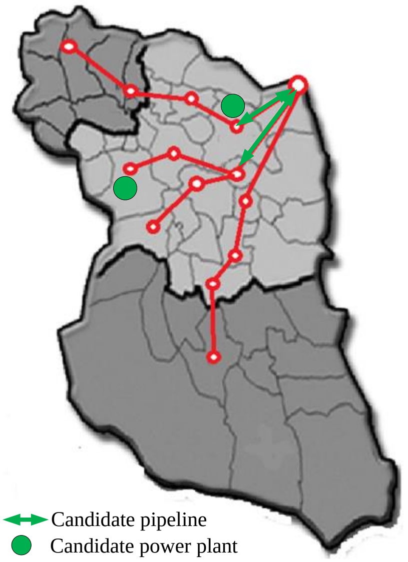


Fig. 2 Expansion planning candidates for generation and pipelines

In table III it is obvious that incorporating DR program results in lower total cost and it is more efficient than new generation installations. However as it can be seen in Fig. 3, with DR penetration levels above 10%, electricity expansion cost does not change anymore. Fig. 3 also indicates that with increased DR penetration level (beyond 20%), DR cost remains unchanged as DR reaches the maximum load shedding action that is available in the load variation range. Fig. 3 also clarifies that with the increase of DR penetration level, electricity network expansion cost reduces. Also as it can be seen in table III and Fig. 3, with a DR penetration level higher than 10%, there is no need to one of the generation candidates anymore.

TABLE III EFFECT OF DR PENETRATION LEVEL

DR	**5%**	**10%**	**15%**	**20%**	**25%**	**30%**
Tot. cost $(10^{9}\$)$	3.96	3.6	3.59	3.59	3.59	3.59
Inv. Cost $(10^{6}\$)$	846.31	523.39	523.39	523.39	523.39	523.39
Gen. candidates	J,B3	B3	B3	B3	B3	B3
DR cost $(10^{6}\$)$	0.32	0.64	0.88	1.01	1.02	1.02

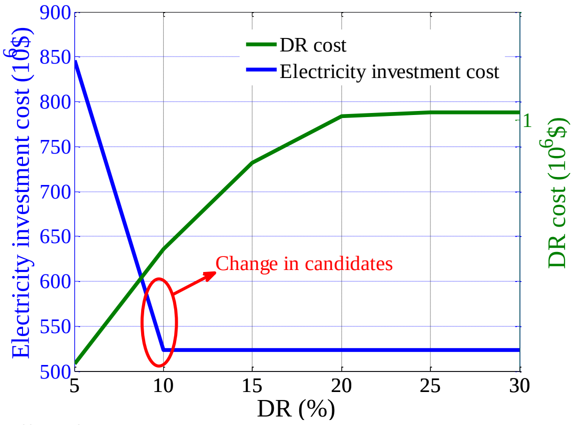


Fig. 3 Effect of DR penetration level on electricity expansion cost

Impact of DR on daily load profile of electricity system in region D is studied in Fig. 4. It is shown that as DR penetration level increases, smoother daily load profile can be achieved.

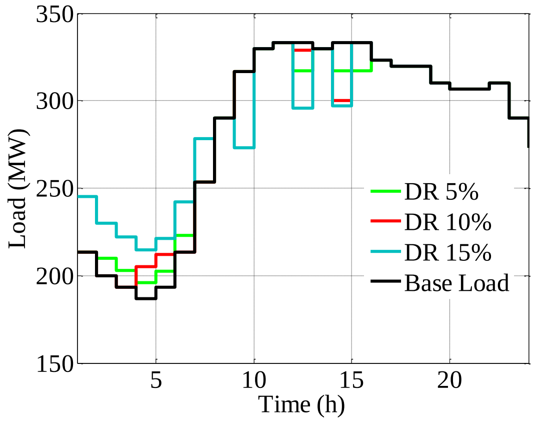


Fig. 4 Effect of DR penetration level on daily load profile

IV. CONCLUSION

In this paper effect of electricity network DR on integrated gas-electricity energy network expansion planning was investigated. Coordinated expansion planning of integrated gas-electricity network was performed by a central entity as Ministry of Energy. DR cost was integrated with operation and investment cost of electricity network so as to find a flexible expansion plan for integrated energy system. In the proposed DR program, load shifting and peak shaving opportunities were modeled to study the effects of flexible loads on integrated energy system expansion plan.

It was shown that DR program could decrease cost of expansion in both gas and electricity networks. With an appropriate penetration level, daily load profile could be smoothed. Also it was shown that how electricity expansion cost can be reduced by using different penetration level of DR programs. Results were examined on a real case study in Iran, in which adequacy of gas-electricity network was satisfied in a period of 15 years with a minimum cost of operational planning.

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