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A Case Study in Iran

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Integrated Expansion Planning of Gas-Electricity System: A Case Study in Iran

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***Abstract*— Gas-fired power plants are connection points between gas and electricity networks which are growing in installation due to their high efficiency rates and flexibilities. The main purpose of this paper is to adjust integrated expansion planning of gas-electricity system. In integrated expansion planning it is assumed that a central entity such as Ministry of Energy is responsible for the expansion of both gas and electricity networks. Results of the proposed method are examined in Khorasan province of Iran as a realistic case study which has a high penetration level of gas-driven units. To demonstrate the effectiveness of the proposed method, results are compared with those of an independent expansion planning method. Also sensitivity to load level growth forecast is analyzed.**

Keywords*— *Gas; Electricity; Expansion planning; Integrated energy system; Optimization; Coordinated scheduling.

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
gu	Index of generation units
$\widehat{gu}$	Index of gas consuming generation units
T	Planning period
GU	Set of generation units
$\mathcal{N}/\mathcal{B}$	Set of nodes/buses of gas/electricity network
$\mathcal{PL}/\mathcal{PL}^A/\mathcal{PL}^P$	Sets of all/active/passive pipelines
$\mathcal{T}$	Set of daily load periods
$\mathcal{TL}$	Set of transmission lines

Variables

$C_{y,d}^{Gas}$	Gas network operation cost in day d of year y
S_i^{Gas}	Gas production in node i (MSCMD)
Cr_i^{Gas}	Curtailed gas in node i (MSCMD)
f_{ij}^{Gas}	Gas flow through pipeline ij (MSCMD)
π_i^{Gas}	Gas pressure in node i (bar)
FC_i^{Gas}	Gas consumption of gas consuming power plants in node i (MSCMD)
S_{ij}^{Comp}	Gas consumption of compressor in pipeline ij (MSCMD)
$C_{y,d}^{Elec}$	Electricity network operation cost in day d of year y
$FC_{m,gu,t}^{Elec}$	Fuel consumption of power plants on day d of year y in electricity network
$p_{m,gu,t}^{gen}$	Power generation of unit gu of bus m at period t (MW)
$PF_{mn,t}$	Power flow through transmission line mn at period t (MW)
$\theta_{m,t}$	Voltage angle of bus m at period t (rad)
Cr_{mt}^{Elec}	Curtailed load at bus m in period t (MW)
OC_t	Operation cost of electricity network
$bin_{ij}^{Pipe}/bin_{mn}^{Trans}/bin_{mg}^{Gen}$	Binary variable indicating existence of pipeline/transmission line/generation

Parameters

λ_i^{Gas}	Gas price in node i of gas network (\$/MSCMD)
$\lambda_i^{Gas\_Cr}$	Curtailed gas price in node i of gas network (\$/MSCMD)
$\lambda_{mt}^{Elec\_Cr}$	Curtailed electricity price in bus m of electricity network (\$/MW)
$\lambda_{m,gu}^{Fuel}$	Fuel price of generation unit gu in bus m
c_{ij}^{Gas}	Constant defining Weymouth equation
l_i^{Gas}	Gas demand at node i (MSCMD)
k_{ij}^{Gas}	Constant defining compressor gas consumption
$\alpha_{m,gu}/\beta_{m,gu}/\gamma_{m,gu}$	Cost function parameters of generation units
$p_{m,t}^{load}$	Power demand at bus m
p_b	Power base unit (MW)
y_{mn}	Series admittance of transmission line mn
d_t	Duration of t period
L_{ij}^{Pipe}	Length of pipeline (km)

A_{ij}^{Pipe}	Diameter of pipeline (inch)
$P_{m,gu}^{rated}$	Power plant rated power (MW)
$cost_{ij}^{Pipe}$ $/cost_{mn}^{trans}$ $/cost_{m,gu}^{Gen}$	Construction cost of pipeline (k$/inch-km)/ transmission line (k$/km)/generation unit (k$/MW)
r	Interest rate

I. INTRODUCTION

While coal still plays a major role in electricity generation, new plants are mainly focused on gas-fired power plants and renewables. In the U.S. roughly a third power generation is performed by coal power plant however the industry is slowly contracting as plants retire and utilities replace them with natural gas and renewables. Also gas-fired power stations in combination with renewables are ideally suited to mitigate renewable fluctuations as they can easily be fired up in just a few minutes [1]-[2].

In the literature there are some papers that study gas-electricity expansion context. Proposed model in [2] provides a leader-follower approach to perform the expansion planning of the integrated gas-electricity network. In this paper electricity network makes decision as the leader and gas network is the follower who tracks the decisions. In [3] a robust model proposes an centralized electricity and natural gas planning with the grid resilience considered as a set of constraints. However this model does not consider compressors in gas network. An iterative process between gas and electricity networks in a combined market is illustrated in [4]. Proposed model in [5] simultaneously minimizes the total cost of gas and electricity networks operational and expansion costs. Additionally it allocates the planned power generating units. The work presented in [6] introduces a multi-area, multi-stage model that integrates the long-term expansion planning of gas and electricity infrastructures. A model that integrates electricity distribution and natural gas networks is presented in [7]. In [8], the expansion of gas-fired power plants, transmission lines and gas pipelines has been carried out with the aim of increasing social welfare. In this model, the adaption cost to new conditions has been used to deal with uncertainties such as gas and electricity market prices. The work presented in [9] provides a model for the expansion of generation, transmission and pipelines in large-scale systems. Proposed method incorporates a three-level framework to solve and coordinate the transmission, generation and gas network expansion problem by using genetic algorithm. A carbon oriented model of gas-electricity expansion problem is introduced in [10] that considers profit-to-cost maximization objective function with a market scheme as price scenarios. Co-optimization planning problem in [11] provides a system with optimal size, location, installation time of new electricity and natural gas resources based on electricity network constraints, natural gas fuel supply availability and reliability criterion. The work presented in [12] uses a two-stage stochastic optimization framework to represent uncertainty in natural gas and electricity demand growth. Expansion planning of gas and electricity networks with bi-directional energy conversion is also formulated in [13] by a bi-level problem. A planning model for gas and electricity networks considering a joint N-1 security and probabilistic reliability is presented in [14].

In this paper an integrated approach to co-expansion planning of gas-electricity planning problem is introduced. Coordinated expansion planning of gas-electricity system is accomplished using an integrated objective function. The expansion planning problem is formulated as a co-optimization problem from the viewpoint of the independent system operator (ISO), where both transmission and generation expansion opportunities are optimized in electricity network and new pipelines are allocated in gas network. Generation expansion determines the size and location of new units and transmission expansion ensures a feasible power delivery. On the other hand the electricity network gas consumption treatment is included in pipeline expansion decisions to ensure a feasible operation of gas network. Results are examined in a realistic case study to demonstrate the effects of proposed integrated method.

In the following sections firstly gas and electricity networks operation are modeled. After that the proposed integrated expansion planning approach is described and results are examined in Khorasan province of Iran as a real world case study which has a high penetration level of gas consuming units.

II. OPERATION PROBLEM FORMULATION

A. Gas operation model

The main objective of gas network operator is to supply the loads with a minimum cost. Hence, the objective function of gas network is to minimize cost of operation and load curtailment. It is subjected to the Weymouth equations [15] and some other technical constraints of gas network. So operation model of gas network for one day could be written as:

$$Min\ C^{Gas} = \sum_i S_i^{Gas} \lambda_i^{Gas} + \sum_i Cr_i^{Gas} \lambda_i^{Gas\_Cr} \tag{1}$$

$$s.t.$$

$$sign\left(f_{ij}^{Gas}\right) f_{ij}^{Gas^2} = C_{ij}^{Gas^2}\left(\pi_i^{Gas^2} - \pi_j^{Gas^2}\right) \quad \forall ij \in \mathcal{PL} \tag{2}$$

$$sign\left(f_{ij}^{Gas}\right) f_{ij}^{Gas^2} \geq C_{ij}^{Gas^2}\left(\pi_i^{Gas^2} - \pi_j^{Gas^2}\right) \quad \forall ij \in \mathcal{PL}^A \tag{3}$$

$$\underline{\pi_i^{Gas}} \leq \pi_i^{Gas} \leq \overline{\pi_i^{Gas}} \quad \forall i \in \mathcal{N} \tag{4}$$

$$\underline{f_{ij}^{Gas}} \leq f_{ij}^{Gas} \leq \overline{f_{ij}^{Gas}} \quad \forall ij \in \mathcal{PL}^P \tag{5}$$

$$0 \leq f_{ij}^{Gas} \leq \overline{f_{ij}^{Gas}} \quad \forall ij \in \mathcal{PL}^A \tag{6}$$

$$\underline{s_i^{Gas}} \leq s_i^{Gas} \leq \overline{s_i^{Gas}} \qquad \forall i \in \mathcal{N} \qquad (7)$$

$$0 \leq Cr_i^{gas} \leq l_i^{gas} \qquad \forall i \in \mathcal{N} \qquad (8)$$

$$\sum_j f_{ij}^{Gas} = s_i^{Gas} + Cr_i^{Gas} + \sum_j f_{ij}^{Gas} - FC_i^{Gas} - l_i^{Gas} - S_{ij}^{comp} \qquad \forall i \in \mathcal{N} \qquad (9)$$

$$S_{ij}^{comp} = f_{ij}^{Gas} k_{ij}^{Gas} \left(\pi_j^{Gas} - \pi_i^{Gas}\right) \qquad \forall ij \in \mathcal{PL}^A \qquad (10)$$

$$1 \leq \frac{\pi_j^{Gas}}{\pi_i^{Gas}} \leq R_{ij}^{Gas} \qquad \forall ij \in \mathcal{PL}^A \qquad (11)$$

$$FC_i^{Gas} = \sum_{t,\widehat{gu}} FC_{m,\widehat{gu},t}^{Elec} \qquad \forall m \in \mathcal{B}, i \in \mathcal{N} \qquad (12)$$

In which, constraints (2)-(3) are Weymouth equations of gas network which relates the gas flow to the pressure difference in passive and active (i.e., pipelines with compressor) pipelines respectively [15]. Constraint (4) bounds pressure in different nodes. Constraint (5) denotes limitation of gas flow in passive pipelines (i.e., pipelines without compressor). Gas flow in active pipelines is limited by (6). Constraint (7) indicates supply bounds in different nodes. Constraint (8) determines bounds on curtailed gas demand at each node. Node flow balance is defined by (9). Compressor uses energy to boost pressure and this energy is estimated as a loss in gas network. Linearized equation for gas consumption of compressors is given in constraint (10) [16]. Pressure ratio in active pipelines is restricted by (11). Constraint (12) is the coupling factor which relates gas and electricity networks through fuel consumption of gas fired power plants.

B. Electricity operation model

Electricity network operator deals with a feasible operation with minimum cost. To simplify the model, DC load flow is used to be sure about technical constraints [17]. The objective function of this optimization problem comprises of two terms. Operation cost and value of lost load.

$$Min\ C^{Elec} = \sum_t d_t OC_t + \sum_{mt} d_t Cr_{mt}^{Elec} \lambda_{mt}^{Elec\_Cr} \qquad (13)$$

$$s.t.$$

$$OC_t = \sum_{m,gu} \lambda_{m,gu}^{Fuel} FC_{m,gu,t}^{Elec} \qquad \forall t \in \mathcal{T} \qquad (14)$$

$$FC_{m,gu,t}^{Elec} = \frac{\alpha_{m,gu} + \beta_{m,gu} p_{m,gu,t}^{gen} + \gamma_{m,gu} p_{m,gu,t}^{gen\ 2}}{GHV} \qquad \forall t \in \mathcal{T}, \forall m \in \mathcal{B}, \forall gu \in GU \qquad (15)$$

$$\sum_{gu} p_{m,gu,t}^{gen} = \sum_n PF_{mn,t} + p_{m,t}^{load} - Cr_{m,t}^{Elec} \qquad \forall t \in \mathcal{T}, \forall m \in \mathcal{B} \qquad (16)$$

$$PF_{mn,t} = p_b \times \sum_n y_{mn}\left(\theta_{m,t} - \theta_{n,t}\right) \qquad \forall t \in \mathcal{T}, \forall mn \in \mathcal{TL} \qquad (17)$$

$$\theta_{ref} = 0 \qquad (18)$$

$$\underline{P_{m,gu}^{gen}} \leq P_{m,gu,t}^{gen} \leq \overline{P_{m,gu}^{gen}} \qquad \forall m \in B, gu \in GU\ \forall t \in \mathcal{T} \qquad (19)$$

$$-\overline{PF_{mn}} \leq PF_{mn,t} \leq \overline{PF_{mn}} \qquad \forall t \in \mathcal{T}, \forall mn \in \mathcal{TL} \qquad (20)$$

$$0 \leq Cr_{m,t}^{Elec} \leq p_{m,t}^{load} \qquad \forall t \in \mathcal{T}, \forall m \in \mathcal{B} \qquad (21)$$

In this optimization constraint (14) defines operation cost of generation units. Fuel consumption of generating units is obtained by their gross heating value using (15). Node balance is indicated by (16). Power flow in transmission lines is obtained using (17). Based on DC load flow reference bus angle is fixed to zero by (18). Generation units' bounds are defined by (19). Constraint (20) determines the power flow limitations in transmission lines. Curtailed load in each bus of electricity network is restricted by (21).

III. COORDINATED EXPANSION PLANNING PROBLEM

In integrated expansion planning it is assumed that a central entity such as Ministry of Energy (i.e., ISO) is responsible for the expansion of both gas and electricity networks. Coordinated expansion planning of gas-electricity system is accomplished using an integrated objective function. The main objective of the ISO is to supply the loads with minimum total cost which includes both operation and investment costs. In this way supplying new load could be achieved by adding new generation units, new transmission lines and new pipes if needed. New opportunities should be located in the system in a way to guarantee the feasible performance and operating point. Hence the objective function of ISO is to minimize the cost of expansion and net present value (NPV) of operation cost during the planning period. So expansion planning model of ISO could be written as:

$$Min\ C^{ISO} = \left\{ \begin{array}{l} \sum_{i,j} bin_{ij}^{Pipe} L_{ij}^{Pipe} A_{ij}^{Pipe} cost_{ij}^{Pipe} + \\ \sum_{m,n} bin_{mn}^{Trans} cost_{mn}^{trans} + \sum_{m,g} bin_{m,gu}^{Gen} P_{m,gu}^{rated} cost_{m,gu}^{Gen} \\ + \sum_{y=1}^{T} (1+r)^{-(y-1)} \sum_d (C_{y,d}^{Gas} + C_{y,d}^{Elec}) \end{array} \right\} \qquad (22)$$

$$s.t.$$

$$(1), (13) \qquad \forall y \in Y,\ d \in D \qquad (23)$$

IV. RESULTS

The test system used to apply the proposed methodology is the Khorasan province of Iran gas and electricity networks. All the formulations were implemented in GAMS software.

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 gas and electricity networks are given in [9] and [18], respectively. We suppose a planning period of 15 years with annual load grows 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 GFPPs such as residential sector. Existing pipelines, transmission lines, and generating 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.

Obtained results of gas network investment problem show that there is a need to increase the capacity of pipeline between regions A and B of Fig. 1. In this case, the investment cost is 19 million dollar while the total cost of investment and operation is 37.19 billion dollar. On the other hand, in electricity network new power plants in F, R and B2 regions are needed. Also, these results indicate that the capacity of F-H transmission line must be increased.

TABLE I: Expansion candidates and their investment costs

Pipe.	Cost (k$/inch-km)	Trans.	Cost (k$/km)	Gen.	Cost (k$/MW)
A-B	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	F-H	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

The cost of investment and operation in electricity network is 7.76 billion dollar in which investment and operation costs are 0.37 and 7.39 billion dollars respectively. Also studies indicate that while VOLL is more than 115 $/MWh and 1200 $/MSCMD in gas and electricity networks respectively, investment would be a better choice.

Results of the proposed integrated method are compared with results of independent method. In independent method, electricity system operator is responsible for electricity network expansion planning and gas operator is responsible for gas network expansion planning. They are deciding on expansion of their network independently. Electricity network expansion is done without considering gas network constraints. On the other hand, gas network is expanded assuming power plant and non-power plant loads grow 3% annually. Independent gas network expansion planning shows that there is no need to install a new pipeline and existing pipelines are sufficient. Results of independent electricity network expansion planning intend to add new generations in Q, S and B2 regions. Despite the integrated method, with an independent method in gas network both A-B and A-K pipelines will be congested so new generations will cause gas load curtailment. Detailed results of independent expansion planning approach are given in Table II for gas and electricity networks. Candidate power plants in both integrated and independent methods and also congested pipelines in independent method are shown in Fig. 2. Obtained results show that, independent expansion planning of gas and electricity networks intends to uncoordinated expansion plans and leads to high amount of gas and electricity load curtailment that causes high NPV of total costs in gas and electricity networks, as it is shown in Table II.

TABLE II: Results of Gas-Electricity expansion

Case	Independent		Integrated	
	Electricity	***Gas***	***Electricity***	***Gas***
Investment cost(10^9\$)	0.35	0	0.37	0.019
Total cost(10^9\$)	70×10^3	6×10^3	7.76	37.19
New lines	-	-	F-H	A-B
New generation units	Q/S/B2	-	F/R/B2	-
New generation capacities	600/400/200		400/400/300	

Uncertainty in load level forecast is also studied in a 20%

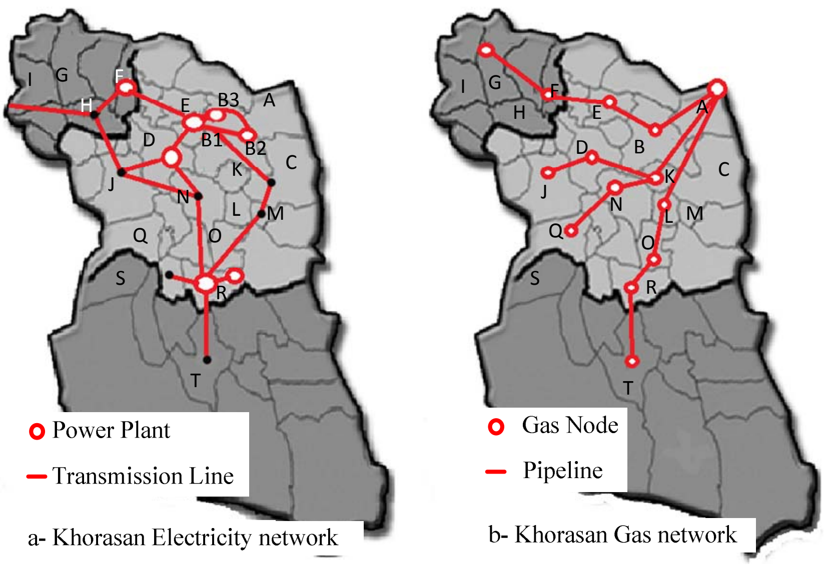

Fig. 1. Khorasan Electricity (A) And Gas (B) Networks

tolerance band. By varying gas and electricity loads of last year of planning period by ±10% and ±20% gas and electricity expansion plans are computed using integrated method. Table IV shows gas and electricity expansion plans, for increasing and decreasing gas and electricity loads by 10 and 20 percent. As Table IV shows the gas and electricity expansion plans are flexible against gas and electricity load change. In other words, if gas and electricity loads increase by 10 or 20 percent the base expansion plan does not change and only transmission line R-T is added, and if gas and electricity loads decrease by 10 or 20 percent new generating unit F is omitted from the base expansion plan.

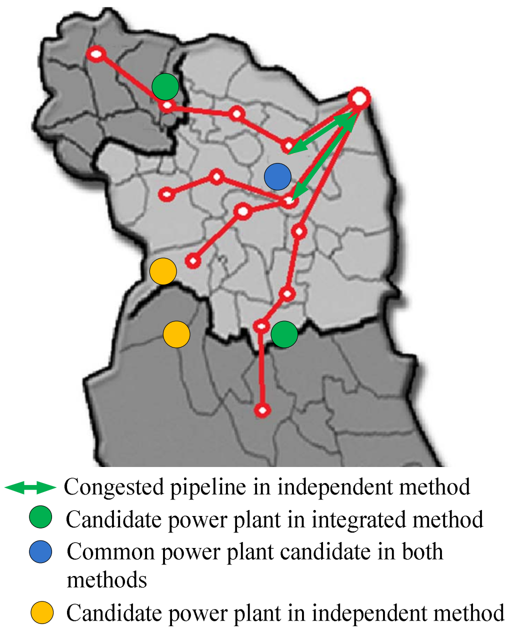

Fig. 2 Results of integrated and independent methods for generation unit and pipeline oppurtunities

TABLE III: Uncertainty in load growth

	New Trans. lines	*New pipelines*	*New Gens.*
Base case	F-H	A-B	F,R,B2
10%+	F-H,R-T	A-B	F,R,B2
20%+	F-H,R-T	A-B	F,R,B2
10%-	F-H	A-B	R,B2
20%-	F-H	A-B	R,B2

V. Conclusion

In this paper an integrated approach to co-expansion planning of gas-electricity planning problem was introduced. The expansion-planning problem was formulated as a co-optimization problem from the viewpoint of the ISO, where in electricity network level, both transmission and generation expansion opportunities were optimized and in gas network level new pipelines were allocated. Generation expansion determined the size and location of new units and transmission expansion ensured a feasible power delivery. On the other hand the electricity network gas consumption was included in pipeline expansion decisions to ensure a feasible operation of gas network. A real case study in Iran was used to demonstrate the effectiveness of the model. Adequacy of gas-electricity network was satisfied in a period of 15 years with a minimum cost of operational planning. Results were compared with those of independent method and it was shown that coordinated expansion planning leads to better results. Sensitivity of the proposed integrated method to load forecast uncertainty was also analyzed in a 20% tolerance band and it was shown that expansion plans are flexible against load level forecast uncertainty.

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