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Expansion co-planning for shale gas integration in a combined energy market

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Abstract Shale gas resources have the potential to significantly contribute to worldwide energy portfolio. A great number shale gas reserves have been identified in many countries. Connections of newly found gas reserves to the existing energy infrastructures are challenging, as many stakeholders and market uncertainties are involved. The proposed co-planning approach is formulated as a mixed integer nonlinear programming problem so as to minimize investments and enhance the reliability of the overall system. We propose a reliability assessment approach that is applicable for the coupled gas and electricity networks. In addition, the IEEE 24-bus RTS and a test gas system are applied to validate the performance of our approach. Based on the simulation results, the novel expansion co-planning approach is a robust and flexible decision tool, which provides network planners with comprehensive information regarding trade-offs between cost and system reliability.

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1 Introduction

As a major clean source of electricity generation, natural gas plays an increasingly important role in the carbon-constrained power industry [1–3]. Many countries have placed great pressure on energy industry to shift power generation from coal to natural gas because it provides greater flexibility to ease the cutting of emissions. Shale gas, one of the most rapidly growing forms of natural gas, has drawn worldwide concerns in the last decade. Comprehensive efforts have been made to develop advanced drilling technologies, because falling behind in the extraction of shale gas may lead to rapid loss in the competitiveness in global energy market. Large shale gas reserves have since been identified in United States, Canada, China, and Australia [4]. On the one hand, there is rising demand for gas; on the other hand, an increasing number of gas reserves have being identified and exploited. Since gas can either be transported to end users in original form or be transformed by gas-fired power generation (GPG) and then be transmitted to customers in electric energy form [2, 5], how to efficiently connect the newly found gas resources to load centers by pipeline-based gas networks becomes an emerging issue for system planners. An effective method for energy network expansion planning can lead to lower capital cost and less environmental impacts. Although there has been noteworthy research underway in formulating more effective network expansion planning approaches, the majority of previous studies placed great emphasis on accommodating renewable energy [6–8]. Owing to the surplus of cheap and abundant shale gas, increasing research interest has been directed towards the utilization of natural gas. Many independent natural gas system operators (ISOs) have acknowledged the importance of nature gas in power engineering. For example, the Australian Energy Market Operator (AEMO) has issued a series of national policies to promote jointly planning and operation of gas and electricity markets for solid progress of energy supply [9], which are expected to underpin solid progress of energy industry in Australia.

In the literature, the centralized coordination of generation and transmission planning has been proposed in many references [10–15]. Co-planning can be performed by a vertically integrated utility or in a market environment [16]. Nevertheless, one critical drawback of the existing generation and transmission planning approaches is that fuel price and availability are considered as uncertain factors [17]. Moreover, there are no system performance evaluation models for the combined gas and electricity networks [18]. However, gas security issues such as pipeline contingencies and pressure losses have been integrated into power system operation planning, i.e. unit commitment, economic dispatch [19, 20]. They failed to be applied to network expansion planning due to the lack of an integrated gas and electricity planning framework. It should be noted that there has been noteworthy research on joint gas and power system planning in a market environment [17, 21–25]. Attempts have been made to study the optimal power flow of multiple energy carriers covering transmission and conversion of energy [5, 21–23]. The optimal energy flow was solved by a detailed steady-state power and gas flow model, which minimizes the operation cost of integrated gas and power system, subject to transmission and capacity constraints [21, 22]. Others have done some work on joint expansion planning of electricity and gas networks without the consideration of reliability [24, 25]. Besides, Ref. [17] proposed an expansion planning approach for the combined gas and power in the context of value chains. However, the integration of gas reserves into existing systems, requiring energy network augmentations or reinforcements, is a key issue that needs further study. To sum up, the overall reliability criterion for the two systems has not been well addressed, in terms of expansion co-planning.

In this paper, our modelling combines several features in a way that has not been done by previous authors. Our model performs co-planning of gas and electricity networks ① using an adequacy calculation based on EENS and ② including load transfer rates between gas and electricity. A relatively new and superior optimization method, history driven differential evolution (HDDE), has been introduced and employed to develop planning solutions efficiently [26]. Specifically, the proposed model is formulated as a co-planning problem, aiming at minimizing capital investments on gas pipelines, GPG plants, and power lines, while meeting reliability criterion for the overall energy networks. The two conflicting objectives are depicted in a Pareto frontier, which can provide network planners with a flexible decision-making tool. To calculate the overall gas and electricity network adequacy, a modified EENS calculation method is adopted based on a Markov chain state-space representation [27]. In addition, on the demand side of multi-energy carrier, the load transfer rate (the percentage of nodal energy loads that can be mutually transferred between gas and electricity) is considered.

2 Natural gas networks

In this section, we will give explicit information regarding how we mathematically model a gas system, including gas market structure, gas flows, gas compressors and gas storage. Equations given in this section will be included into our formulated optimization problems in next section as physical constraints of a gas system. Note that gas price is a complex issue, as it could be influenced by international demand and transactions. However, this issue should not undermine the quality of this paper, since the major contribution of this paper lies on the formulation of expansion co-planning for the coupled two systems while considering conflicting objectives, i.e. investment cost and system reliability. The proposed model is suitable to model the physical and economic interactions between gas and power systems, and only local electricity and gas demands are considered.

2.1 Gas market

The natural gas market usually consists of two parts: ① the financial market, which is based on transactions of future contracts; ② the physical market, which involves cash flows for the actual gas deliveries at the specific delivery points [9]. As a supplement to forward contract portfolios, in Australia's market structure, a day-ahead market completes daily gas trading [28]. Normally, gas is dispatched in cost-order from the cheapest to the most expensive sources until load is satisfied [9]. Gas prices are determined on the preceding day by market participants, on the basis of localized supply and demand conditions, while other impacts such as exporting and international trading are not considered in this paper. As the time intervals for trading and delivering gas and power are inconsistent, the fluctuating gas demand for GPG needs to be offset by stored gas, e.g. linepack [28]. Stored gas can also reduce the price volatility in gas markets.

2.2 Gas flow equations

The Bernoulli fluid equation is widely used to describe the steady-state gas flow along a horizontal pipeline. It can be expressed in (1) and (2), [21, 22].

$$\Theta_{ij} = \sqrt{\frac{\pi^2 R_{air}}{64}} \frac{\Gamma_0}{\rho_0} \sqrt{\frac{D_{ij}^5}{F_0 L_{ij} \Gamma \, \Phi_0 \left(\frac{R_{air}}{R_{gas}}\right)}} \tag{1}$$

$$\text{sign}\left(S_{ij}\right) S_{ij}^2 = \Theta_{ij}^2 \left(\rho_i^2 - \rho_j^2\right) \tag{2}$$

where S_i^{gas} is gas volumetric flow rate along node *i, j*; Θ_{ij} a constant that depends on pipe properties of length, diameter etc.; Γ_0, ρ_0 the quantities at standard conditions of temperature and pressure; ρ_i, ρ_j the inlet and outlet absolute pressure (N/m^2); D_{ij} the internal diameter of pipe *ij* (mm); F_0 the dimensionless friction factor; L_{ij} the length of pipe *ij* (m); Γ the temperature of gas (K); Φ_0 the dimensionless compressibility factor; and R_{air}, R_{gas} the gravity for air and gas.

We can use gas flow models in (1) and (2) to construct a series of nodal balance constraints including all supplies, loads and nodal inflows and outflows, for the subsequent optimization problem.

2.3 Compressors

Compressors stations are indispensable for maintaining pressure differences along pipelines [8]. As we know, gas pressure gradually drops along with distance it travels due to frictions [4]. The nonlinear and non-convex nature of gas networks is caused by the complexity of compressors [10]. The empirical equation is given in (3) [25]:

$$P_i^{\text{comp}} = \frac{S_i^{\text{comp}} \varphi}{\eta_i (\varphi - 1)} \left[\left(\frac{\rho_i^{\text{out}}}{\rho_i^{\text{in}}} \right)^{\frac{\varphi - 1}{\varphi}} - 1 \right] \tag{3}$$

where P_i^{comp} is the compressor power *i* (10^5 W); S_i^{comp} the gas volumetric flow rate at compressor; φ the polytropic exponent of empirical equations; η_i the overall efficiency of compressor *i*; and ρ_i^{out}, ρ_i^{in} the outlet and inlet pressures of a compressor (Pa).

Compressors are important to adjust nodal pressures, which two key variables are for determine gas flows along pipelines, linked to gas pressure variables in (1) and (2). Meanwhile, compressors need to consume some gas during operation. Therefore, they should be considered as gas load, which is part of nodal balance constraints.

2.4 Gas storage

It is imperative that gas storage is taken into account, as it plays an important role in: ① balancing gas flows; ② maintaining operational pressures; ③ reducing price volatility. Underground gas storage is also important for balancing supply and demand dynamically, as well as providing a potential substitute gas source if supply is disrupted [25]. The volume of gas required in storage to maintain an adequate pressure is called cushion gas, which refers to a lower limit of the storage, Ψ_i^{Min} (m^3) [25], and a upper limit Ψ_i^{Max} (m^3) is the storage capacity. The amount of working gas should be within the limits. $P_i^{\text{gas,inject}}$ and $P_i^{\text{gas,withdrawal}}$ are the injection and withdrawal rate of gas (m^3/s). The time interval ($t_2 - t_1$) is the working period of the storage. In this paper, since our simulation interval is one hours, the time interval for gas storage is also set as one hour.

$$\Psi_i^{\text{Min}} \le \int_{t_1}^{t_2} \left| P_{i,t}^{\text{gas,inject}} - P_{i,t}^{\text{gas,withdrawal}} \right| \mathrm{d}t \le \Psi_i^{\text{Max}} \tag{4}$$

3 Formulation of co-planning model

We formulated a multi-objectives (MO) problem for minimizing the expansion investment, while maintaining a high reliability standard for system supply redundancy, subject to a variety of technical constraints.

3.1 Detailed co-planning model

For simplicity, our co-planning is assumed to be a static model, i.e. single stage optimization. Define the vector $\boldsymbol{C}$ comprising the costs of each element of potential expansion plans, including gas power plants, gas pipes, and electricity transmission lines. Also define the vector $\boldsymbol{\beta}$ of corresponding decision variables, i.e. the amount of each asset constructed. The purpose of the optimization is to calculate the trade-off between cost and reliability to support decision-making by planners. The trade-off is shown as a Pareto frontier in Sect. 4. Our first objective is to minimize the expansion investments.

Min

$$\boldsymbol{C}^{\mathrm{T}} \boldsymbol{\beta} = \begin{bmatrix} \boldsymbol{C}_{\text{plant}} \\ \boldsymbol{C}_{\text{pipe}} \\ \boldsymbol{C}_{\text{line}} \end{bmatrix}^{\mathrm{T}} \begin{bmatrix} \beta_{\text{plant}} \\ \beta_{\text{pipe}} \\ \beta_{\text{line}} \end{bmatrix} \tag{5}$$

We add maintenance cost to the capital cost of gas power plants, gas pipelines, and electricity transmission lines, as a part of the fixed cost of expansion plans. The economic terms capital recovery factor (CRF) is used to determine investment costs as a coefficient [6]. Denote the discount rate or the present worth rate by α, and denote the life span of the proposed project by *LSP*. The annual capital payment (ACP) is given by the product of $\boldsymbol{C}$ and *CRF*.

$$CRF = \frac{\alpha (1+\alpha)^{LSP}}{(1+\alpha)^{LSP} - 1} \tag{6}$$

Our second objective is to maximize the reliability of the coupled gas and power system. In this paper, expected energy not supplied (EENS) is selected as the reliability index and this should be minimized as follows.

Min

$$\boldsymbol{EENS}\left(EENS_{\text{gas}}, EENS_{\text{elec}}\right) \tag{7}$$

Subject to

$$\begin{cases} P_i^{\text{sup,gas}} + \sum S_{ij}^{\text{gas}} = \sum S_{ji}^{\text{gas}} + P_i^{\text{load,gas}} \\ \zeta_i^{\text{Min}} \le \dfrac{P_i^{\text{load,elec}}}{P_i^{\text{load,elec}} + \lambda^{\text{ge}} P_i^{\text{load,gas}}} \le \zeta_i^{\text{Max}} \end{cases} \tag{8}$$

$$S_{ij}^{\text{gas}} \le S_{ij}^{\text{gas,Max}} \tag{9}$$

$$\rho_i^{\text{Min}} \le \rho_i \le \rho_i^{\text{Max}} \tag{10}$$

$$P_i^G - P_i^{\text{load,elec}} = \sum_{n=1}^{N} |Y_{in} V_i V_n| \cos(\theta_{in} + \delta_n - \delta_i) \tag{11}$$

$$Q_i^G - Q_i^{\text{load,elec}} = \sum_{n=1}^{N} |Y_{in} V_i V_n| \sin(\theta_{in} + \delta_n - \delta_i) \tag{12}$$

$$S_{ij}^{\text{elec}} \le S_{ij}^{\text{elec,Max}} \tag{13}$$

$$V_i^{\text{Min}} \le V_i \le V_i^{\text{Max}} \tag{14}$$

$$\begin{cases} P_i^{\text{G,Min}} \le P_i^G \le P_i^{\text{G,Max}} \\ Q_i^{\text{G,Min}} \le Q_i^G \le Q_i^{\text{G,Max}} \end{cases} \tag{15}$$

$$P_i^{\text{G,Min}} \le P_i^G \le \lambda^{\text{ge}} P_i^{\text{load,gas}}, \textit{if } i \in \Omega_{\text{GPG}} \tag{16}$$

$$\rho_i^{\text{in}} \ge \rho_i^{\text{in,Min}} \tag{17}$$

$$\rho_i^{\text{out}} \le \rho_i^{\text{out,Max}} \tag{18}$$

$$1 < \frac{\rho_i^{\text{out}}}{\rho_i^{\text{in}}} \le \xi_i^{\text{Max}} \tag{19}$$

$$\begin{cases} Y_{ii} = y_i^0 + \sum \left(y_{ij}^0 + \eta_{ij}\gamma_{ij}\right), \; i \ne j \\ Y_{ij} = -\left(y_{ij}^0 + \eta_{ij}\gamma_{ij}\right), \; i \ne j \end{cases} \tag{20}$$

where $P_i^{\text{load,gas}}$, $P_i^{\text{load,elec}}$ is the forecasted gas and electricity loads respectively; $P_i^{\text{sup,gas}}$ the gas supply at bus i, Note gas storage can be considered as suppliers or consumers, gas compressors are modelled as loads, and gas network nodal balance constraint in (8) should include models in (1)–(4); λ^{ge} the heat rate of gas, and gas load for compressors is converted by $\frac{P_i^{\text{comp}}}{\lambda^{\text{ge}}}$; ξ_i^{Min} and ξ_i^{Max} the minimum and maximum load transfer rate respectively; S_{ij}^{gas}, S_{ij}^{elec} the gas volumetric flow and power flow between branch i–j, with the maximum flow rate $S_{ij}^{\text{gas,Max}}$ and $S_{ij}^{\text{elec,Max}}$. The gas flow calculation is given by (1) and (2); ρ_i the gas pipe nodal pressure, with the minimum maximum pressure tolerance ρ_i^{Min} and ρ_i^{Max}. The calculation of gas flow and pressure is based on (1)–(2); P_i^{G}, Q_i^{G} real and reactive power outputs of generator i; $Q_i^{\text{load,elec}}$ the forecasted reactive power load; θ_{in} the angle of admittance element Y_{in} in Y; V_i,V_n are bus voltages with angles δ_i, δ_n respectively; Ω_{GPG} the nodes with gas power plants whose outputs will be constrained by gas availability in gas networks, as shown in (16). Equations (17)–(19) denote the constraints of gas compressors, such as limits of inlet and outlet pressures, the maximum compression pressure ratio. Y_{ii}, Y_{ii}^0 are new and old self-admittance, Y_{ij}, Y_{ij}^0 are new and old mutual-admittance. γ_{ij} is the new circuit admittance of branch i–j.

In the proposed model, two main interconnectors of gas and power systems are load centers and gas-fired power generation (GPG), which are denoted by (8) and (16). Nodal balance constraints in gas networks and mutually transferrable energy loads between the two systems are given by (8). Outputs of GPG that are subject to the impacts of gas transmission constraints and security issues are given by (16), e.g. pipeline flow limits, pipeline outage, and lack of gas supply.

3.2 EENS calculation

The expected reliability of supply for the coupled gas and power system is calculated by the expected differences in supply and load quantities, which follow two different PDFs with m, n and $n \in \boldsymbol{\Omega}$, $m \in \boldsymbol{\Omega}$, where $\boldsymbol{\Omega}$ is the aggregation of the components of the coupled gas and power system. ***EENS*** is calculated by (21) to [29]:

$$\boldsymbol{EENS} = \sum_{j=1}^{n} \sum_{i=1}^{m} \max\left(0, \; P_i^{\text{load}} - P_j^{\text{sup}}\right) \gamma_i^{\text{load}} \gamma_j^{\text{sup}} \tag{21}$$

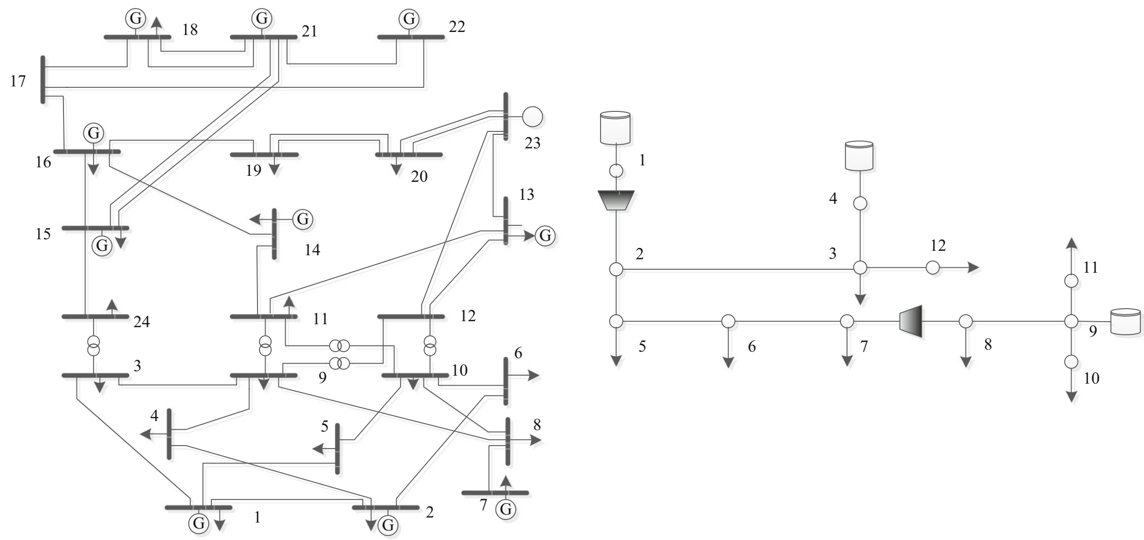
$$\boldsymbol{P}^{\text{sup}} = \left[\boldsymbol{P}_{\text{sup,elec}}, \boldsymbol{P}_{\text{sup,gas}}\right]^{\text{T}} = \begin{bmatrix} P_1^{\text{sup,elec}}, & P_2^{\text{sup,elec}}, & \ldots, & P_m^{\text{sup,elec}} \\ P_1^{\text{sup,gas}}, & P_2^{\text{sup,gas}}, & \ldots, & P_m^{\text{sup,gas}} \end{bmatrix} \tag{22}$$

$$\boldsymbol{P}^{\text{load}} = \left[\boldsymbol{P}_{\text{load,elec}}, \boldsymbol{P}_{\text{load,gas}}\right]^{\text{T}} = \begin{bmatrix} P_1^{\text{load,elec}}, & P_2^{\text{load,elec}}, & \ldots, & P_n^{\text{load,elec}} \\ P_1^{\text{load,gas}}, & P_2^{\text{load,gas}}, & \ldots, & P_n^{\text{load,gas}} \end{bmatrix} \tag{23}$$

An operating state of the coupled gas and power system is only considered to be successful if it contributes to reliability of energy supply, and its capacity is equal and greater than load. We define a factor matrix $\boldsymbol{H}$ to describe the system working condition of state k at time t, then

$$\boldsymbol{H}_{kt} = \begin{cases} 1, & \sum\left(\boldsymbol{P}_{kt}^{\text{load}}\right) \le \sum\left(\boldsymbol{P}_{kt}^{\text{sup}}\right) \\ 0, & \sum\left(\boldsymbol{P}_{kt}^{\text{load}}\right) > \sum\left(\boldsymbol{P}_{kt}^{\text{sup}}\right) \end{cases} \tag{24}$$

A new state probability matrix γ_{out} is formulated to describe the transposed work factor matrix $\boldsymbol{H}$ under the state probabilities of gas and power supplies, and loads.



(a) Base IEEE 24-bus RTS system **(b)** Base 12 bus gas system

Fig. 1 Base case of the two systems

$$\gamma_{\text{out}} = \left[\boldsymbol{H}^{\text{T}}\gamma^{\text{sup,gas}}\gamma^{\text{load,gas}}, \boldsymbol{H}^{\text{T}}\gamma^{\text{sup,elec}}\gamma^{\text{load,elec}}\right] \tag{25}$$

A weighting matrix $\boldsymbol{W}$ is employed to determine the average reliability of the coupled gas and power supply from system working states 1 to K. $\boldsymbol{W}$ is used to obtain the average contribution of each working state to the overall probability of energy supply during each time interval, especially considering the time delay effect of gas storage [27]. T denotes the length of totally investigated period. Equation (25) should be updated with the weighting factor as $\hat{\gamma}_{\text{out}} = \boldsymbol{W}^{\text{T}}\gamma_{\text{out}}$, as shown in (26). The average reliability is the product of the average weight of each scenario and its probability [27]. An updated supply state matrix $\boldsymbol{V}$ is defined for the calculation of $\boldsymbol{EENS}$ in (28). $\hat{t}$ denotes the time interval duration of one interested period.

$$\boldsymbol{W} = \frac{1}{T}\begin{bmatrix} \sum_{t=1}^{T} H_{\text{elec}}(1,t), & \sum_{t=1}^{T} H_{\text{gas}}(1,t) \\ \vdots & \vdots \\ \sum_{t=1}^{T} H_{\text{elec}}(K,t), & \sum_{t=1}^{T} H_{\text{gas}}(K,t) \end{bmatrix} \tag{26}$$

$$\boldsymbol{V} = (1-\boldsymbol{H})\boldsymbol{P}^{\text{sup}} + \boldsymbol{H}\boldsymbol{P}^{\text{load}} \tag{27}$$

$$\boldsymbol{EENS} = \begin{bmatrix} EENS_{\text{gas}} \\ EENS_{\text{elec}} \end{bmatrix} = \hat{t}\begin{bmatrix} \sum_{t=1}^{T}\left(\boldsymbol{P}_t^{\text{load,gas}} - \boldsymbol{V}_t\right)\hat{\gamma}_{\text{out}} \\ \sum_{t=1}^{T}\left(\boldsymbol{P}_t^{\text{load,elec}} - \boldsymbol{V}_t\right)\hat{\gamma}_{\text{out}} \end{bmatrix} \tag{28}$$

3.3 Solution algorithm

The combined gas and electricity system planning is a complicated mixed integer optimization problem. A relatively new and superior optimization algorithm, namely history driven differential evolution (HDDE), is introduced and employed to solve the formulated optimal problem. In addition to benefits such as the non-uniform crossover, arithmetical combinations of individuals, searching directly with floating point representation, HDDE is a more accurate, fast and robust optimization method [26]. A binary partitioning (BP) that guides the search process is applied to memorize all the solutions visited before. Each node in the BP tree represents a newly generated solution, and hence the entire solution space comprises several sub-spaces defined by BP nodes distance measure, i.e. Chebyshev distance. After that, we are able to store two data fields minFit and numChild denoting the minimum fitness value of all descendant nodes and the number of descendant nodes respectively. As searching information are stored in the BP tree, high valuable information can be obtained to guide the search direction. In addition, HDDE employs not only the conventional DE operator, but also pseudo-gradient and global search operators to generate new solutions by using the predefined topology distance in the BP tree. More technical detailed and explanations of HDDE can be found in [26].

4 Case studies

(1) The proposed planning approach was studied on a modified IEEE 24-bus reliability test sytems (RTS), plus a

Table 1 Parameters of candidate plans

Type	Generator unit (p.u.)	Max pressure (kPa)	Diameter (mm)	Voltage (kV)	Capacity (p.u.)	Cost (M$/MW or M$/km)	Maintenance cost (% capital cost)
Gas power plant	50	–	–	–	0–150	1	0.01
Power line	–	–	–	330	150	0.5	0.05
Gas pipe	–	10150	660	–	12	0.6	0.05

Notes: 1 h = p.u.; for gas plant, 1 p.u. = 1 MW; for electricity line, 1 p.u. = 1 MVA; for gas flow, 1 p.u. = GJ/h, 1 p.u. = 1 kPa

Table 2 Existing gas pipeline parameters

No	Branch	Length (km)	Capacity (p.u.)	Outage rate (1/yr)	Outage duration (hours)
1	(1)–(2)	10	7	0.24	12
2	(2)–(3)	12	7	0.44	11
3	(4)–(3)	15	7	0.25	12
4	(3)–(12)	8	7	0.35	16
5	(2)–(5)	8	7	0.36	11
6	(5)–(6)	10	7	0.35	12
7	(6)–(7)	15	10	0.40	16
8	(8)–(7)	10	10	0.28	11
9	(9)–(8)	20	10	0.38	11
10	(9)–(11)	15	10	0.25	11
11	(9)–(10)	20	10	0.05	11

benchmark gas network, as given in Fig. 1. The detailed system parameters are given in [30, 31]. Parameters of planning candidates are given in Table 1, and other relevent study parameters are given in Tables 2, 3 and 4, including gas storage state rates, gas pipeline lengths, capacities and outage rates, nodal pressure obligations, storage capacities, working rates of generators, and etc. The new shale gas reservoir is located at node 13. Generators are located at electricity nodes 18, 21, and 22, which are gas-fired units supplied by gas nodes (12), (5), and (11) respectively. The coupled loads are at electricity nodes 5, 6, 8 and gas nodes (5), (6), (8). The derated working states of generators are simplified as entire mean time to failure (MTTF) and mean time to repair (MTTR). The proposed gas power plants consist of units of 50 MW, whose MTTF and MTTR are the same as generators at node 5. The required $EENS_{max}$ for coupled gas and power system is 0.25 %. The life-spans of gas power plants, pipes and power lines are 60, 60, and 40 years. The heat rate for gas is 35 MJ/m^3. For simplicity, the min and max transferrable node load percetanges are 10 % and 25 %. The total natural gas load is 1040 GJ/hour. Line construction costs are set to be proportional against lengths. The discount rate is 8 %. Three cases were established as: ① Establish a benchmark case from the perspective of power system planners. Assume that there is a gas power plant near the gas reservoir. In order to absorb the generation capacity of this plant, power system planners should locate the optimal connection routine considering both cost and reliability; ② Decisions are made separately for the gas and power networks. Connect the gas reservoir to the nearest node, where a new gas power plant is built up. Based on their own perspectives, gas and power system owners have to expand the existing gas and power networks, due to any possible constraints that may arise from injecting a

Table 3 Gas study parameters at node

Node	Distance to node (13) (km)	Pressure min–max (p.u.)	Storage capacity (p.u.)	Nodal generator MTTF (h)	Nodal generator MTTR (h)
(1)	100	828–1035	0.5	–	–
(2)	120	1725–2070	0.5	–	–
(3)	50	1518–1725	0.5	–	–
(4)	90	2484–2760	0.5	–	–
(5)	80	1518–1725	0.8	2940	60
(6)	100	1587–1725	0.8	–	–
(7)	80	1725–2208	0.6	–	–
(8)	70	897–1242	0.6	–	–
(9)	60	1242–1518	0.5	–	–
(10)	150	897–1380	0.5	–	–
(11)	200	897–1380	0.5	1980	20
(12)	160	1035–1518	0.5	1960	40

Table 4 Distance of newly found gas reservoir to power network nodes

Node	Distance (km)	Node	Distance (km)
1	150	13	140
2	120	14	260
3	50	15	220
4	200	16	140
5	250	17	60
6	230	18	90
7	180	19	110
8	160	20	320
9	280	21	280
10	220	22	240
11	350	23	140
12	180	24	150

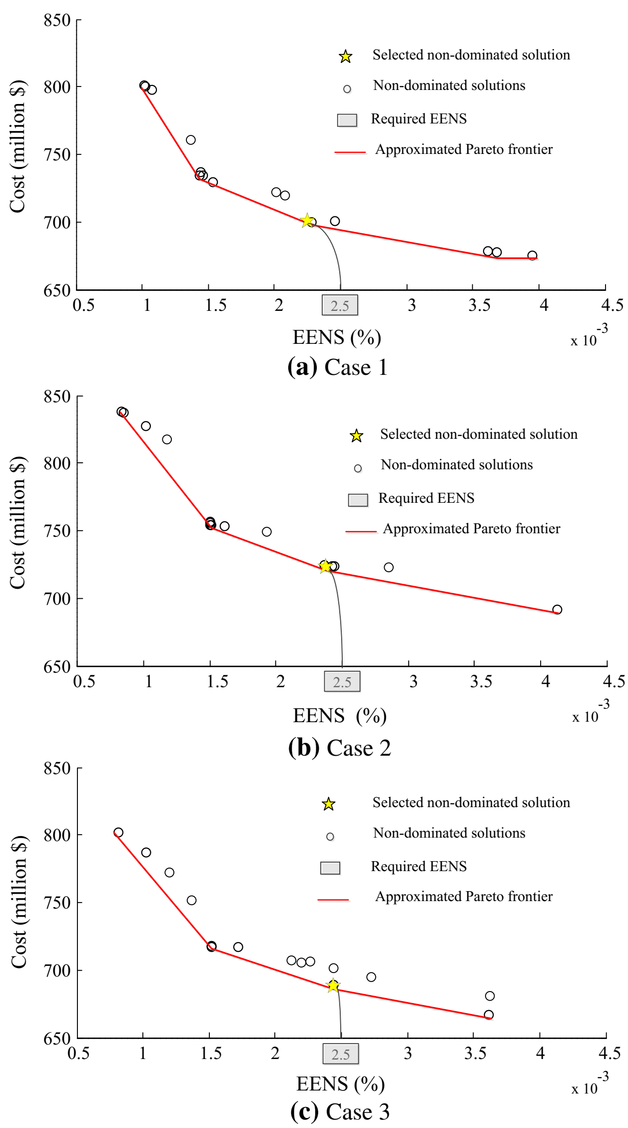


Fig. 2 Pareto optimality solutions for three cases with objectives of EENS and capital investment cost

significant amount of gas or power at this location; ③ Decisions are made coordinately among the gas plant owner, gas and power network owners. In order to benefit the overall coupled gas and power system reliability at the minimum cost, two system planners should reroute the connection paths and determine the optimal location of a gas power plant.

A Pareto frontier is depicted in Fig. 1 at the edge of possible solutions, which are highlighted by the bold lines. A regulatory approach is applied to determine the bottom line of the system reliability objective, which is squared out. Therefore, the optimal solutions should be on the left-hand side of 0.25 % horizontally. As shown in Fig. 2, within the reliability requirement, the objective values of investment costs are shown by lines crossing the vertical axes. The chosen solutions for each case are denoted by stars. The numerical results of chosen plans are given in Table 5. It should be noted that expansion co-planning of the coupled gas and power networks in case 3 have the lowest capital investment, due to the planning coordination among gas power generators, gas transmission companies, and power transmission companies. The candidate locations of the gas power generator require the least network augmentation, to absorb the additional gas energy either in the primary form or in the electric form. Hence, the utilization efficiency of the overall gas and power networks is higher in case 3.

Table 5 Results of three cases

Case	EENS (%)	Gas plant capacity (p.u.)	ACP (million $)	Number of added circuits	Number of added pipes
1	0.2256	150	691.2548	3	–
2	0.2475	100	726.8547	3	2
3	0.2488	100	668.5248	2	2

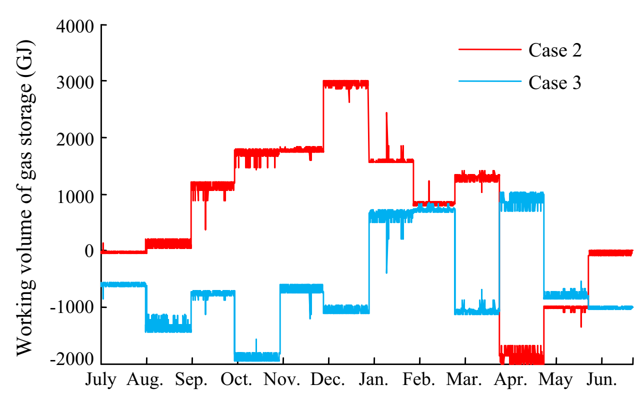
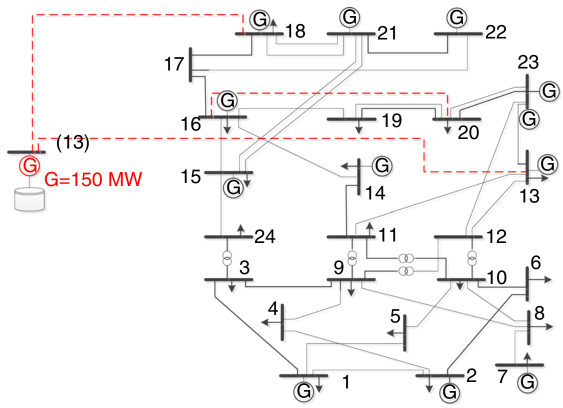
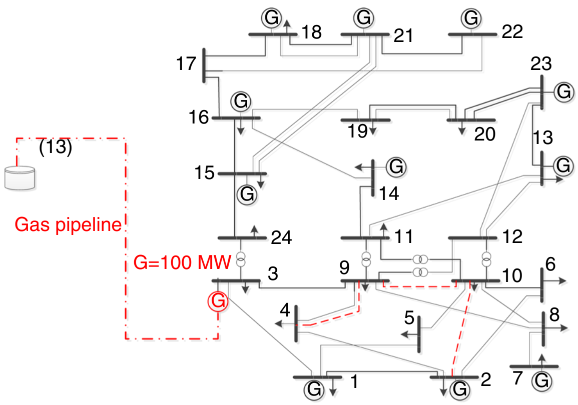


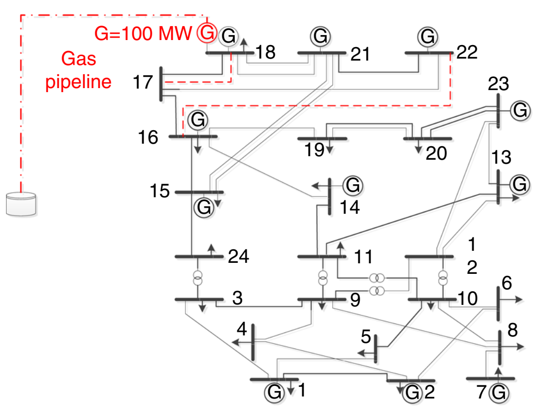
Fig. 3 Summed working volume of gas in gas networks for cases 2 and 3 (note that positive values mean gas to be extracted, negative values mean gas to be stored)



(a) Case 1: To absorb the generation capacity at node 13, the optimal connection circuits are found by minimizing investment and EENS, and the existing network needs augmentation.



(b) Case 2: The newly found gas reservoir is connected by a gas pipeline to the nearest node 3, where a new gas-fired power generation will be built. Three additional circuits are required to absorb the new generation capacity.

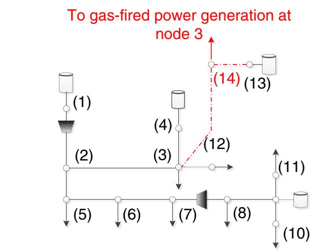


(c) Case 3: Decision making is coordinated and negotiated. A gas-fired power plant is built at node 18 with a gas delivery pipeline and two additional power lines. This expansion plan can benefit the overall system

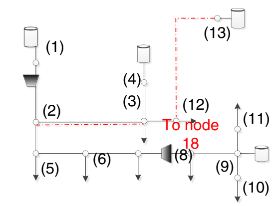
Fig. 4 Chosen expansion plans in power networks for three cases

Moreover, as is illustrated in Fig. 3, gas storage can offset the gas supply and load deviations by storing or injecting gas. In security situations such as pressure losses and pipeline contingencies, the system reliability would be enhanced with the working gas storage. Large gas extractions happen in winter in both cases, but case 2 requires higher storage capacity. It is worth mentioning that with the increasing development of gas-fired power plants, the traditional cold-weather-driven gas consumption has significantly changed (the increased gas loads in March and April in Fig. 3). From the results, we can find that the gas-fired power plant needs higher capacity in case 1, because the power load is partially transferred into gas load in the other two cases. The detailed expansion plans for three cases are visualized in Figs. 4 and 5.

Furthermore, to evaluate the EENS robustness of the proposed expansion plans, we conducted sensitivity analysis with four parameters for cases 2 and 3: four

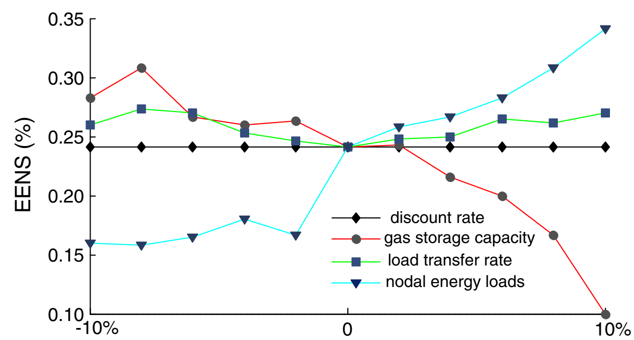


(a) Case 2: Gas node (14) is close to power networks, the existing gas networks needs to expand to deliver gas to power eneration.

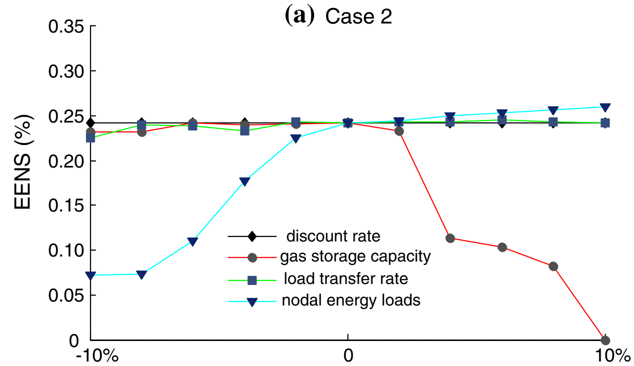


(b) Case 3: New gas reservoir is connected to the existing node (12) for fuel supply. The existing pipeline (2)-(3) requires augmentation

Fig. 5 Chosen expansion plans in gas networks for three cases



(a) Case 2



(b) Case 3

Fig. 6 Sensitivity analysis with four parameters for two cases parameters, i.e. discount rate, gas storage capacity, nodal load transfer rate, and nodal loads are allowed to vary ± 10 %. As shown in Fig. 6, variation of four parameters can easily lead to violation of the EENS requirement in case 2 (lines above 0.25 %). By contrast, in case 3, the violation would happen only when nodal loads increase more than 7.5 %. Therefore, with the coordination of gas and power networks, the plan has low capital cost and is robust to input variations.

5 Conclusion

Shale gas resources have the potential to significantly contribute to worldwide energy portfolio. The efficient exploitation of new shale gas reserves requires further augmentation of the existing energy infrastructure. Since natural gas can be used in primary form or in electric energy form, energy infrastructure expansion planning should coordinately consider the development of GPG plants, gas pipelines, and power lines. In this paper, an integrated approach was proposed to determine effective energy network expansion plans. Mathematically, the co-planning model is formulated as a multi-objective co-optimization problem (MOCOP). Also, a relatively new and superior solution algorithm called HDDE is employed to solve the formulated expansion co-planning problem. The conflicting objectives of cost and reliability are depicted in a Pareto frontier. Moreover, a new approach is presented to evaluate the reliability of coupled energy networks, taking into account security issues in both gas and electricity networks. A Markov chain state-space representation is proposed to calculate EENS in system adequacy evaluations. By modelling the physical and economic interactions between gas and electricity, the optimal connection approaches for gas reserves can be determined while identifying the bottlenecks in transmission. Based on case studies on the IEEE 24-bus RTS and a benchmark gas system, it can be seen that the proposed model can provide comprehensive information on the interactions between the two systems, and it is an effective decision-making tool, which gives network planners the flexibility to choose trade-offs between investment cost and system reliability.

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