Reliability-Based Optimal Planning of Electricity and Natural Gas Interconnections for Multiple Energy Hubs

Xiaping Zhang, Liang Che, Mohammad Shahidehpour, Ahmed S. Alabdulwahab, and Abdullah Abusorrah

***Abstract*—This paper presents a reliability-based optimal planning model for an interconnection of energy hubs with multiple energy infrastructures. Energy hub represents a coupling among various energy infrastructures for supplying electricity and natural gas loads. The proposed planning problem determines a least-cost network of transmission lines and natural gas pipelines for interconnecting energy hubs from a given set of candidate paths that satisfy probabilistic reliability criteria. The minimal cut-maximal flow algorithm is applied for network flow analyses and calculating transfer capabilities of a multiple energy system. So, in contrast to a single energy infrastructure, the proposed hub planning model enables a synergetic strategy to design multiple energy networks for optimizing the supply economics and satisfying the reliability criteria. Numerical simulations demonstrate the effectiveness of the proposed reliability-based planning approach to interconnect energy hubs with multiple energy infrastructures.**

***Index Terms*—Multiple energy hub system, reliability-based planning, electricity and natural gas interconnection.**

NOMENCLATURE

Indices:

t	Index for period
h	Index for energy hub
i	Index for generating units
l	Index for transmission line
p	Index of natural gas pipelines

Sets:

EL	Set of existing transmission lines
EP	Set of existing natural gas pipelines
CL	Set of candidate transmission lines
CP	Set of candidate natural gas pipelines
ECT	Minimum cut set pair in electrical power network
GCT	Minimum cut set in the natural gas network

Parameters:

NT	Number of periods in the duration time
NG	Number of gas-fired units within energy hub
L^E	Electricity power output within energy hub
L^G	Natural gas output within energy hub
D^E	Electricity power peak load deficiency
D^G	Natural gas output peak load deficiency
a, b, c	Fuel function coefficient of gas-fired unit
η	Energy conversion efficiency
κ	Dispatch factor
H	Coupling matrix
IC	Installed non-gas generating capacity
C^{f^E}	Minimum cut set capacity with electricity
C^{f^G}	Minimum cut set capacity with natural gas

Variables:

TC	Investment cost of transmission line
PC	Investment cost of natural gas pipeline
E	Energy input within a hub
L	Energy output within a hub
X	Investment state of natural gas pipeline
Y	Investment state of transmission line
f^E	Electricity branch flow
f^G	Natural gas pipeline flow
AC	Total available capacity

I. INTRODUCTION

THE GROWING reliance on natural gas as a primary fuel for electricity generation has brought the discussion on the interdependency of electricity and natural gas to the center point [1], [2]. The widespread utilization of highly efficient combined heat and power (CHP) plants can also affect the supply chain of various types of energy services including electricity, natural gas, and heat. In such cases, it is unlikely that an independent design of a single energy infrastructure can meet potential challenges of future energy supplies. A comprehensive design for the optimal coordination of various energy supply and delivery systems is essential to maintaining

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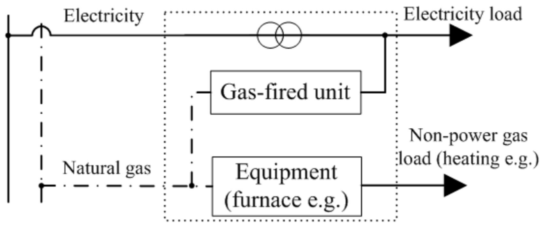

Fig. 1. Energy hub with electricity and natural gas systems.

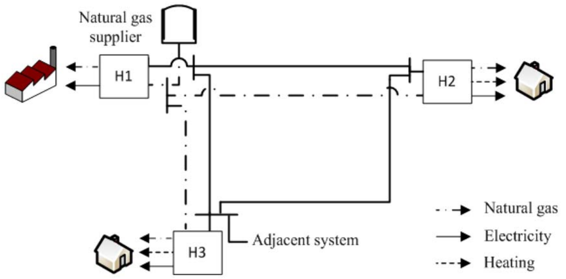

Fig. 2. Interconnection of three energy hub systems.

a sustainable and reliable energy infrastructure. The energy hub concept established under these conditions represents an interface among energy participants (producers, aggregators, consumers) and energy system carriers [3], [4].

An energy hub features input, output, conversion, and storage of multiple energy systems in a functional energy delivery unit. Fig. 1 depicts an energy hub configuration for exchanging electricity, natural gas, and heating supplies. Energy hubs can offer more efficient energy networks by switching the resource-constrained demand of an energy carrier to other forms of energy for the delivery at peak periods.

The input hub port is connected to electricity and natural gas supplies. Inside the energy hub, multiple hardware devices for energy conversion include power transformers, natural gas-fired units, and furnace. At the output port, loads are supplied by multiple energy carriers. Energy carriers in a hub are characterized by their cost and availability, which offer options for optimizing the hub system operation cost.

The coupling of energy carriers in a hub brings together potential benefits of conventional and often mutually independent energy supply systems [5]. From the system reliability perspective, multiple energy hubs increase the availability of energy supplies to individual loads since the hub is no longer fully dependent on a single infrastructure.

Consider an energy delivery system with three hubs depicted in Fig. 2, in which natural gas-fired generation establishes a connection between electricity and natural gas networks, with a certain redundancy of energy flow which offers supply flexibility to hub loads. Specifically, in order to meet an increasing level of electricity loads at H2, one can either install a natural gas pipeline (H1-H2) to generate more electricity or directly deliver electricity through a new transmission line (H3-H2). This plan provides an alternative to the energy system planners to make comprehensive decisions considering the energy feasibility and economics among other factors.

A conventional interconnection planning of energy infrastructures has traditionally considered one form of energy, e.g., electricity through power transmission system or natural gas through pipeline systems. As such, the economic benefits of interconnected power systems are discussed as a function of tie line capacity in [6]. A probabilistic method is used to investigate the reliability of interconnected power systems in [7] and [8]. Reference [9] introduced a transmission system expansion plan considering probabilistic reliability criteria. An expansion planning method for natural gas networks with multiple pressure levels is presented in [10].

In recent years, further efforts have been devoted to the co-optimization of multiple energy infrastructures as the interdependency of electricity and natural gas continues to attract additional attention [11], [12]. A long-term multi-area expansion planning of integrated electricity and natural gas was presented in [13], which considered the natural gas value chain through pipelines from the supply to end-use consumers. Reference [14] proposed a planning model of electricity and natural gas distribution systems with a high penetration of distributed generation resources. These studies often focused on the economics of optimal integrated resource planning without addressing the reliability issues for natural gas customers. A general optimization and modeling framework is developed in [15] for coupled energy flow studies in multiple energy infrastructures. The influence of energy storage capacity and prediction horizon on the cost of optimal multiple energy supply is discussed in [16], which involve the energy carrier including electricity, natural gas and heat.

We propose a reliability-based optimal planning model for an interconnection of multiple energy hubs. The planning problem considers a least-cost selection of network components (i.e., transmission lines and natural gas pipelines) for interconnecting multiple energy hubs, which can satisfy the stated probabilistic reliability criteria. In contrast to the previous work, the proposed model considers probabilistic reliability evaluation deriving from component outage statistics in a multiple energy system. In addition, the minimal cut-maximal flow algorithm in the network flow analysis is applied to calculate transfer capabilities in interconnected energy hub systems for a specific form of energy. This interconnection planning method allows optimal exchanges among multiple energy carrier networks and offers a new degree of freedom in energy supply to improve the reliability of interconnected energy hub systems.

This feature plays an essential role in the reliability evaluation of a multiple energy hub system since the single hub reliability will be affected by transferring either electricity or natural gas among interconnected hubs. The proposed model can be utilized by energy system planners for enhancing the reliability of a multiple energy system. Specifically, for utilities with electricity and natural gas infrastructures, energy hubs represent a bounded geographical area with natural gas-fired units, electricity, and heating resources. The proposed approach enables a more synergic strategy to design energy delivery networks in accordance with regional planning criteria.

The rest of the paper is organized as follows. Section II introduces the general mathematical modeling of the energy hub. Section III presents the basics of the minimum-cut sets network flow analysis in multiple energy system. Sections IV and V present the formulation and framework of optimal multiple energy infrastructure interconnection planning model with illustrative examples. The conclusion drawn from the study is provided in Section VI.

II. ENERGY HUB

Consider an energy hub model with various energy carriers $\alpha, \beta, \ldots, \gamma$. Within the hub, energy is converted to various forms for meeting the hub load. The energy transfer from an input hub port to an output port is expressed as:

$$\underbrace{\begin{pmatrix} L_\alpha \\ L_\beta \\ \vdots \\ L_\gamma \end{pmatrix}}_{L} = \underbrace{\begin{pmatrix} H_{\alpha\alpha} & H_{\beta\alpha} & \cdots & H_{\gamma\alpha} \\ H_{\alpha\beta} & H_{\beta\beta} & \cdots & H_{\gamma\beta} \\ \vdots & \vdots & \ddots & \vdots \\ H_{\alpha\gamma} & H_{\beta\gamma} & \cdots & H_{\gamma\gamma} \end{pmatrix}}_{H} \underbrace{\begin{pmatrix} E_\alpha \\ E_\beta \\ \vdots \\ E_\gamma \end{pmatrix}}_{E} \tag{1}$$

In which the energy at input and output ports are represented by $E = [E_\alpha, E_\beta, \ldots, E_\gamma]$ and $L = [L_\alpha, L_\beta, \ldots, L_\gamma]$, respectively. The H matrix is the forward coupling matrix for energy conversion, which represents the converter efficiency and the hub internal topology. Consider a converter device which converts energy carrier α into β with a coupling factor of $H_{\alpha\beta}$.

$$L_\beta = H_{\alpha\beta} E_\alpha \tag{2}$$

where E_α and L_β denote energy input and output, respectively. For a single-input single-output converter, the coupling factor corresponds to the converter's efficiency. For a fixed converter efficiency, the coupling matrix represents a linear transformation of input to output. The conversion efficiency can also be modeled as a function of its operating point. In this work, we consider a fixed average converter efficiency to simplify the hub topology model and effectively reduce the computational complexity of a reliability-based interconnection problem for the sake of discussion.

In each hub, electricity and natural gas are considered as an energy input. The coupling matrix represents three converter devices: transformer, natural gas-fired generators, and other natural gas load devices (i.e., natural gas furnace for residential and industrial use). Here, the energy input vector E comprises electricity and natural gas:

$$E = \begin{pmatrix} E^{el} \\ E^{gas} \end{pmatrix} \tag{3}$$

The load demand vector L comprises electricity L^{el} and natural gas loads L^{gas} for other natural gas customers:

$$L = \begin{pmatrix} L^{el} \\ L^{gas} \end{pmatrix} \tag{4}$$

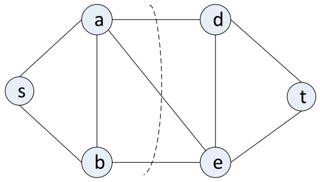

Fig. 3. Six-node undirected network.

Input E and output L vectors are linked via the conversion coupling matrix expressed as:

$$\underbrace{\begin{pmatrix} L^{el} \\ L^{gas} \end{pmatrix}}_{L} = \underbrace{\begin{pmatrix} \eta^{el} & (1-\kappa)F^{-1} \\ 0 & \kappa\eta^{gas} \end{pmatrix}}_{H} \underbrace{\begin{pmatrix} E^{el} \\ E^{gas} \end{pmatrix}}_{E} \tag{5}$$

where η^{el} denotes the power transformer efficiency and η^{gas} is the average efficiency of other gas loads. F^{-1} represents the conversion function of natural gas-fired generators from gas to electricity, which is the inverse function of the fuel curve. Additionally, a dispatch factor κ is introduced for natural gas since natural gas is consumed by both generators $(1-\kappa)E^{gas}$ and other natural gas loads (κE^{gas}).

III. MINIMAL CUT SET FLOW NETWORK ANALYSIS

In this study, we consider a general case of undirected network connection graph analyses rather than specifying the direction of each arc (i.e., transmission line, pipeline) in a hub. The objective of interconnected network flow analysis is to find the maximum energy flow among hubs [17] which can be used as input data to optimize the reliability-based interconnection planning. The natural gas pipeline and electricity transmission lines are modeled as linear flow networks so that the minimal cut-maximal flow algorithm can calculate the system transfer capability for a specific form of energy.

Consider an undirected network $G = [N; \alpha]$ comprising a set N of nodes with a set α of linking arcs. Each arc is related with two nodes, and the relation is represented as a pair (i, j). Each arc from i to j has a capacity of $f_{ij}^{\max}$ representing the maximal flow through the arc. Normally there are several source nodes where energy can enter. Similarly, sink nodes are where energy can flow out. We are primarily concerned with the maximal energy that flows from source to sink. Assume a flow f of $C{=}C(f)$ with source s and sink t; the maximal flow problem will maximize the variable C such that,

$$\sum_j f_{ij} - \sum_j f_{ji} = \begin{cases} C, & i = s \\ -C, & i = t \\ 0, & otherwise \end{cases} \tag{6}$$

$$0 \le f_{ij} \le f_{ij}^{\max}, \quad \text{for every arc } (i, j) \tag{7}$$

To find the maximal flow from s to t, we first define a cut that separates s and t nodes into two complementary sets, S and T, with $s \in S$ and $t \in T$. Observe a network shown in Fig. 3 where $S = \{s, a, b\}$ and $T = \{d, e, t\}$ with one separating cut.

Usually, a network contains several separating cuts in which the capacity of a cut is calculated as:

$$\sum_{i\in S, j\in T} f_{ij}^{\max} \tag{8}$$

Consider a *Lemma:* If [S,T] is a separating cut in a network, with input at source s and output at sink t, and f is the flow with a value equal to C then,

$$C = \sum_{i\in S, j\in T}\left(f_{ij} - f_{ji}\right) \text{ and}$$
$$C \leq \sum_{i\in S, j\in T} f_{ij}^{\max} \tag{9}$$

The Lemma indicates that any network flow must be equal to or less than the capacity of any cut [18]. While a finite network contains a finite number of cuts, there will be a separating cut with minimum capacity which is called a minimal cut. In other words, for an arbitrary flow and arbitrary cut, the net flow across the cut is bounded by the cut capacity, which leads to the *Minimal cut-maximal flow theorem* for a linear network. The theorem states that the maximal flow from source to sink is equal to the minimal cut capacity relative to the source and the sink.

Several efficient algorithms are provided in the literature for identifying all the minimal cut sets of a given source and sink pair [19], [20]. In this work, the topology of multiple energy hubs is described by the transmission lines and natural gas pipelines which link the energy hubs. We do not incorporate the transport losses of electricity or natural gas through the energy transportation infrastructures since we mainly focus our attention on the network topology design. A hub which has satisfied the reliability criterion (surplus) is labeled as a source hub, and will otherwise be listed as a sink hub in the proposed algorithm.

IV. PLANNING MODEL FOR INTERCONNECTED HUBS

A. *Interconnection Planning for Multiple Energy Hubs*

The proposed optimal multiple energy hub interconnection planning is a least-cost selection problem of network elements to be placed between hubs from a given set of candidate paths in order to achieve a satisfied reliability performance.

1) Objective: The objective is to minimize the total investment cost associated with new infrastructures including electric power transmission lines and natural gas pipelines. The investment states of the infrastructures are defined as binary variables, i.e., Y and X.

$$Min \sum_{l\in CL} TC_l \cdot Y_l + \sum_{p\in CP} PC_p \cdot X_p \tag{10}$$

2) Constraints: The optimization of interconnection planning is subject to two types of reliability constraints, deterministic and probabilistic constraints. A deterministic reliability constraint requires no shortage of energy supply for each energy hub system. For each energy carrier, the maximal energy flow into a destination hub should be greater than or equal to the forecasted system peak demand deficiency. The maximal flow can be obtained from the total capacity of the branch involved in the minimum cut set as derived in Section III. The deterministic reliability constraint expressed as:

$$\sum_{l\in ECT}\left[C^{f^E} = \sum_{l\in EL} f_l^{E\max} + \sum_{l\in CL} Y_l \cdot f_l^{E\max}\right] \geq D^E \tag{11}$$

$$\sum_{p\in GCT}\left[C^{f^G} = \sum_{p\in EP} f_p^{G\max} + \sum_{p\in CP} X_p \cdot f_p^{G\max}\right] \geq D^G \tag{12}$$

A probabilistic constraint (13) will require that the resource adequacy level at each hub satisfy a reliability criterion which is measured by the loss-of-load expectation (LOLE). LOLE is defined in (14) as the average number of days or hours in a given period (usually one year) in which the peak load in a hub is expected to exceed the sum of available generating capacity.

$$LOLE_h \leq LOLE^{\text{limit}} \tag{13}$$

$$LOLE_h = \sum_{t=1}^{NT} P_t\left(AC_h \leq L_t^E\right) \tag{14}$$

$$AC_h = IC + C^{f^E} \cdot \eta^{el} + C^{f^G} \cdot (1-\kappa)F^{-1} \tag{15}$$

Here, P_t is the probability of loss of load on period t, L_t^E is the forecasted peak load, AC_h is the total available capacity at energy hub h. LOLE is a complex probabilistic function of available generating capacity AC_h and daily peak load duration curve ξ as shown in (14). In each hub, the available generating capacity is determined by the installed non-gas generating capacity IC, and assisted capacity (energy input) from external network of interconnected hubs. The assisted capacity depends on the operation condition of assisting hubs and the interconnecting energy network topology which gives the minimum cut set capacity C^{f_E}, C^{f_G} for each source and sink pair of the multi-hub system.

Equations (10)-(12) represent an integer optimization problem while the decision variables are investments states of transmission lines and natural gas pipelines. Equations (13)-(15) represent a generating capacity adequacy evaluation process, deriving from the available capacity based on the hub configuration and the interconnection network topology. In this model, the energy flow to each hub is obtained from the minimal cut capacity associated with the investment states variables of candidate network elements. By selecting the best interconnection path, we are actually looking for the optimal switching point between electricity and natural gas to supply the load while satisfying the probabilistic reliability criterion at each hub.

A conventional generating capacity adequacy study evaluates the adequacy of a hub configuration by measuring the available capacity and calculating the reliability indices [21]. The capacity outage probability table is set out using a widely used recursive algorithm [22]. However, the interconnection plays a key role in evaluating the generation capacity adequacy in a hub, which provides electric power assistance or natural gas supply through multiple energy networks. Therefore, in Parts B and C we present the capacity adequacy evaluation process of a hub based on the assisted energy. Here, we

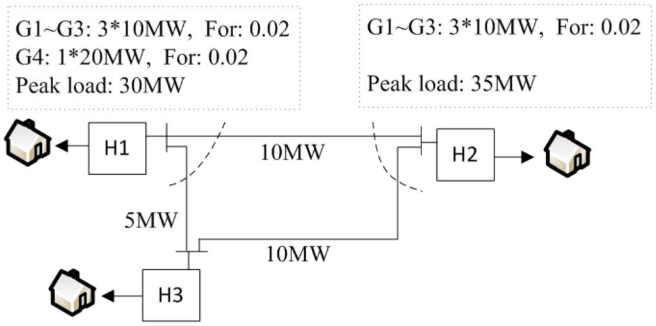

Fig. 4. Electricity networks of three-energy hub system.

TABLE I
CAPACITY OUTAGE PROBABILITY

State	Capacity on outage (MW)	Individual probability	Cumulative probability
1	0	0.9224	1.0000
2	10	0.0565	0.0776
3	20	0.0200	0.0212
4	30	0.0012	0.0012

assume the interconnection system is fully reliable for a group of energy hubs. However the assumption will not alter the interconnection planning procedure presented in this paper.

B. Electricity Power Assistance

The interconnection benefits will depend on the installed capacity and load level at each hub, transmission line topology and capacity, and interconnection agreements. Here, we consider an interconnection agreement based on a no load-loss sharing policy [23], which implies that the assistance available to a hub is limited to a minimum of (available reserve and minimal cut capacity quantities). Meanwhile, a hub which has satisfied its LOLE criterion can provide assistance to a destination hub. We use the equivalent unit approach to calculate the available assisting capacity of individual hubs.

In Fig. 4, Hub2 is assisted by Hub1 in a three-hub interconnected system. Hub1 is represented by an equivalent multi-state unit for accommodating the deficiency in Hub2. The capacity outage probability table for Hub1 is shown in Table I, where the 20 MW of surplus capacity in Hub1 is fully available for assistance without considering the network limits. The capacity assistance level of Hub1 is shown in Table II, which level can be interpreted as an equivalent assisting unit of Hub1.

We consider the transmission line system as undirected network and Hub1 and Hub2 as a pair of source and sink. The cuts in Fig. 4 separate the hubs into two complementary sets. According to the maximal flow-minimal cut theorem, the maximal flow from Hub1 to Hub2 is equal to the minimal cut capacity of 15MW. Table III shows the capacity assistance provided by Hub1 which is modified by the maximal flow capacity constraint. This equivalent multi-state unit is added to the existing capacity of assisted Hub2.

TABLE II
CAPACITY ASSISTANCE

State	Assistance (MW)	Capacity on outage(MW)	Individual probability	Cumulative probability
1	20	0	0.9224	1.0000
2	10	10	0.0565	0.0776
3	0	20	0.0212	0.0224

TABLE III
NETWORK-CONSTRAINED CAPACITY ASSISTANCE

State	Assistance (MW)	Capacity on outage(MW)	Individual probability	Cumulative probability
1	**15**	0	0.9224	1.0000
2	10	10	0.0565	0.0776
3	0	**15**	0.0212	0.0224

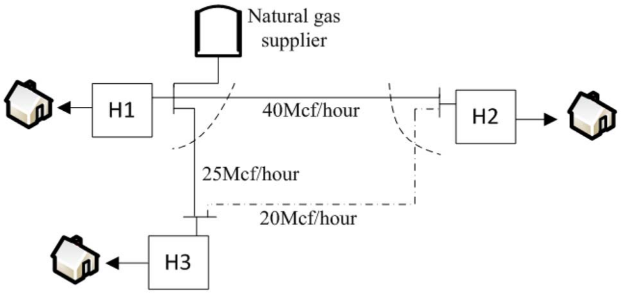

Fig. 5. Natural gas networks of three-energy hub system.

C. Natural Gas Assistance

The available fuel supply in a given period is constrained by the natural gas pipeline network. The natural gas-fired generators usually rely on the lowest priority service (i.e., interruptible natural gas transportation service) which is priced on a volumetric basis. Hence, the availability of natural gas for power generation depends on the high-priority gas consumption by residential, commercial and industrial loads. The fuel constraint for energy Hub h is expressed as:

$$\sum_{i=1}^{NG}\Big[F_i = a_i(P_i)^2 + b_iP_i + c_i\Big] \le (1-\kappa)C^{f_G} \qquad (16)$$

where $(1-\kappa)C^{f_G}$ is the natural gas available to gas-fired generating units. Here, C^{f_G} denotes the maximum arrival gas flow at a hub, which is the minimum cut set capacity at this node of the natural gas network. The dispatch factor can be viewed as an indicator of energy consumption priorities for different natural gas customers, which is derived from the historical consumption data.

In Fig. 5, we use the same system presented in Section IV-B to discuss the available capacity at Hub2. The fuel function coefficients are $a = 0.001, b = 1.5, c = 10$ for all gas-fired units. Assume pipeline from Hub2 to Hub3 is a newly installed pipeline with a capacity of 20Mcf/hour. The previous maximal natural gas flow from supplier to Hub2 was 40Mcf/hour, which had limited the maximal capacity to 20MW. The capacity outage probability table for Hub2 is shown in Table IV. When the new pipeline is installed, the maximal gas flow amount

TABLE IV
CAPACITY OUTAGE PROBABILITY

State	Capacity on outage (MW)	Individual probability	Cumulative probability
1	0	0.9604	1.0000
2	10	0.0392	0.0396
3	20	0.0004	0.0004

TABLE V
CAPACITY OUTAGE PROBABILITY WITH NEWLY INSTALLED PIPELINE

State	Capacity on outage (MW)	Individual probability	Cumulative probability
1	0	0.9412	1.0000
2	10	0.0576	0.0588
3	20	0.0012	0.0012

from supplier to Hub2 is equal to the minimal cut capacity of 60Mcf/hour.

This fuel supply can supply the 30MW natural gas-fired units. The revised capacity outage probability table is shown in Table V.

V. INTERCONNECTION PLANNING ALGORITHM

The proposed interconnection planning model represents an integer optimization problem with probabilistic constraints as expressed by (13)-(15). This problem cannot be solved directly by a commonly used optimization solver because the generating capacity adequacy evaluation process cannot be expressed by analytical equations associated with integer variables. Therefore, we resort to an iterative process, which is depicted in Fig. 6.

The input data for the proposed algorithm consist of:

- Existing generating unit capacity, forced outage rate, fuel type, fuel function and electricity load duration curve.
- Natural gas supplier volume, non-utility gas loads.
- Network topology, transmission line capacity, natural gas pipeline capacity, dispatch factor.

The detailed solution procedure is presented as follows:

1) Evaluate the resource adequacy of each energy hub to identify deficient and sufficient hubs. A hub which has fulfilled its reliability criterion is defined as a sufficient hub (i.e., source node) to provide assistance to a deficient hub (i.e., sink node).
2) For all identified source and sink pairs, calculate the minimum cut set based on the prospective network topology which contains the candidate transmission lines and natural gas pipelines.
3) Solve an integer programming problem using (10)-(12) to get an interconnection solution for new transmission lines and pipelines.
4) Reevaluate the LOLE at each deficient hub based on the updated network topology. The equivalent unit for the assisted hub will be updated when a new transmission line is deployed. Similarly, the available fuel for a hub will be renewed when a new gas pipeline is deployed.

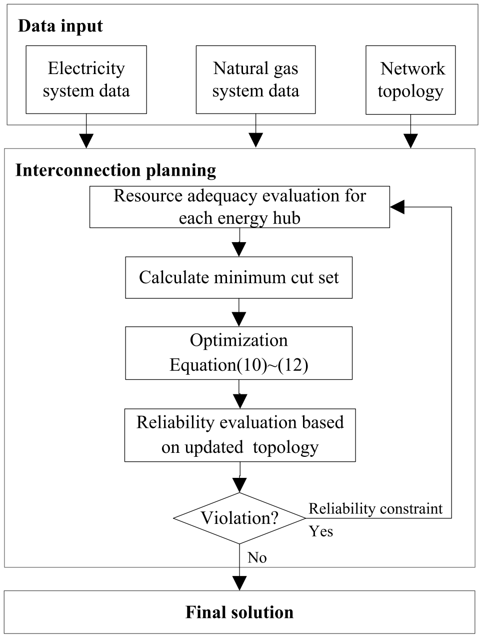

Fig. 6. Interconnection planning in multiple energy hubs.

5) If the hub LOLE cannot meet the stated reliability criterion, a new constraint will be formed based on the hub fuel provision and added to the integer programming problem in Step 3) for updating the interconnection planning solution. In this regard, we consider the following two scenarios:
   - ***Scenario1*:** The fuel requirement for the gas-fired units at this hub cannot be fully supplied by the existing gas network. Constraint (17) is generated and fed back to the integer optimization problem for the next iteration. This constraint will enforce a new candidate transmission line or pipeline involved in the minimum cut set of the deficient hub to be added to the existing hub system. Here, $\overline{Y}$ and $\overline{X}$ represent the decision variables in the previous iteration.

$$\sum_{l\in ECT} Y_l + \sum_{p\in GCT} X_p > \sum_{l\in ECT} \overline{Y_l} + \sum_{p\in GCT} \overline{X_p} \quad (17)$$

   - ***Scenario2*:** The fuel provision is sufficient. This indicates that the addition of a new pipeline will not improve the LOLE. Thus, constraint (18) is generated which indicates that the reliability can only be improved by an electricity power assistance supplied through new transmission lines.

$$\sum_{l\in ECT} Y_l > \sum_{l\in ECT} \overline{Y_l} \quad (18)$$

6) The entire iterative process (steps 3-5) will be repeated until an interconnection graph is planned that will satisfy all the energy hub reliability criteria.

The integer programming problem in step 3) is solved by an optimization solver (e.g., GUROBI). The reliability constraint added to the integer problem (in step 5) could introduce a new transmission line or pipeline for the least investment plan.

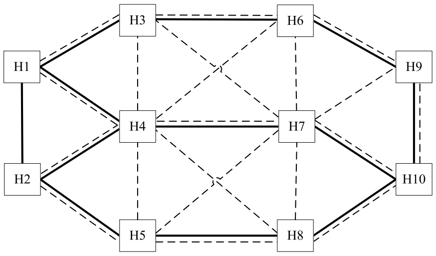

Fig. 7. Existing and candidate electrical transmission network graph.

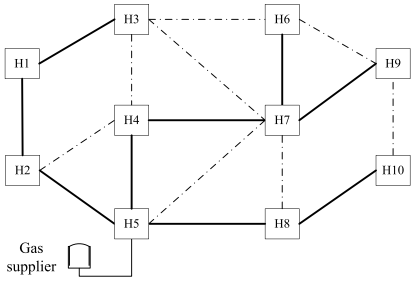

Fig. 8. Existing and candidate natural gas network graph.

However, this method may result in a locally optimal solution because the reliability constraint will add the least cost component. Therefore, the solution in the first iteration which provides an initial search point plays a critical role in searching for the final solution. In specific cases, we may obtain a group of viable solutions and select the best one by adjusting the initial solution.

VI. NUMERICAL RESULTS

The proposed interconnection planning model for the multiple energy hub system is analyzed with a 10-hub system which constitutes an interconnected structure of the existing and planned electricity and natural gas networks. The initial electric power system graph is shown by solid lines in Fig. 7, which comprises 12 existing transmission lines and 30 generating units located at different hubs. A set of 20 candidate transmission lines (dotted line) is considered to interconnect the 10 hubs as shown in Fig. 7.

The initial natural gas system is composed of 9 pipelines and 1 natural gas supplier as shown in Fig. 8. The dispatch factor of high-priority gas loads ranges from 0.3 to 0.4 in different hubs. A set of 8 candidate natural gas pipelines (dotted line) is considered in Fig. 8. The topological system data are given in *motor.ece.iit.edu/data/EneryHubInter.xlsx.*

The investment cost and the capacity associated with the candidate transmission lines (L) and natural gas pipelines (P) are given in Table VI. Fig. 9 shows the annual electricity load duration curves at the two hubs with the largest electricity loads. The peak load is 114MW (Hub3) and 100MW (Hub9) respectively. The required reliability criterion is stated as $LOLE \leq 1 day/\mathrm{yr}$ in Cases 1 and 2.

We consider the following three cases in this study:

Case1: Interconnection planning of electricity network without installing any new gas pipelines.

TABLE VI
CANDIDATE TRANSMISSION LINE AND PIPELINE CHARACTERISTICS

NO.	*From hub*	*To hub*	*Capacity (MW/Mcf)*	*Investment Cost (p.u.)*	*Investment state*	
					Case 1	*Case 2*
L1	1	3	10	2.6	-	-
L2	1	4	10	2.8	-	-
L3	2	4	10	2.8	-	-
L4	2	5	10	2.5	1	-
L5	3	4	20	5.2	-	-
L6	4	5	20	5.3	-	-
L7	3	6	10	2.4	-	1
L8	3	7	30	7.8	-	-
L9	4	6	30	7.3	1	-
L10	4	7	10	2.6	1	-
L11	4	8	30	8.0	-	-
L12	5	7	30	7.7	-	-
L13	5	8	10	2.6	1	-
L14	6	7	20	5.2	-	-
L15	7	8	20	5.3	-	-
L16	6	9	10	2.6	1	1
L17	7	9	30	7.9	-	-
L18	7	10	10	2.6	-	-
L19	8	10	10	2.7	1	-
L20	9	10	10	2.8	1	1
P1	2	4	450	8.7	-	-
P2	3	4	340	6.6	-	1
P3	3	6	370	7.2	-	-
P4	3	7	510	10.0	-	-
P5	5	7	730	14.2	-	-
P6	7	8	480	9.4	-	-
P7	6	9	380	7.4	-	-
P8	9	10	390	7.6	-	1

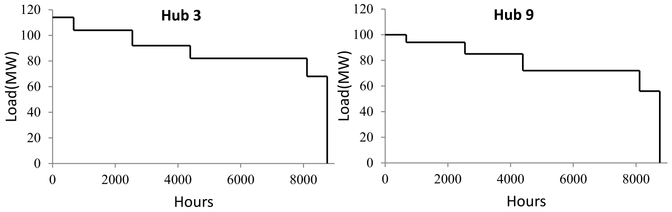

Fig. 9. Load duration curves.

Case2: Interconnection planning of electricity and natural gas networks.

Case3: Impact of dispatch factor of high-priority gas loads on the planning results.

These cases are discussed as follows:

Case 1: In this case, new lines enhance the hub reliability performance by the assisting electricity power. Table VII shows the initial hub reliability levels.

Hub3 and Hub9 have the highest installed generating capacity which meets the LOLE limit. In this case, the two hubs are located at the natural gas network terminal where the available fuel supply is constrained by the pipeline capacity. Hub1 and Hub2 have the best reliability performance (sources), which provide assistance to deficient Hub6 and Hub10 (sinks). Fig. 10 shows 4 minimum cut set with a capacity of 20 MW, which are identified based on the existing topology of transmission lines for the source (Hub1 and Hub2) and the sink (Hub6) pair.

Similarly, 12 minimum cut sets with a capacity of 30 MW are identified for the source (Hub1 and Hub2) and the sink (Hub10) pair. Under the no load-loss sharing policy,

TABLE VII
COMPARISON OF RELIABILITY INDICES AT THE ENERGY HUB (CASE1,CASE2)

Hub	**Capacity (MW)**	**LOLE (hrs/yr)**		
		Initial value	**Case 1**	**Case 2**
1	200	0.5108	-	-
2	220	0.4258	-	-
3	240	1.0076	-	0.3614
4	170	0.8965	-	-
5	180	0.9142	-	-
6	120	16.208	0.6376	0.5561
7	180	0.8824	-	-
8	180	0.9280	-	-
9	240	1.0018	-	0.3552
10	110	12.467	0.6115	0.5317

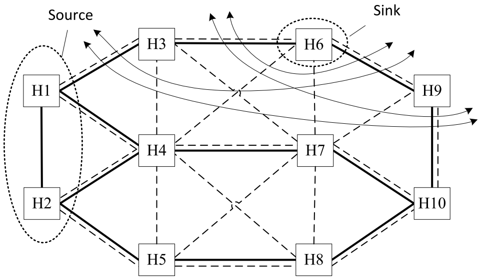

Fig. 10. Minimum cut set for the source (H1 and H2) and sink (H6) pair.

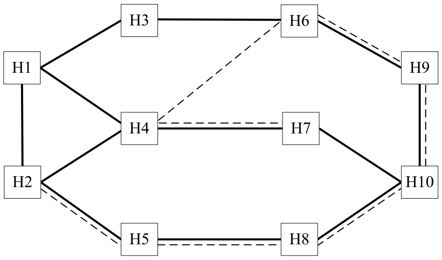

Fig. 11. Electrical transmission network (Case 1).

the capacity assistance from the source to the sink hub can only be transferred up to available reserve or minimal cut capacity, whichever is limiting. In this example, the minimal cut capacity is limiting.

The new optimal interconnection topology is shown in Fig. 11, with dotted lines representing the new lines. Seven transmission lines (L4,L9,L10,L13,L16,L19,L20) are added with a total investment cost of 23.1p.u. The new transmission line topology increases the maximal assistance to 60MW for the two identified sources and sink pairs. This increased capacity assistance improves the reliability of the deficient hubs. Table VII gives the updated LOLE at Hub6 and Hub10 for the reinforced network topology, which are reduced to 0.6376 and 0.6115 days/yr, respectively.

Case 2: In this case, both Hub3 and Hub9 initially suffer fuel shortages which are constrained by the pipeline capacity. The natural gas-fired units cannot be fully supplied which results in a low LOLE despite a largely installed generating capacity. The two hubs are defined as sink in the natural gas network while Hub5 is defined as source with an access to the natural gas supply.

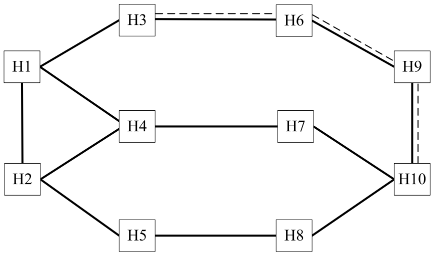

Fig. 12. Electrical transmission network graph (Case 2).

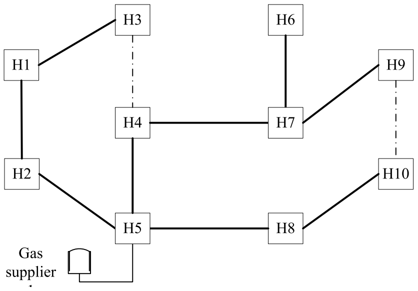

Fig. 13. Natural gas network graph (Case 2).

The optimal topology of electricity and natural gas network is shown in Figs. 12 and 13. Two new gas pipelines (P2,P8) and three new transmission lines (L7,L16,L20) are added with a total investment cost of 22 per unit. The new pipelines increase the available gas capacity to Hub3 and Hub9 to 700 and 795Mcf/hour, respectively. The dispatch factor of high-priority natural gas loads in the two hubs is 0.4 in this case. The new natural gas network can fully supply the natural gas-fired units at the two hubs, which enables them to provide electric capacity assistance to deficient Hub6 and Hub10.

This optimal plan only involves three new transmission lines to ensure that Hubs 6 and 10 satisfy the reliability criterion ($LOLE \leq 25$hrs/yr). For deficient Hub6, the new topology supports the maximal assistance of 40MW from one source (Hub1,2,3) and 30MW from the other (Hub9). Likewise, the deficient Hub10 will receive the maximal assistance of 50MW and 30MW from the two sources, respectively. The LOLEs of Hub 6 and Hub10 are improved to 0.5561 and 0.5317 days/yr, respectively, which are lower than those in Case 1.

In this case, rather than depending solely on transmission lines to increase the reliability in Hub 6 and Hub9, we improve the natural gas transportation capability to the hubs with the additional installed capacity of natural gas-fired generation. This example also indicates that the multiple energy interconnection planning offers more comprehensive decisions for upgrading the hub capacity to supply hub loads and satisfy the stated reliability criterion.

Case 3: In this case, the impact of dispatch factor of high-priority natural gas loads on the interconnection planning is considered. Within each hub, natural gas-fired generators rely on lowest priority services which are priced solely on a volumetric basis. Their supply also depends on the natural gas

TABLE VIII
COMPARISON OF RELIABILITY INDICES AT THE ENERGY HUB (CASE3)

κ	***New transmission lines***	***New gas pipelines***	***Investment Cost (p.u.)***
0.3	L7, L16, L20	P2,P7	21.8
0.4	L7, L16, L20	P2,P8	22.0
0.5	L9, L10, L16, L20	P7	22.7

consumption by high-priority gas loads. The optimal interconnection plans that consider a varying dispatch factor are given in Table VIII. The $\kappa = 0.4$ solution was discussed in Case 2. When the dispatch factor is reduced to $\kappa = 0.3$, the optimal plan replaces gas pipeline P8 with pipeline P7 at a lower investment cost of 21.8p.u. This is because a minimal cut capacity of 600Mcf / hours from gas supplier to Hub9 with a dispatch factor of 0.3 enables a sufficient supply for gas-fired generators at this hub. However, the optimal plan will include one gas pipeline and four transmission lines when the dispatch factor is increased to $\kappa = 0.5$. The gas-fired generator at Hub3 will not provide any assistance to Hub6 due to the unfulfilled fuel demand resulting from a higher dispatch factor for high priority gas loads. The planning solution indicates that it is more economical to invest on transmission lines to improve the reliability of Hub6 compared with the installation of new pipelines to supply the gas-fired generation at Hub3. The higher dispatch factor will result in a slightly higher investment cost of 22.7p.u. to satisfy the stated reliability criterion.

We tested the proposed model with a 10-hub system and considered both the electricity and natural gas network as undirected graphs. The technical challenge for providing the planning solution for larger interconnected hubs is that the computation burden to deduce the minimal cut sets ascends rapidly with the complexity of the graph and the number of source-sink pairs. Therefore, we may apply a directed network connection graph analysis by specifying the direction of each arc component (i.e., transmission line, pipeline) of a large-scale electricity and gas network. For interconnected hubs which implement a unidirectional assistance operating agreement, this is a reasonable prerequisite which can effectively reduce the computation effort.

VII. CONCLUSION

This paper proposed a reliability-based interconnection planning model to optimize the topology of multiple energy hubs. The solution determines a least-cost selection of network elements (i.e., transmission line and natural gas pipelines) which satisfies the stated reliability criteria by optimally linking the multi-energy hubs. The minimal cut-maximal flow algorithm in the network flow analysis is applied to calculate the transfer capabilities for a specific form of energy in the multiple energy hubs. The model was tested on ten interconnected hubs. Case studies demonstrated that the coupling of multiple energy hubs offers more flexible options by allowing energy transfers as electric power or natural gas through the interconnected network. In contrast to solely relying on a single energy infrastructure, the proposed multi-energy hub model enables a synergic strategy to design hub networks and deliver energy to satisfy the stated reliability criteria.

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