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Second-Order Cone Programming for Linepack in Multistage Stochastic Co-Expansion Planning Power and Natural Gas Systems with Natural Gas Storage

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ABSTRACT: The interdependency between power and natural gas is so tight, especially where natural gas extraction is economical. Therefore, co-expansion planning is imperative for having efficient systems with minimum cost. In this paper, multistage stochastic co-expansion planning power and natural gas systems is presented. Natural gas load flow (NGLF) is modeled with the Weymouth equation, a non-linear and non-convex problem. In order to overcome the non-convexity of the problem, mixed-integer second-order cone programming (MISOCP) is utilized to solve NGLF. Furthermore, linepack constraints are added to exploit the natural gas stored in the pipeline for co-expansion planning, mainly at the transmission level where voluminous pipelines are used and linepack is noticeable. Natural gas storage is considered in the model to alleviate operational and investment costs. Decreasing the investment and operational costs of co-expansion planning is the objective of the model. Investment decisions can be taken more than once so that investment costs can be divided into the whole planning horizon to avoid an enormous budget at the beginning of the planning horizon. Power and natural gas load growth are taken into account as long-term uncertainties. The proposed model is applied in a real case of southwestern Iran. The results determine that by implementing the proposed model, the investment and operational costs decrease 6.3% and 14%, respectively.

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1- INTRODUCTION

Natural gas power plants (NGPPs) and natural gas storage play an important role, especially in a country with a rich natural gas reservoir. Natural gas becomes one of the essential sources in power system since NGPPs has lower CO2 emission and higher efficiency rate than other fossil fuel power plants [1]. Natural gas storage has received much attention in recent years due to natural gas consumption fluctuation in different seasons. An enormous amount of natural gas can be stored in natural gas storage for an extended time compared to electricity. This stored natural gas becomes handy in the high electrical and gas demand seasons. Natural gas storage prevents natural gas and power systems from investing in unnecessary new infrastructure [2]. Natural gas storage can alleviate the need for new infrastructure investment by supply natural gas consumption in peak hours.

NGPPs become a vital component of power systems, so natural gas and power systems' interdependency begins tight. A significant increase in the interdependency of natural gas and power systems, and natural gas and electricity growth demand result in natural gas and power systems needing long-term integrated expansion planning [3]. The location of NGPPs is a critical decision, since energy can be conveyed in a raw form with natural gas pipelines or electricity form with transmission lines. Distributed Generation (DG) based on natural gas source is presented in planning of distribution systems by [4] with aim of minimizing investment costs. Additionally, in distribution systems long-term planning is modeled by considering stochastic in active and reactive power demands in [5].

Numerous experiments have established to take integrated expansion planning power and natural gas systems to account. A review of integrated power and natural gas networks coordination is prepared in [6]. Different kinds of solving methods, uncertainties and components that link natural gas and power network together are described. Energy hub is regarded in expansion planning of power and natural gas systems by [7]. Additionally, gas-fired distributed generations are utilized in the system, which the heat is produced and used in heat demand reduction. Expansion planning power and natural gas systems in an integrated and restricted gas and electricity market are investigated in [8], and social welfare and consumer benefits are evaluated. Flexible expansion co-planning power and natural gas is introduced by [9] to fill the gap between theoretical research and practical need for future scenarios in order to enhance systems' robustness. Different uncertainties such as interest rate, load growth and wind power output in joint expansion planning of power and

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natural gas systems are assumed in [10]. New solution method is proposed in [11] to conquer long computational time in large-scale systems for natural gas load flow. Additionally, placement and sizing of new generations and type, and end of new transmission lines are discovered in the large system. Compared to this paper, it is discovered that natural gas storages can mitigate investment cost, especially in large-scale systems. Moreover, linepack is not considered, which can change the investment decisions.

Numbers of studies are regarding different kinds of storage in expansion planning. The trade-off between construction power system or natural gas instructions and electrical storage is analyzed to minimize investment and operational costs in [12]. Liquefied natural gas storage is taken into account by [13] in a long-term multistage for expansion planning of integrated power and natural gas systems to minimize investment and operational costs and determine optimal location and installation times of new facilities. Expansion planning of integrated power and natural gas networks is considered with natural gas storage to maximize social welfare. Additionally, linearization is introduced by [14] to overcome nonlinear nature of natural gas flow in pipelines. The role of natural gas storage in managing short-term uncertainties in expansion planning of power and natural gas systems is proposed in [15]. A bi-level model is proposed for expansion planning power and natural gas systems, which hybrid algorithm is used to solve bi-level problem. Moreover, Power to Gas (PtG) is defined as another linkage by [16], and natural gas storage is used.

Some papers use voltage or pressure in the planning of power and natural gas systems. Voltage and pressure are added in expansion planning results in the non-convex mathematical formulation. Second-order cone programming (SOCP) is used by [17] to overcome non-convexity emerge from adding voltage and pressure to the expansion equations. Multistage expansion planning power and natural gas systems with considering nonanticipativity constraints which are used to reveal uncertainties gradually in the planning horizon, and piecewise linearization is implemented to model gas flow by [18]. A novel mixed-integer second-order cone programming (MISOCP) model of steady-state natural gas flow is proposed in [19] to assimilate bidirectional flow and linepack. AC power flow and Weymouth equations are implemented in [20] to minimize the investment cost of joint electricity and natural gas transmission planning and a convex approximation is used to make the problem computationally tractable. A multi-objective problem in which investment and operational cost and voltage stability index are objectives is implied by [21]. PtG technology is established as another linkage between natural gas, power systems, wind power output and electrical load are taken into account as uncertainties.

In this paper, a multistage stochastic co-expansion planning power and natural gas systems are proposed to minimize operational and investment costs. Investment decisions can be made at the beginning of each stage, hence there is no need for an enormous budget at one stage. Long-term uncertainties in electrical and natural gas load growth are modeled through scenario realization. MISOCP is presented to solve the Weymouth equation in the existing and candidate pipeline. Furthermore, linepack in existing and candidate pipeline and natural gas storage is incorporated in the model to exploit advantages of stored natural gas in linepack and natural gas storage in co-expansion planning of power and natural gas systems.

The main paper's contributions are determined below:

- MISOCP is represented to solve the Weymouth equations and model linepack in existing and candidate pipelines.
- Natural gas storage and linepack are utilized together to minimize investment and operational costs in power and natural gas systems.
- Impact of natural gas storage and linepack on investment decisions such as, transmission lines and pipelines are analyzed.

The rest of the paper is organized as follows: Objective function and constraints of co-expansion planning power and natural gas systems are modeled in Section 2. Afterward, MISOCP is described in Section 3. Numerical results are conducted in Section 4. Finally, conclusions are drawn in Section 5.

2- EXPANSION PLANNING POWER AND NATURAL GAS SYSTEMS

The main component of power and natural gas systems is modeled with the mathematical equations in this paper. Every component has its constraints, which need to be considered. The constraint is divided into two parts, investment constraint and operational constraint.

2-1- OBJECTIVE FUNCTION

The objective function is described in Eq. (1) for investment costs. It includes three segments: the generation, transmission and storage investments. NGPP capacity which needs to be constructed, is obtained from Eq. (1a). Transmission line and pipeline construction are decided with binary variables in Eq. (1b). Natural gas storage investment capacity is calculated in Eq. (1c). Net present value (NPV) is calculated by multiplication Eq. (1d) in Eq. (1) [22].

$$Z_{INV} = \sum_{w\in W}[\rho_w^{scen}\sum_{y\in Y}\{A^{NPV}(z_{INV}^{NGPP}+z_{INV}^{T}+z_{INV}^{GS})\}] \quad (1)$$

$$z_{INV}^{NGPP} = \sum_{g\in Ø^{PG}} IC_g^{NGPP} PI_{g,y,w}^{NGPP} \quad (1a)$$

$$z_{INV}^{T} = \sum_{(p,q)\in\Omega^{PPL}} IC_{p,q}^{PL} X_{p,q,y,w}^{PL} + \sum_{(n,m)\in\Psi^{PTL}} IC_{n,m}^{TL} X_{n,m,y,w}^{TL} \quad (1b)$$

$$z_{INV}^{GS} = \sum_{gs\in Ù^{PGS}} IC_{gs}^{GS} SI_{gs,y,w}^{GS} \quad (1c)$$

$$A_{INV}^{NPV} = (1+ir_y)^{-st_y} \tag{1d}$$

The variable operational cost for power and natural gas systems are defined in Eq. (2). The NGPPs production cost is described in Eq. (2a). The natural gas production and natural gas storage operational costs are explained in Eq. (2b) and Eq. (2c). Natural gas storage operational cost relates to the amount of natural gas storing and releasing from storage. NPV of operational cost is calculated by multiplication Eq. (2d) in Eq. (2).

$$Z_{OP} = \sum_{w\in W}[\rho_w^{scen}\sum_{y\in Y}\{A_{OP}^{NPV}\sum_{o\in O}(\omega_o\sum_{t\in T}\omega_t[z_{OP}^{NGPP}+z_{OP}^{GP}+z_{OP}^{GS}])\}] \tag{2}$$

$$z_{OP}^{NGPP} = \sum_{g\in G} OC_g^{NGPP} P_{g,y,w,o,t}^{NGPP} \tag{2a}$$

$$z_{OP}^{GP} = \sum_{s\in S}\chi_s^{GAS} XS_{s,y,w,o,t} \tag{2b}$$

$$z_{OP}^{GS} = \sum_{gs\in GS} OC_{gs}^{GS}(SR_{gs,y,w,o,t}^{GS}+RR_{gs,y,w,o,t}^{GS}) \tag{2c}$$

$$A_{OP}^{NPV} = (1+ir_y)^{-st_y}\left(\frac{(1+ir_y)^{st_y}-1}{ir_y(1+ir_y)^{st_y}}\right) \tag{2d}$$

2-2- constraints

Constraints of expansion planning consist of three main parts: power systems, natural gas, and coupling natural gas with power systems constraints.

2-2-1- Power System Constraints

Maximum investible or budget for NGPP that can be built is declared in Eq. (3). Generation of the candidate and existing NGPP are constrained by Eq. (3a) and Eq. (3b). DC power flow is used for the candidate and existing transmission line, which is presented in Eq. (4) and Eq. (4a). The maximum power that can flow through existing and candidate transmission lines is denoted in Eq. (4b) and Eq. (4c) [23]. The power-demand balance is presented in Eq. (5) for each bus n.

$$0 \le \sum_{y\in Y} PI_{g,y,w}^{NGPP} \le \overline{PI}_g^{NGPP} \tag{3}$$

$$0 \le P_{g,y,w,o,t}^{NGPP} \le \sum_{y'\le y} PI_{g,y',w}^{NGPP} \tag{3a}$$

$$0 \le P_{g,y,w,o,t}^{NGPP} \le \overline{P}_g^{NGPP} \tag{3b}$$

$$\begin{aligned}&-(1-\sum_{y'\le y}X_{(n,m),y',w}^{TL})M \le PF_{(n,m),y,w,o,t}\\ &-\beta_{(n,m)}(\theta_{n,y,w,o,t}-\theta_{m,y,w,o,t}) \le (1-\sum_{y'\le y}X_{(n,m),y',w}^{TL})M\end{aligned} \tag{4}$$

$$PF_{(n,m),y,w,o,t} = \beta_{(n,m)}(\theta_{n,y,w,o,t}-\theta_{m,y,w,o,t}) \tag{4a}$$

$$\underline{PF}_{(n,m)} \le PF_{(n,m),y,w,o,t} \le \overline{PF}_{(n,m)} \tag{4b}$$

$$\sum_{y'\le y}X_{(n,m),y',w}^{TL}\underline{PF}_{(n,m)} \le PF_{(n,m),y,w,o,t} \le \sum_{y'\le y}X_{(n,m),y',w}^{TL}\overline{PF}_{(n,m)} \tag{4c}$$

$$\sum_{g\in\O_n^G} P_{g,y,w,o,t}^{NGPP} = \sum_{m\in\O_{(n,m)}^{TL}} PF_{(n,m),y,w,o,t} + L_n^E f_{n,o,t}^E LG_{w,y}^E \tag{5}$$

where $\overline{A}$ and $\underline{A}$ show maximum and minimum of parameter A.

2-2-2- Natural Gas Constraints

Gas production is limited by the maximum capacity of natural gas units, which is clarified in Eq. (6). Investible natural gas storage is declared in Eq. (7). The minimum and maximum capacity of natural gas storage are defined in Eq. (8). Natural gas storage storing and releasing rate are a proportion of its built capacity, which are clarified in Eq. (9) and Eq. (9a). The amount of natural gas is stored in the storage is defined in Eq. (10) [24]. Weymouth equation is carried out to relate pressure and natural gas flow in Eq. (11). This equation is non-convex, which can be relaxed by MISOCP relaxation [25]. The MISOCP constraints are provided in Section 3. Constraint Eq. (12) represents natural gas production and consumption balance at each node p.

$$XS_{s,y,w,o,t} \le \overline{XS}_s \tag{6}$$

$$0 \le \sum_{y\in Y} SI_{gs,y,w}^{GS} \le \overline{SI}_{gs}^{GS} \tag{7}$$

$$0.1\sum_{y'\le y} SI_{gs,y',w}^{GS} \le S_{gs,y,w,o,t}^{GS} \le \sum_{y'\le y} SI_{gs,y',w}^{GS} \tag{8}$$

$$SR_{gs,y,w,o,t}^{GS} \le 0.2\sum_{y'\le y} SI_{gs,y',w}^{GS} \tag{9}$$

$$RR_{gs,y,w,o,t}^{GS} \le 0.2\sum_{y'\le y} SI_{gs,y',w}^{GS} \tag{9a}$$

$$S^{GS}_{gs,y,w,o,t} = S^{GS}_{gs,y,w,o,t-1} + \eta_{gs} SR^{GS}_{gs,y,w,o,t} - RR^{GS}_{gs,y,w,o,t} \quad (10)$$

$$GF_{(p,q),y,w,o,t} = C^{PL}_{(p,q)} sgn(\pi_p, \pi_q)\sqrt{|\pi^2_{p,y,w,o,t} - \pi^2_{q,y,w,o,t}|}$$

$$\text{sgn}(\pi_{p,y,w,o,t}, \pi_{q,y,w,o,t}) = \begin{cases} 1, & \pi_{p,y,w,o,t} \geq \pi_{q,y,w,o,t} \\ -1, & \pi_{p,y,w,o,t} \leq \pi_{q,y,w,o,t} \end{cases} \quad (11)$$

$$\sum_{s \in \Omega^S_P} XS_{s,y,w,o,t} + \sum_{gs \in \Omega^{GS}_P} (RR^{GS}_{gs,y,w,o,t} - SR^{GS}_{gs,y,w,o,t}) = \sum_{q \in \Omega^{PL}_{(p,q)}} GF_{(p,q),y,w,o,t} + \sum_{g \in \Omega^G_P} U^G_{g,y,w,o,t} + L^{NG}_p f^{NG}_{p,o,t} LG^{NG}_{w,y} \quad (12)$$

2-2-3- Power and Natural Gas Linkage Constraint

In this paper, NGPP is the only linkage between power and natural gas systems, which is described in Eq. (13). This equation denotes the linear linkage between power production and natural gas consumption of NGPP.

$$U^G_{g,y,w,o,t} = H_g P^{NGPP}_{g,y,w,o,t} \quad (13)$$

3- MISOCP RELAXATION OF WEYMOUTH EQUATION

In this section, the subscripts y, w, o and t are dropped to simplify the equations. The MISOCP relaxation of Weymouth equation Eq. (11) is carried out in Eq. (14)- Eq. (19). One binary variable is defined in Eq. (14) to specify the gas flow direction and obviate sign function from Eq. (11). If $df_{p,q} = 1$ gas flow from node p to q, otherwise $df_{p,q} = 0$ gas flow from node q to p, according to [26]. Constraints in Eq. (14a)- Eq. (14c) are denoted Gas flow in the pipeline and can be positive or negative. In positive mode, gas flows from p to q, and in negative form gas flows from q to p. Gas flow is explained as the average of outflow and inflow in Eq. (14d) and Eq. (14e). Each side of Eq. (11) is squared. As a result, a new auxiliary variable is defined in Eq. (15) to relax quadratic term $GF^2_{(p,q)}$ into its convex envelopes.

$$df_{(p,q)} + df_{(q,p)} = 1 \quad (14)$$

$$GF_{(p,q)} = GF^+_{(p,q)} - GF^-_{(p,q)} \quad (14a)$$

$$0 \leq GF^+_{(p,q)} \leq df_{(p,q)} \overline{GF}_{(p,q)} \quad (14b)$$

$$0 \leq GF^-_{(p,q)} \leq (1 - df_{(p,q)}) \overline{GF}_{(p,q)} \quad (14c)$$

$$GF^+_{(p,q)} = \frac{GF^{out}_{(p,q)} + GF^{in}_{(p,q)}}{2} \quad (14d)$$

$$GF^-_{(p,q)} = \frac{GF^{out}_{(q,p)} + GF^{in}_{(q,p)}}{2} \quad (14e)$$

$$\zeta(p,q) \geq GF^2_{(p,q)} \quad (15)$$

$$\zeta(p,q) \leq (\underline{GF}_{(p,q)} + \overline{GF}_{(p,q)}) GF_{(p,q)} - \underline{GF}_{(p,q)} \overline{GF}_{(p,q)} \quad (15a)$$

Two auxiliary variables are used for the right-hand side of Eq. (11) which are defined in Eq. (16). The squared pressure difference between the two end nodes in Eq. (11) is described by two auxiliary variables in Eq. (16). McCormick relaxation technique, which is utilized for bilinear term appears in Eq. (16a), is defined in Eq. (17) [27]. Finally, the convex form of Eq. (11) is expressed in Eq. (18) [19]. If $df_{p,q} = 1$, Eq. (18a) becomes unbounded and Eq. (18) is modeled MISOCP of Weymouth equation. All the equations in this section are written for both existing and candidate pipeline. Only for candidate pipeline, Eq. (19) should be added to MISOCP. This constraint ensures that if prospective pipeline is not constructed, gas flow is zero.

$$pr^-_{(p,q)} = \pi_p - \pi_q \quad , \quad pr^+_{(p,q)} = \pi_p + \pi_q \quad (16)$$

$$pr^-_{(p,q)} pr^+_{(p,q)} = \pi^2_p - \pi^2_q \quad (16a)$$

$$\xi_{(p,q)} \geq \underline{pr}^-_{(p,q)} pr^+_{(p,q)} + pr^-_{(p,q)} \underline{pr}^+_{(p,q)} - \underline{pr}^-_{(p,q)} \underline{pr}^+_{(p,q)} \quad (17)$$

$$\xi_{(p,q)} \geq \overline{pr}^-_{(p,q)} pr^+_{(p,q)} + pr^-_{(p,q)} \overline{pr}^+_{(p,q)} - \overline{pr}^-_{(p,q)} \overline{pr}^+_{(p,q)} \quad (17a)$$

$$\xi_{(p,q)} \leq \underline{pr}^-_{(p,q)} pr^+_{(p,q)} + pr^-_{(p,q)} \overline{pr}^+_{(p,q)} - \underline{pr}^-_{(p,q)} \overline{pr}^+_{(p,q)} \quad (17b)$$

$$\xi_{(p,q)} \leq \overline{pr}^-_{(p,q)} pr^+_{(p,q)} + pr^-_{(p,q)} \underline{pr}^+_{(p,q)} - \overline{pr}^-_{(p,q)} \underline{pr}^+_{(p,q)} \quad (17c)$$

$$\zeta(p,q) \leq {C^{PL}_{(p,q)}}^2 \xi_{(p,q)} + \overline{GF}^2_{(p,q)} (1 - df_{(p,q)}) \quad (18)$$

$$\zeta(p,q) \leq -{C^{PL}_{(p,q)}}^2 \xi_{(p,q)} + \overline{GF}^2_{(p,q)} df^-_{(p,q)} \quad (18a)$$

$$X^{PL}_{p,q} \underline{GF}_{(p,q)} \leq GF_{(p,q)} \leq X^{PL}_{p,q} \overline{GF}_{(p,q)} \quad (19)$$

Algorithm 1. Multistage Stochastic Co-expansion Planning Power and Natural Gas Systems

Step 1	**Input:** Time, operation conditions, scenarios, stages, and power and natural gas systems data
Step 2	**For** Cases **Do**
Step 3	Find minimum $Z_{INV}+Z_{OP}$
Step 4	s.t.
	Power systems constraints (3) – (5)
	Natural gas constraints (6), (12), and (13)
	MISOCP relaxation of Weymouth equations (14) – (19)
Step 5	**If** Natural gas storage $\in$ Case **Then**
	Add natural gas storage constraints (7) – (10)
	Else
	Continue;
	End
Step 6	**If** Linepack $\in$ Case **Then**
	Add linepack constraints (21) – (21b)
	Else
	Continue;
	End
Step 8	**Solve** MISOCP **Using** CPLEX solver
Step 7	**Export** Outputs
	End

It is possible to exploit compressor and linepack constraints in Eq. (20) and Eq. (21). The compressor's operational cost is denoted in Eq. (20), which is added to Eq. (2) in Section 2-1. Compressors can boost nodal pressure, which is defined in Eq. (20a). It is assumed that the direction of gas in the compressor is from node p to q. The maximum capacity of the compressor is determined in Eq. (20b) [28]. The linepack of each pipeline is calculated by average pressure at adjacent nodes and pipeline specification. Hourly linepack changes and mass conservation is given in Eq. (21a). Constraint Eq. (21b) is declared the sum of linepack at the final hour t_T, must not be lower than linepack at the beginning time t_0.

$$z_{OP}^{CP}=\sum_{c\in\omega^{CP}} OC_c^{CP} GF_{c,y,w,o,t}^{CP} \tag{20}$$

$$\frac{pr^{-}_{(p,q),y,w,o,t}+pr^{+}_{(p,q),y,w,o,t}}{2}\underline{R}_c^{CP}\le\frac{pr^{-}_{(q,p),y,w,o,t}+pr^{+}_{(q,p),y,w,o,t}}{2}\le\frac{pr^{-}_{(p,q),y,w,o,t}+pr^{+}_{(p,q),y,w,o,t}}{2}\overline{R}_c^{CP} \tag{20a}$$

$$0\le GF_{c,y,w,o,t}^{CP}\le\overline{GF}_{c,y,w,o,t}^{CP} \tag{20b}$$

$$LP_{(p,q),y,w,o,t}=K_{(p,q)}^{PL}\frac{pr^{+}_{(p,q),y,w,o,t}}{2} \tag{21}$$

$$\begin{aligned}LP_{(p,q),y,w,o,t}&=LP_{(p,q),y,w,o,t-1}+GF_{(p,q),y,w,o,t}^{in}\\&-GF_{(p,q),y,w,o,t}^{out}+GF_{(q,p),y,w,o,t}^{in}-GF_{(q,p),y,w,o,t}^{out}\end{aligned} \tag{21a}$$

$$\sum_{(p,q)\in\Omega^{PL}} LP_{(p,q),y,w,o,t_T}\ge\sum_{(p,q)\in\Omega^{PL}} LP_{(p,q),y,w,o,t_0} \tag{21b}$$

4- SOLUTION ALGORITHM

The multistage stochastic co-expansion planning power and natural gas systems solution's procedure is denoted in Algorithm 1. To solve this algorithm, Mixed Integer Quadratically Constrained Programs (MIQCP) model is implemented in General Algebraic Modeling System (GAMS) 25.1.2 software [29] and solved with Cplex solver on an Intel core i7 at 2.8 GHz, with 16 GB RAM. It takes 23 hours to reach solution for all cases.

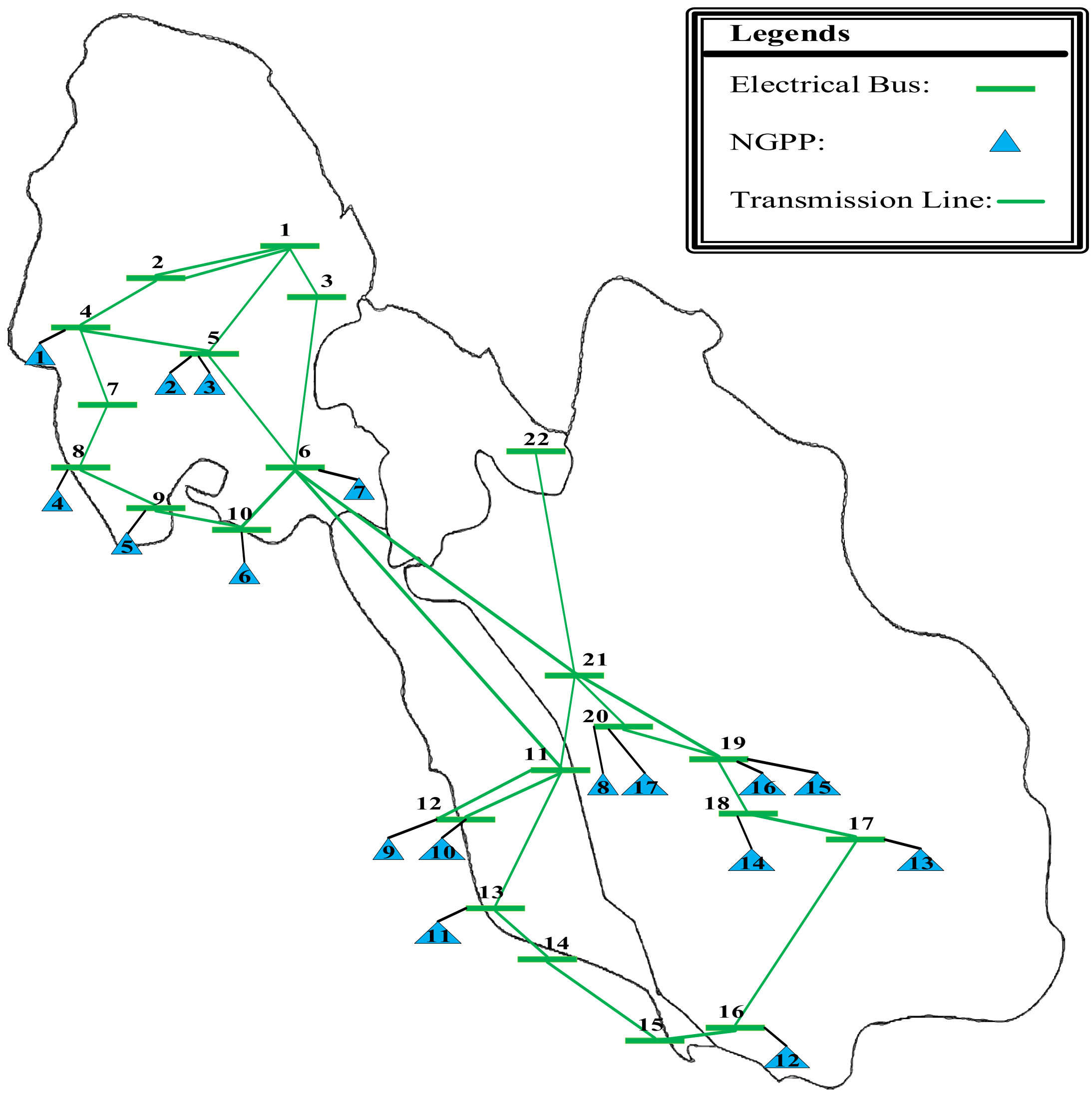

Fig. 1. Power System Topology

5- NUMERICAL RESULTS

The productivity of the model is described in Section 2 and Section 3. The model is tested on the real power and natural gas systems in southwestern Iran. Power system has 22 buses, 29 transmission lines, and 17 NGPP's, which are depicted in Fig. 1. One candidate line which is Parallel to existing transmission line can be added. Candidate NGPP's with the same characteristics as the existing one can be constructed. More details of the power system can be found in [30]. The natural gas system comprises 23 nodes, 39 pipelines, 3 compressors and 6 natural gas production units, which is illustrated in Fig. 2. Complementary data of the natural gas system can be found in [11]. Planning horizon time is ten years, which investment decisions can be taken in the beginning and middle of the horizon time. Two scenarios are considered to model electrical and natural gas load growth, which are presented in Table 1. f in Eq. (5) and Eq. (12) at each operation and time is determined in Table 2. The expansion costs are derived from [31].

To explore the relation between expansion planning costs, natural gas storage and linepack, four cases are defined below:

- Case 1: Base systems without considering the natural gas storage and linepack.
- Case 2: Systems with considering natural gas storage.
- Case 3: Systems with considering linepack.
- Case 4: Systems with considering natural gas storage and linepack.

Investment and operational costs for different cases at different stages are pictured in Figs. 3 and 4. Costs at Stage 1 and Stage 2 can be found in Figs. 3 and 4 in the bottom and middle of each box. In addition, the total NPV of the stages can be observed at the top of each box. The highest investment cost belongs to Case 1.

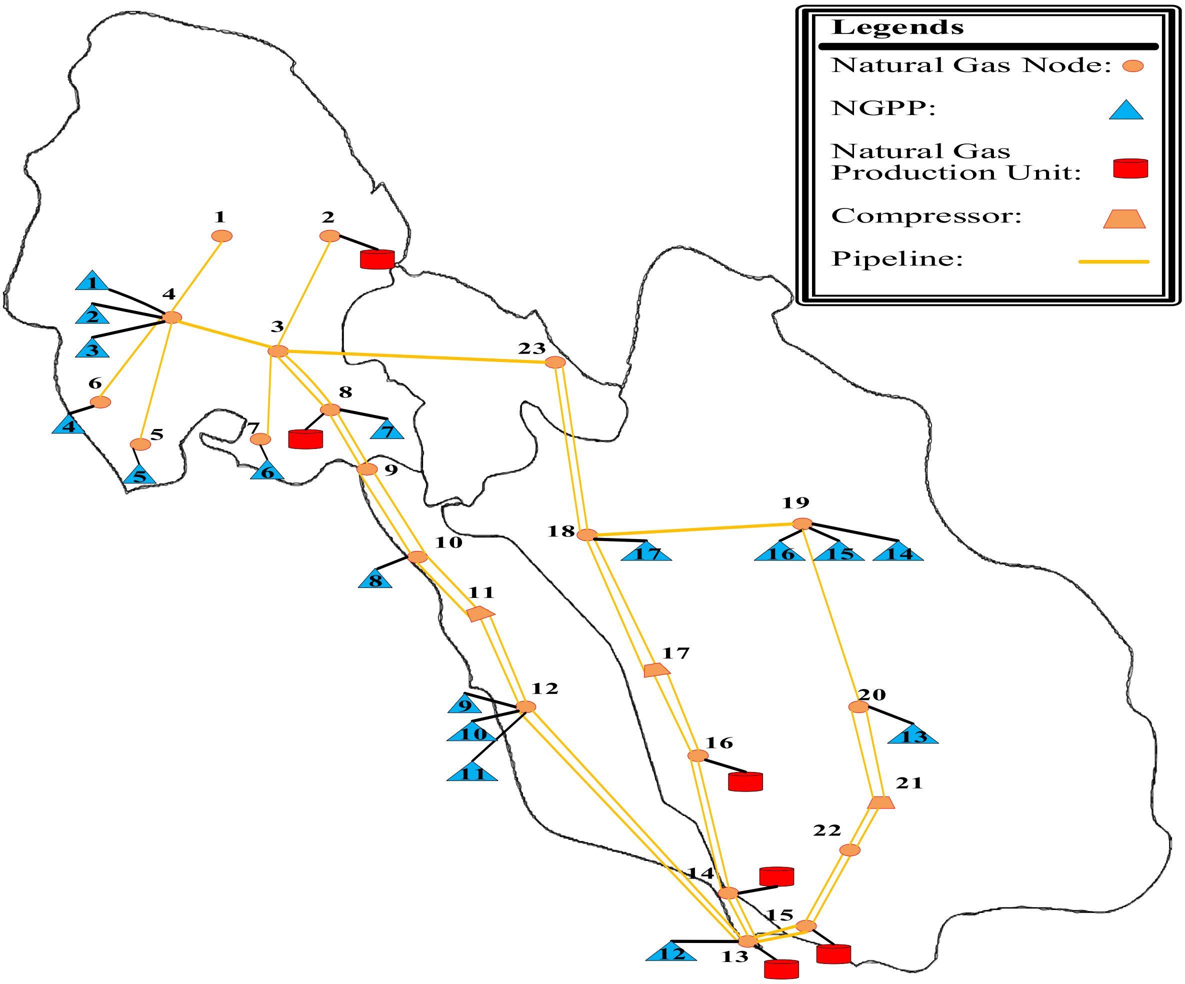

Fig. 2. Natural Gas System Topology

Table 1. Scenario Features and Probabilities

Scenarios	Uncertainties		Probability
	Electrical Load Growth	Natural Gas Load Growth	
w_1	5 (% $p.a.$)	4 (% $p.a.$)	0.6
w_2	3 (% $p.a.$)	2 (% $p.a.$)	0.4

Table 2. Operation Condition and Time

Time (Hours)	Load Type	Operation Condition (Days)		
		o_1 (183)	o_2 (93)	o_3 (89)
t_1 (7)	Electrical Load	0.54	0.6	0.48
	Natural Gas Load	0.54	0.48	0.6
t_2 (12)	Electrical Load	0.72	0.64	0.8
	Natural Gas Load	0.72	0.64	0.8
t_3 (5)	Electrical Load	0.9	1	0.8
	Natural Gas Load	0.9	0.8	0.1

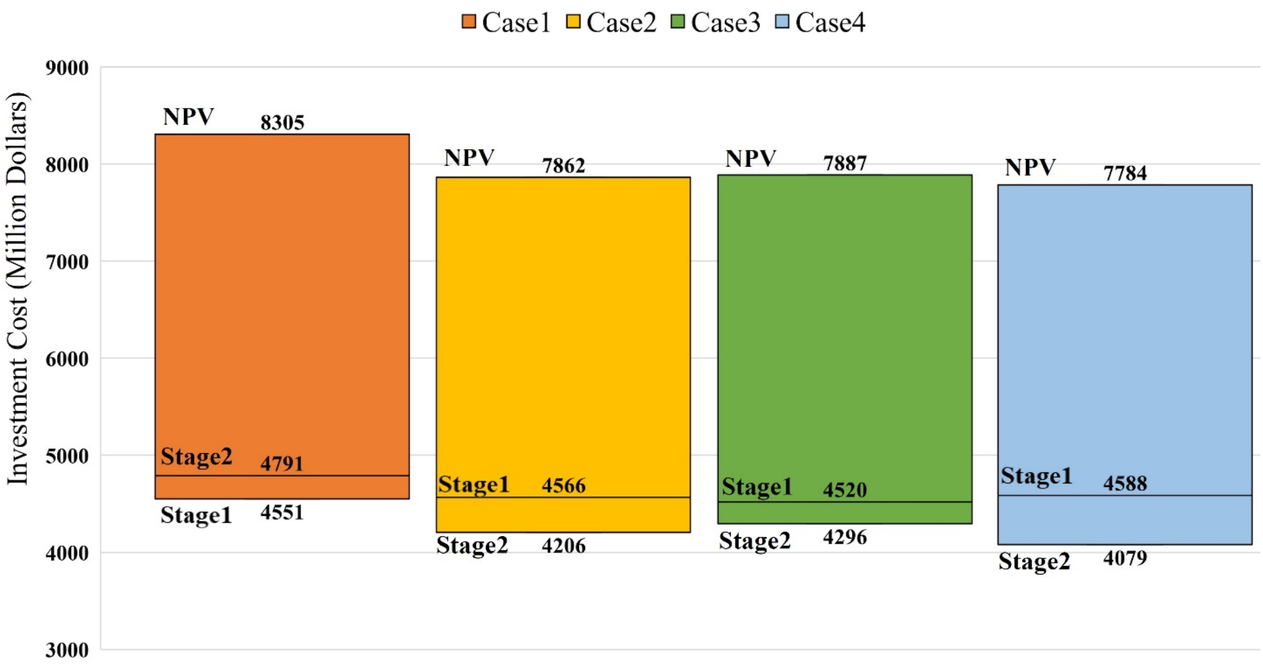

Fig. 3. Investment Cost in Different Cases

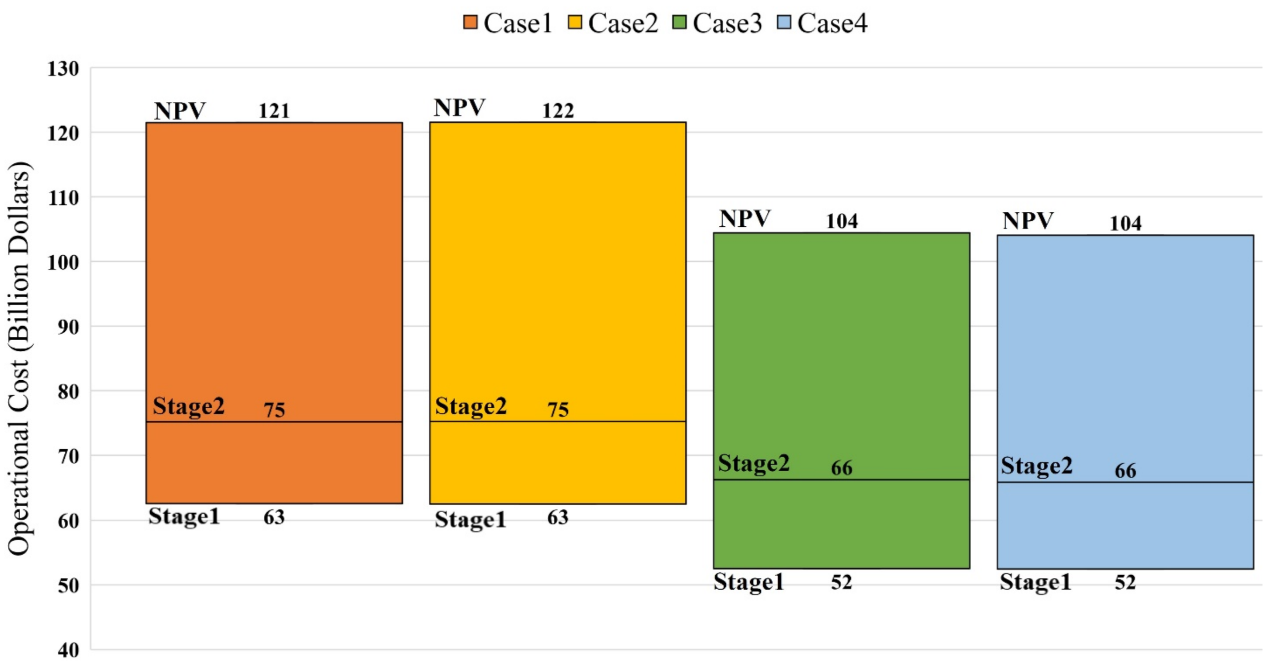

Fig. 4. Operational Cost in Different Cases

In Case 2, candidate natural gas storage can be built at natural gas nodes 5, 11, 13, 17 and 21 with a maximum capacity of 0.1 million cubic meters. All investible storage capacity is built at the beginning of the planning horizon. The total amount of natural gas is stored in natural gas storage at different operation conditions and times can be seen in Fig. 5. Natural gas is stored in gas storage at t_1. This stored natural gas is released at t_2. At Stage 1, the investment cost of Case 2 is scarcely higher than Case 1 due to investing in natural gas storage at this stage. Nevertheless, as revealed in Fig. 3 Case 2 has a reasonably lower NPV investment cost than Case 1. Inspection of Fig. 3 indicates that natural gas storage becomes useful in Stage 2 when electrical and natural gas loads grow.

In Case 3, the influence of linepack in co-expansion planning is investigated. The total amount of natural gas that remains in the pipelines at different operation conditions and times is represented in Fig. 6. The minimum natural gas that should stay in all the pipelines is shown at the

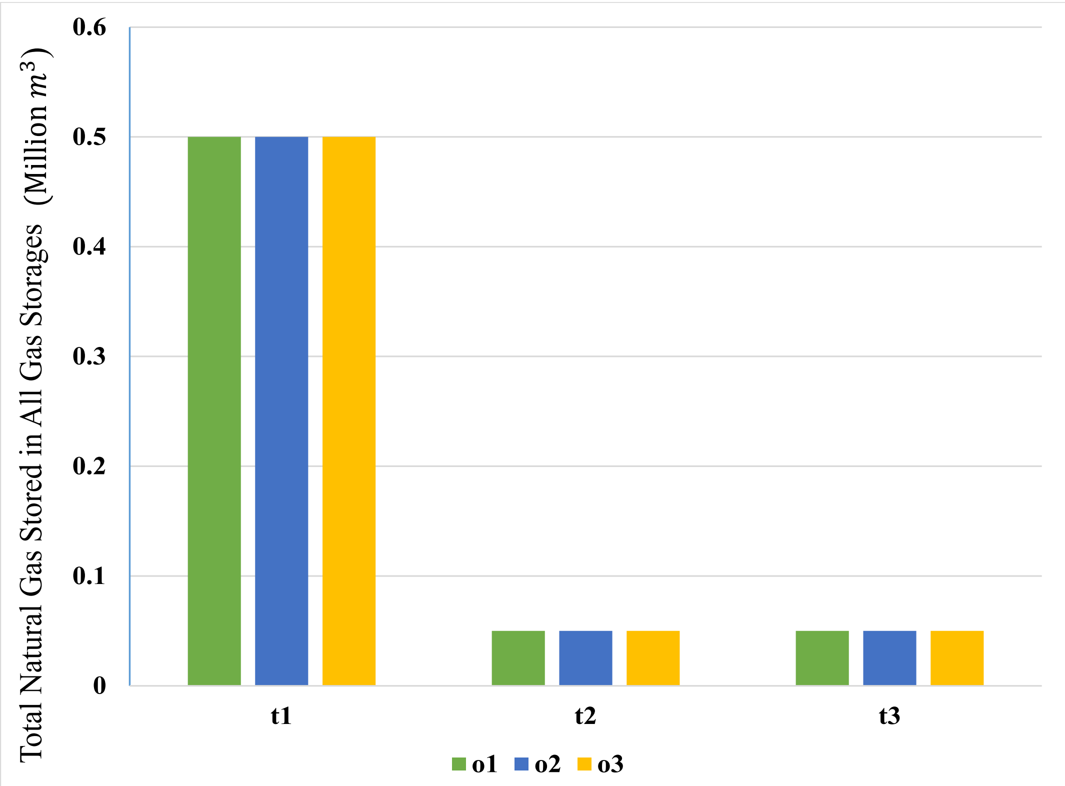

Fig. 5. Natural Gas Stored in Gas Storage at Stage 1

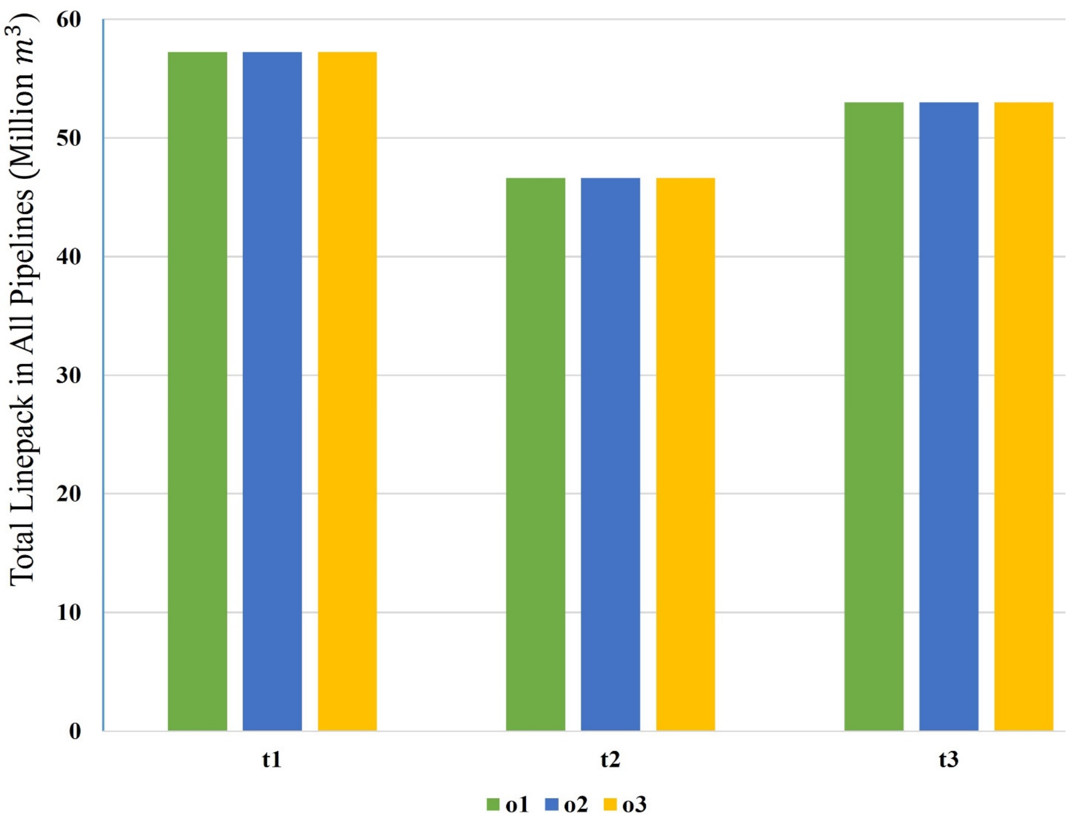

Fig. 6. Natural Gas Stored as Linepack at Stage 1

Table 3. Candidate Transmission Lines and Pipelines Are Built

	Transmission Lines Building	Pipelines Building
Case 1	19-20, 20-21	3-4, 4-5
Case 4	4-5, 5-6, 9-10, 20-21	4-5

time t_2. Linepack analogous to natural gas storage, storing and releasing gas at the same time. The operational cost decreases dramatically by 14%. The reason for this decline is the considerable amount of natural gas that is stored in the pipelines at off-peak hours and releases in peak the hours, as shown in Fig. 6.

In Case 4, the lowest investment and operational cost are derived. When natural gas storage and linepack are considered in co-expansion planning of power and natural gas, pipeline investment cost in the natural gas system is declined, since natural gas is stored in the low demand hours and is used to preserve pipelines from congestion. Besides, power transmission lines are preserved. The total number of pipelines invested in this case is one, which is drastically less compared to Case 1 with four pipelines investment.

In Case 1 and 4, the trade-off between constructing transmission lines and pipelines is demonstrated in Table 3. Moreover, natural gas storage and linepack can shift from building new pipelines to building new transmission lines which have lower investment cost compared to the pipelines.

In comparison with [11], the results enhance and the number of pipelines and transmission lines which are built in these cases reduce. As a result, total investment cost decrease, which shows the role of natural gas storage in expansion planning. On the other hand, linepack is considered as another type of storage which can alleviate the enormous budgets for investment.

6- CONCLUSION

In this study, natural gas storage and linepack were implemented in co-expansion planning power and natural gas systems to mitigate investment and operational costs. Without considering natural gas, the storage and the linepack had the highest cost, especially when the electrical and natural gas load growth were uncertain, which is shown how gas storage and linepack can be helpful in minimizing investment cost in expansion planning. Results provided compelling evidence that natural gas storage with linepack declined the net present value of the investment and operational costs by 6.3% and 14%. Moreover, the congestion in the pipelines and transmission lines were alleviated. These systems were far less sensitive to electrical and natural gas load growth uncertainties.

It was shown that natural gas storage and linepack had beneficial effects on conveying energy in the expansion planning, since the best possible way was chosen by considering linepack and storage to transfer energy. When pipelines' investment cost was high, transmission lines were built to reduce expansion planning costs. In addition, by dividing the planning horizon into two section, best time for expansion planning of new infrastructure were found. Additionally, by dividing the planning horizon into two section, best time for expansion planning of new infrastructure were found. Different uncertainties were modeled through scenarios to have better expansion planning results.

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NOMENCLATURE

Parameters

f, M Constant to change base load and large enough constant

IC, OC Investment and operational cost ($)

ir, st Interest rate and stage duration

L, LG Base load (m^3/h, MW) and load growth

β, χ Susceptance (B) and natural gas production cost ($/$m^3$/h)

η Efficiency of storage

ρ, ω Scenario probability and number of days or hours

Sets

Subscript

g Natural gas power plant

gs, s Natural gas storage and natural gas production unit

m, n Power system buses

o, t Operation and time

p, q Natural gas system nodes

y, w Year and scenario

Variables

C, LP Weymouth constant (m^3/h/psi) and linepack state (m^3)

P Output power of power plant (MW)

PI Capacity of candidate power plant constructed (MW)

PF, GF Power and gas flow (MW), (m^3/h)

S State of natural gas storage (m^3)

SI Capacity of candidate storage constructed (m^3)

SR, RR Storing and releasing rate of natural gas storage (m^3/h)

$_eX$ Binary variables for investment decisions of transmission

XS Natural gas production of natural gas unit (m^3/h)

θ Voltage angle (rad)

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