Coordination of Interdependent Electricity Grid and Natural Gas Network – A Review

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Abstract— Purpose of review: The fast growth of gas-fired generating units and the new emerging power-to-gas (PtG) technology have intensified the interdependency of the electricity grid and the natural gas network. Indeed, the security and economy of one system could directly and significantly affect that of the other. In observing these new trends and changes, a coordinated optimization between the two energy systems has attracted increasing attentions in recent years, which is believed to derive much more satisfactory solutions than optimized separately. Thus, this paper provides a comprehensive review of existing works on the coordination of interdependent electricity grid and natural gas network. Recent findings: The paper first highlights the modeling of key coupling components and discusses various coordination strategies of the two energy systems. The review then focuses on three major aspects of the coordination: coordinated short-term scheduling, coordinated long-term expansion planning, and energy market and energy hub. Summary: Research and practical implementation on coordination of the interdependent electricity and natural gas system (IENS) are still in the infant stage. Challenges and potential future research directions that could further benefit the secure, reliable, and economic operation and planning of future IENS are summarized.

Index Terms— Coordination; electricity grid; energy hub; energy market; natural gas network; operation; planning.

I. Introduction

In recent decades, public concerns over climate changes and depletion of fossil fuels have been promoting significant investments in renewable generation. According to the International Energy Agency (IEA), the annual wind generation will reach 2182 TWh by the year 2030, which increases about seven times from 2009 [1]. Furthermore, because of prominent advantages of gas-fired units including lower carbon emission, cheaper capital cost, higher efficiency, and faster response capability, gas fuel consumption of the electric power sector has increased sharply from 27% of total gas load in the natural gas system in 2005 to 39% in 2016 [2]. It is expected that gas-fired units could effectively offset variability and uncertainty of renewable energy resources, such as wind and solar generation [3]. Specifically, as the penetration level of renewable generation increases, fast response gas-fired units could be quickly called to maintain instantaneous generation-load balance and ensure the security of electric power systems, which however is also restricted by gas fuel availability from the natural gas network.

Indeed, the widely deployed electric-driven compressors and newly emerged Power-to-Gas (PtG) technology, together with the proliferation of gas-fired units, have intensified and accelerated the interdependency of electricity grid and natural gas network. Electric-driven compressors are widely used in the natural gas network to compensate pressure losses, which however heavily rely on reliable electricity supply from the power grid. The PtG technology is promising in the way that excessive electricity, mainly from renewable generation, could be effectively converted into compatible natural gas [4]-[5]. Furthermore, in recent years, the interdependency of electricity grid and natural gas network has been gradually extending from the transmission level to the distribution level as a result of the technical and financial benefits of distributed gas-fired generators. The interactions between electricity grid and natural gas network at generation, transmission, and distribution levels are highlighted in Figure 1. This review will focus on interactions of the two energy systems on generation and transmission levels.

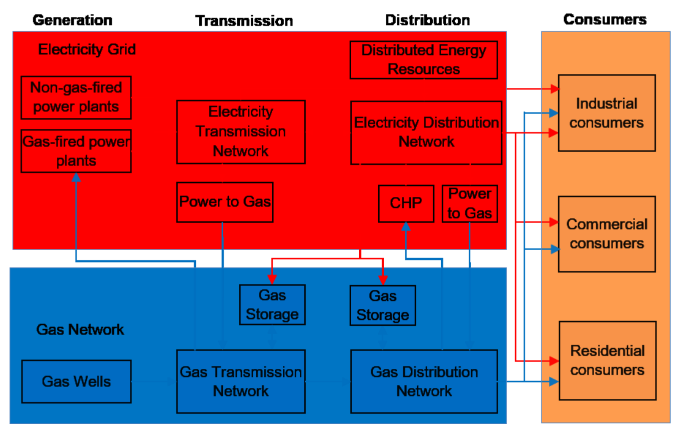

Fig. 1 Interaction between electric power system and natural gas system

Indeed, under the highly interdependent circumstance, the economic and secure operation of one energy systems would directly impact and be influenced by that of the other [6]-[7]. Specifically:

- *Interdependency in operation cost*: Gas market price will directly affect generation cost of the electric power system; while natural gas system operators are facing with more gas load volatility induced by gas-fired units whose dispatches are frequently adjusted more often to offset variations of electrical loads and renewable generations, which may in turn increase operation cost of the natural gas system.
- *Interdependency in secure operation*: Gas supplier outages, gas pipeline contingencies, and gas pressure losses could lead to forced outage of multiple gas-fired units; while outages of generators or electric transmission lines could result in the

shutdown of multiple electric-driven compressor stations.

Consequently, considering the strong interdependency, modeling and optimizing the electricity grid and the natural gas network as a whole integrated energy system (e.g., the interdependent electricity and natural gas system (IENS)) could increase the security and economy of both energy systems.

This paper provides a comprehensive review of the state-of-the-art researches in the field of the coordination of electricity and natural gas systems. This article first provides an overview of IENS, including the key coupling components and various coordination strategies. Next, coordinated short-term scheduling of the IENS is discussed, followed by a review of coordinated long-term expansion planning of the IENS as well as energy market and energy hub. Finally, challenges and potential future research directions in this field are discussed.

II. Interdependent Electricity and Natural Gas Systems

The electricity grid and the natural gas network are among the largest and most complex networked systems in the world. Indeed, effective and efficient generation and delivery of energy to individual consumers requires extensive and elaborate system facilities for energy production, transmission, and distribution. The two energy systems share certain similarities while also presenting distinct characteristics that would impact their operations, including:

- Similarity
  - *Energy Production*: generating units generate electricity while gas production wells produce natural gas, which are both restricted by their generation capacities.
  - *Energy Transportation*: transformers change voltage levels while compressor stations adjust gas network pressures, both of which can enhance energy transportation capabilities.
  - *Energy Delivery*: electricity is delivered via transmission/distribution power lines while natural gas is delivered via gas pipelines, both of which are constrained by their physical characteristics. That is, electricity delivery capability is simulated via Direct Current (DC)/ Alternating Current (AC) power flow models with linear/nonlinear equations [8]-[9], and the delivery of gas would follow partial differential equations (PDEs) [10]-[11] or Weymouth equations [12]-[13].
- Difference
  - *Speed of Energy Flow*: electricity travels at the speed of light, while natural gas travels much slower with the speed of 40-60 mi/h. Indeed, due to the compressibility of natural gas and its slower velocity, natural gas infrastructure presents a slower dynamics, and natural gas can be stored in pipelines known as line-pack. In turn, electric power supply and demand is balanced instantaneously, while it would take a longer time for natural gas system to balance gas production and the swings in gas demand.
  - *Energy Storage*: large-scale electric energy storage is still uneconomical with current development in storage technologies, while natural gas can be economically stored in large storage facilities and/or gas pipelines, whose flexibilities are beneficial in balancing daily/ seasonal gas demand variations or handling pipeline contingencies [14].

This section provides an overview on key coupling components of the IENS and various coordination strategies.

A. *Coupling Components*

Gas-fired units, electric-driven compressors, and PtG facilities represent linkages between the electricity grid and the natural gas network. Specifically, in an IENS, the electricity grid relies on the natural gas network for supplying gas fuel to gas-fired units and absorbing natural gas converted from PtG facilities, while the natural gas network relies on the electricity grid to operate electric-driven gas compressors for facilitating natural gas transportation.

- *Gas-fired Units*

Gas-fired units consume natural gas to generate electricity, which leads to a growing reliance of the electricity grid on the natural gas network. Accordingly, several concerns on interdependent reliability between the two energy systems need be carefully considered.

1) Unlike coal and oil, natural gas is usually not stored on-site. That is, gas-fired units rely on just-in-time delivery of gas fuel through the natural gas network.
2) Residential gas loads have higher priorities than gas-fired power plants. Thus, peak gas demands of these natural gas end-users could significantly affect the delivery of interruptible gas service to gas-fired power plants.
3) As an inspiring feature for offering flexible dispatch and fast ramping capabilities, gas-fired units are expected to play an important role in offsetting variability and uncertainty associated with renewable resources. In turn, the natural gas network needs to provide enhanced operational flexibility for supporting volatile gas demands of gas-fired units.

Gas-fired generating units include single-cycle gas turbines, combined-cycle gas plants, and dual-fuel generating units. A single-cycle gas turbine is a combustion engine that converts natural gas into mechanical energy, which further drives a generator to produce electricity. A combined-cycle unit includes multiple gas turbines and steam units, in which each gas turbine operates in the same way as regular single-cycle gas turbines, while waste heat from gas turbines is collected toward steam units to generates extra power [15]-[16]. A fuel-switching unit could switch from natural gas to other fuel types when facing with gas fuel shortage during natural gas peak demand periods, and this fuel diversity could be very effective in shaving peak gas demands and maintaining the security and economy of IENS [17]-[18].

Gas consumption of a gas-fired unit is modeled as in (1).

$$G_{it} = \left[F_i\left(P_{it}\right) + SU_{it} + SD_{it} \right] / \mathrm{HHV} \tag{1}$$

where i and t are respectively indices of gas turbines and time periods; P_{it} and G_{it} are respectively real power output and gas fuel consumption of gas-fired unit i at time t; $F_i(\cdot)$ represents heat rate curve of gas-fired unit i; SU_{it} and SD_{it} are respectively startup and shutdown gas consumptions of gas-fired unit i at time t; HHV is the high heating value that equals to 1.026 MBtu/kcf.

- *Gas Compressor Stations*

Compressor stations facilitate the transportation of natural gas from one location to another by increasing natural gas pressure. Because distance, friction, and elevation difference slow down the movement of natural gas and reduce pressure, compressor stations are deployed along the pipeline route to maintain gas network pressures. Compressor stations are mainly driven by two types of engines: 1) gas-fueled compressors that consume natural gas in pipelines to drive gas turbines or reciprocating engines; and 2) electric-driven compressors that are powered by high voltage electric motors and considered as electrical loads in the electricity grid. The detailed model of a gas compressor located between outlet node m and inlet node n of the natural gas network is presented as in (2)-(4), where Equation (2) describes relationship of pressures on two terminals of the gas compressor and Equations (3)-(4) calculate energy consumption of a gas compressor [19]-[21].

$$R_c^{\min} \le \max(\pi_{mt}, \pi_{nt}) / \min(\pi_{mt}, \pi_{nt}) \le R_c^{\max} \tag{2}$$

$$H_{ct} = \theta_c \cdot G_{ct} \cdot \left[\left(\pi_{mt} / \pi_{nt} \right)^{Z_c \cdot ((\delta_c - 1)/\delta_c)} - 1 \right] \tag{3}$$

$$Q_{ct}\left(H_{ct}\right) = a_c \cdot H_{ct}^2 + b_c \cdot H_{ct} + d_c \tag{4}$$

where c is index of compressor stations; π_{mt}/π_{nt} is gas pressure of node m/n at time t; $R_c^{\min} / R_c^{\max}$ is the minimum/maximum compressor ratio; H_{ct} represents the horsepower needed to increase gas pressure from π_{nt} to π_{mt}; G_{ct} is gas flow through gas compressor c at time t; θ_c, Z_c, and δ_c are compressor constant, compressibility factor, and specific heat ratio; a_c, b_c, and d_c are coefficients. An electric-driven compressor is directly considered as an electric load with the demand of H_{ct} in the electricity grid, while a gas-fueled compressor is considered as a gas load with $Q_{ct}(\cdot)$ being the quantity of natural gas needed to produce the required amount of horsepower.

However, the nonlinear gas compressor model (2)-(4) could impose great challenges on tractability and computational efficiency. Typically, simplified energy consumption models (5)-(6) [22]-[23] are usually used, where β_c^1 and β_c^2 are constant energy consumption factors to calculate electricity and natural gas consumptions. For instance, β_c^2 could take the value of 0.03-0.05, as compressor stations normally consume about 3-5% of the total transported gas.

$$H_{ct} = \beta_c^1 \cdot G_{ct} \tag{5}$$

$$Q_{ct} = \beta_c^2 \cdot G_{ct} \tag{6}$$

- *PtG Facilities*

Traditionally, excessive renewable energy could be absorbed by electric energy storage assets such as batteries, pumped storage devices, or compressed air facilities. However, due to technical restrictions and economic considerations, these techniques usually can only provide very limited energy storage capacities.

In comparison, the natural gas network, line-pack of pipelines especially, presents itself as a perfect gas storage medium. Specifically, PtG, as a new promising technology, could effectively convert excessive renewable energy into compatible natural gas that can be potentially stored, transported, and reutilized via the existing natural gas infrastructure. In turn, the energy waste in terms of renewable energy curtailment can be effectively mitigated. Indeed, existing researches [24] agree that PtG facilities can benefit the electric power system in terms of facilitating load leveling, enhancing renewable energy utilization, and providing ancillary services [7].

PtG consumes electricity to produce hydrogen or synthetic natural gas. PtG contains two main processes [25]: 1) electrolysis which converts electric power into hydrogen, and 2) methanization which further converts hydrogen along with carbon dioxide into methane. Typically, efficiencies of converting electricity to hydrogen and further to methane are about 54%-77% and 49%-65%, respectively [26]. In addition, in practice, there are technical and legislative restrictions on the amount of hydrogen that can be blended into the natural gas network, whereas methane is compatible with natural gas and no such restrictions exist.

PtG facilities present themselves as electrical loads in the electricity grid, and as gas producers in the natural gas network. That is, PtG facilities consume electricity from the electricity grid and deliver gas into the natural gas network, which can be modeled through energy conversion factor ϕ, efficiency η_a, and HHV as in (7) [24], [27]-[28].

$$G_{at} = \phi \cdot P_{at} \cdot \eta_a / \mathrm{HHV} \tag{7}$$

B. *where a is index of compressor stations, and ϕ =3.4 MBtu/ MWh.Coordination Strategies*

As interdependency of the electricity grid and the natural gas network is being intensified, it may not be practically reasonable or physically feasible to model the two energy systems separately and optimize them individually. Four types of coordination strategies have been discussed in literature, to address interdependency between the electricity grid and the natural gas network.

1) *Incorporating natural gas network constraints into power system optimization models* (i.e., security-constrained unit commitment). It has been well recognized that natural gas transmission capacities may be unavailable for delivering gas fuel to gas-fired units due to the higher priority of residential gas loads, especially when electrical loads and gas loads peak at the same time. In this case, supply-demand balance in the electric power system could be impacted and unit commitment statuses of various types of generators need to be adjusted for security and economics purposes. In turn, power system researchers have included natural gas transmission constraints in the security-constrained unit commitment problem [17], [29]-[31]. Gas supply uncertainty and gas price variability are

also considered in [32] to study the effect of natural gas supply shortage on optimal scheduling of the electric power system.

2) *Incorporating dynamic gas consumptions of the electric power system into natural gas system optimization models*. A few natural gas system studies have investigated impacts of the rapid increase in gas-fired units on pressure levels and security of the natural gas network. Specifically, time-varying gas consumptions of gas-fired units are simulated in the natural gas optimization problem to explore the impact of a large fleet of gas-fired units [33]-[35] on daily operation efficiency of the natural gas network.

3) *Sequential optimization of the electricity grid and the natural gas network* [36]-[37]. [36] reported a study that optimizes the electricity and natural gas systems of Great Britain in a queue, which is summarized as follows: (i) The electric power system model is first solved to determine optimal schedule and fuel consumptions of individual generators including gas-fired units, while neglecting the natural gas system; (ii) The natural gas system model is solved with fixed gas demands from gas-fired units according to the solution from the electric power system model in (i); and (iii) If gas load shedding occurs in (ii), a heuristic method is sought for reducing power outputs and gas consumptions of gas-fired units in order to mitigate gas load shedding. However, it is noteworthy that this sequential strategy cannot guarantee global optimality of the IENS.

4) *Integrated co-optimization of the IENS*. Unlike the sequential coordination strategy, the integrated model considers the electricity grid and the natural gas network as a whole for minimizing the total cost associated with both energy systems. In turn, an optimal solution for the entire IENS can be achieved [24], [38]-[40]. Furthermore, considering policy restrictions that the electricity grid and the natural gas network may belong to different system operators and the information exchange could be limited, researchers have explored decentralized algorithms for deriving high-quality coordination solutions of the IENS while preserving decision independency and information privacy of the two systems [41]-[44].

III. Coordinated short-term scheduling

Coordinated short-term scheduling of the IENS determines optimal unit commitment and economic dispatch of generating units as well as gas productions of gas wells to meet electricity and gas demands. The obtained solution provides hourly schedule of generating units, natural gas production wells, and PtG facilities, as well as power flows in electric transmission lines and gas flows in pipelines. In this section, literatures on the coordinated short-term scheduling of the IENS are categorized according to different natural gas network models being used. In addition, studies on the impacts of PtG and line-pack on the coordinated short-term scheduling of the IENS are also reviewed.

A. Natural Gas Network Models

- *Transportation Gas Network Model*

This linear model simplifies the natural gas network as a transportation network while neglecting its distinct physical characteristics. The transportation model is presented as in (8)-(9) [17], [45]-[47], in which hourly pipeline gas flow is limited by the maximum pipeline transportation capacity (8) and daily maximum natural gas transported through a pipeline is further constrained via (9).

$$G_{pt} \le G_p^{\max} \tag{8}$$

$$\sum_t G_{pt} \le G_p^{\text{day,max}} \tag{9}$$

where p is index of pipelines; G_{pt} is average gas flow of pipeline p at time t; $G_p^{\max}$ and $G_p^{\text{day,max}}$ are hourly and daily maximum pipeline transportation capacities.

- However, as this model ignores the nonlinear relationship between gas flows and nodal pressures, it may lead to solutions of poor quality or even outside acceptable operational ranges of the IENS. In turn, this model is rarely used for studying coordinated scheduling of the IENS.*Transient-state Gas Network Model*

The transient natural gas network model is governed by a group of PDEs [10], [11], [39], which describe the time and space-coupled natural gas flows with complex boundary conditions. This transient model can simulate slower traveling speed of natural gas flows and derive results that closely match real-world operation status. However, the improved accuracy comes with the price of high computational burden [11], [39].

- Indeed, PDEs bring significant challenges to computational tractability of the coordinated short-term scheduling model. One way to approximate PDEs is through numerical methods, such as explicit finite-difference methods, implicit finite-difference methods, and finite element methods [48]. Implicit finite-difference methods solve equations involving dependent variables in both current and future time slots, and explicit finite-difference methods calculate dependent variables of future time slots via solutions of dependent variables at current time slot. Indeed, implicit methods are used more often because they offer the best performance in terms of numerical stability, efficiency, and high accuracy [49]-[50]. Specifically, Euler finite difference numerical technique is used to replace derivative expressions in space and time with difference quotients [10], [51]. Reference [52] uses Wendroff difference form to approximate solutions to gas flow PDEs. The Laplace transform is utilized in [11] to convert gas flow PDEs from time domain into frequency domain, which are further discretized into algebraic equations and solved by implicit finite-difference methods. *Steady-state Gas Network Model*

With a few assumptions [10], the transient model can be simplified to the well-known steady-state Weymouth gas flow equation (10)-(11), which is widely accepted and mostly used in coordinated short-term scheduling of the electricity grid and the natural gas network. In (10), gas flow in a pipeline is expressed as a nonlinear function of nodal pressures and pipeline characteristics.

$$G_{pt} = \text{sgn}(\pi_{mt}, \pi_{nt}) \cdot K_p^{\text{gf}} \cdot \sqrt{\left|\pi_{mt}^2 - \pi_{nt}^2\right|} \tag{10}$$

$$\text{sgn}(\pi_{mt}, \pi_{nt}) = \begin{cases} 1, & \pi_{mt} \geq \pi_{nt} \\ -1, & \pi_{mt} < \pi_{nt} \end{cases} \tag{11}$$

where K_p^{gf} is gas flow constant of pipeline *p*, which depends on characteristics of pipelines such as temperature, length, diameter, friction, and natural gas composition.

The sgn function in (10) can be represented as an equivalent linear model via the Big-M method with additional binary variables [24], [43]. However, the Weymouth equation is still nonlinear because of squared gas pressures. Researchers have proposed different methods, including Newton-Raphson method, piecewise linearization, and direct methods, to solve the coordinated scheduling of IENS with nonlinear Weymouth equations.

1) Newton-Raphson Method

Newton-Raphson method, which is similar to the Newton-Raphson-like method for solving the AC power flow problem of power systems, is popular in solving nonlinear equations. However, one drawback of Newton-Raphson method is that it requires a large number of iterations and the solution is sensitive to initial setting on the natural gas operating point.

Newton-Raphson method has been used to solve the natural gas allocation problem [29]-[30], [53]-[54] and obtain the unified power and gas flows [19]. [55]-[56]. Specifically, (i) In the coordinated short-term scheduling of electricity grid and the natural gas network, the gas allocation problem is usually formulated as a feasibility check subproblem, in which gas consumptions of gas-fired units are determined by the master unit commitment problem and non-negative gas load shedding variables are added to ensure its feasibility. If the cumulative amount of gas load shedding is larger than a predefined threshold, a corresponding natural gas usage cut will be generated and fed back to the master unit commitment (UC) problem for adjusting gas consumptions of gas-fired units; and (ii) In the unified power and gas flow analysis problems, Newton-Raphson method is applied to obtain a unified energy flow solution for the IENS where AC power flow model and nonlinear compressor model could be included.

2) Piecewise Linearization Method

Piecewise linearization approach approximates nonlinear Weymouth constraints via a set of piecewise linear equations, resulting in a mixed-integer linear programming (MILP) model that can be solved by commercial softwares like Gurobi and Cplex. Specifically, natural gas flow is approximated in a 3-D Euclidean space with a set of linear constraints in [31], [57]. Reference [58] compared three different models for linearizing quadratic terms of gas flows and node pressures in (10), including convex combination model, multiple choice model, and incremental model. Theoretical and computational analysis indicates that the incremental model outperforms the other two techniques. Indeed, the most promising advantage of incremental model is its computational performance for optimizing gas network operations [38], [59].

Piecewise linearization has been used in the coordinated short-term scheduling of electricity grid and natural gas network considering the security and uncertainty of the IENS. (i) Deterministic approaches are proposed in [38], [60]-[61] to analyze the interdependency of the electricity grid and natural gas network while neglecting uncertainties of the IENS. (ii) N-1 contingencies are included in [62]-[63] to ensure that the IENS is operated economically and securely so that any single contingency will not cause violations or load shedding. (iii) Stochastic optimization [31], [53], [57], interval optimization [64], and robust optimization [24], [43], [65]-[66] are applied to coordinate the IENS under uncertainties of electrical loads and wind generations.

3) Direct Methods to Solve the Nonlinear Model

Researchers have also proposed to use heuristic search algorithms or commercial nonlinear programming (NLP) solvers for directly solving the nonlinear optimization model. (i) Heuristic search algorithms, such as the elitist non-dominated sorting genetic algorithm (NSGA-II) [67] and gravitational search algorithm (GSA) [68], have been used in the coordinated short-term scheduling of electricity grid and natural gas network. A decision tree-based security dispatch is proposed in [69] to calculate the secure region of the IENS against credible contingencies that may lead to system violations. The advantage of these heuristic search algorithms is that multi-objectives could also be included to obtain solutions with diverse preferences instead of a single objective solely addressing the total operation cost [67]-[68]. (ii) With the recent development of commercial NLP solvers, a high quality suboptimal solution can be obtained. With the help of NLP solvers, more nonlinear constraints could be included to increase the system modeling accuracy, such as AC power flow model and nonlinear fuel consumption of compressors. Popular NLP solvers used by researchers include BONMIN 64, Xpress Optimization Suite [21], [70]-[71], IPOPT [28], and CONOPT3 [72].

B. Impact of PtG and Line-pack

PtG and line-pack could bring significant benefits to the coordinated short-term scheduling of the IENS. The advantage of introducing PtG in the coordinated scheduling of IENS is discussed in [28], [40], [43]. It is demonstrated that PtG can contribute in reducing renewable energy curtailment and relieving electricity transmission congestion by converting excessive generation into natural gas [21], [52]. It can also be utilized as additional gas reserve to supply gas demand during gas peak load periods [73].

Line-pack represents the quantity of natural gas stored in gas pipelines, which plays an important role in maintaining minimum offtake pressures, sustaining gas flow characteristics, and handling variations in gas demand that may not be balanced instantaneously by gas production wells [21], [28]. Specifically, line-pack capabilities provide the operational flexibility and reliability of the natural gas system to supply gas demand and gas-fired units. It is also indicated that line-pack can be effective tool to support gas loads when contingency in the natural gas network happens [62]. Line-pack of a pipeline is modeled as in (12)-(14) [36], [38], [43], which accounts for dynamic characteristics of the natural gas system via varying incoming and outgoing gas flows. Equation (12) illustrates that the line-pack of a pipeline is proportional to the average pressure of the pipeline. Therefore, increasing node pressures of a pipeline will increase the line-pack and vice versa. In addition, the change of total volume of natural gas contained in a pipeline is equal to the difference of incoming and outgoing gas flows (13), and (14) further calculates the average gas flow through a pipeline.

$$E_{pt} = K_p^{\text{lp}} \cdot \left(\pi_{mt} + \pi_{nt}\right) \Big/ 2 \tag{12}$$

$$E_{pt} = E_{p,t-1} + G_{pt}^{\text{in}} - G_{pt}^{\text{out}} \tag{13}$$

$$G_{pt} = \left(G_{pt}^{\text{in}} + G_{pt}^{\text{out}}\right) \Big/ 2 \tag{14}$$

where K_p^{lp} is the line-pack constant; E_{pt} represents the quantity of gas stored in pipeline p at time t; G_{pt}^{in} and G_{pt}^{out} are respectively incoming and outgoing gas flows of pipeline p at time t.

IV. Coordinated long-term expansion planning

The coordinated long-term expansion planning problem of the IENS determines the type, capacity, location, and time of new components to be invested over the planning horizon, for ensuring the reliable and cost-effective delivery of electricity and natural gas to end-users. The objective is to minimize the total investment cost and operation cost in order to supply electricity and natural gas demands, subject to a set of technical constraints and reliability criteria. In literature, candidate components to be invested in would include generators, transmission lines, PtG facilities, gas wells, pipelines, compressor stations, and gas storages. In addition, the simplified load block method is usually used in the long-term co-optimization expansion planning problem as a trade-off between computational efficiency and solution accuracy.

A. Deterministic Coordinated Expansion Planning

As availability of the natural gas has profound impacts on the power generation expansion planning, the effect of generation expansion planning, including gas-fired units, of the electricity grid on the natural gas network is studied in [74]. The electricity generation expansion planning models presented in [75] consider the interaction between electricity generation expansion with gas production, gas storage, and gas transportation capacities in the natural gas industry. On the other hand, network expansion planning of the IENS is studied in [76] where optimal investment in candidate assets including electricity transmission lines and gas pipelines, together with compressors and gas storage facilities, is considered.

It is well recognized that the co-optimized expansion planning of energy production and transmission can obtain more satisfactory results in comparison to separate solutions. Reference [77] was among the first to study integrated production and transmission expansion planning of IENS with a multi-area and multistage model, which jointly incorporates the natural gas value chain and the electric power value chain. Since then, considering that natural gas flow model has more significant influence on computational time, a multi-period integrated framework for the electricity generation expansion planning, electricity transmission expansion planning, and natural gas network expansion planning [78] is developed to effectively solve expansion planning problem of large-scale systems. [79] discussed an integrated gas and electricity planning model, in order to effectively cut carbon emission of power systems and achieve higher market efficiency in the cost benefit analysis. Furthermore, in recognizing that the nonlinearity of IENS introduced by AC power flow and Weymouth gas equation brings significant challenges in solving the expansion planning problem, new linearization techniques [80] and convexification approaches [81] are used to transform nonlinear convex problems into computationally tractable convex optimization models. A novel piecewise linear approximation and first-order Taylor series approximation based linear reformulation approach is introduced in [80] to further enhance computational efficiency. In addition, a computationally tractable convex formulation for the expansion planning of the IENS is proposed in [81], by applying the second-order cone relaxation to the nonlinear non-convex AC power flow model and the Weymouth gas flow equations.

B. Coordinated Expansion Planning with Uncertainties

In the long-term expansion planning problem, system planners are facing with various uncertainties such as energy price fluctuation, system load growth uncertainties, availability of production resources/transmission facilities, and retirement/ replacement of system components. Thus, it is of practical importance to take these uncertainty factors into account when making reliable system expansion planning decisions.

Reliable electricity delivery is of the core value in the entire power industry, which could be evaluated via deterministic or probabilistic reliability criteria. The deterministic N-1 criterion is widely used in electricity grid planning to ensure system reliability, which requires that the normal operation should be maintained without any loss-of-load under any single contingency outage. The N-1 criterion is incorporated in [82]-[83] to derive reliable expansion plans of the IENS. On the other hand, probabilistic reliability criteria consider stochastic nature of system component outages, i.e., simultaneous outages of multiple generators and/or transmission lines [84]. Probabilistic reliability-based criteria are used in the joint expansion planning of IENS to ensure that the electricity grid would meet certain reliability requirements, such as expected-energy-not-supplied (EENS) [85]-[86], loss-of-energy-probability (LOEP) [87], and loss-of-load-expectation (LOLE) [88]. Reference [23] further proposes a joint N-1 and probabilistic reliability criterion for the IENS, in order to derive a balanced solution that adequately addresses low-probability/high-impact events while also ensuring the overall reliability. However, such deterministic N-1 and probabilistic reliability criteria are usually applicable in evaluating reliability of the electricity grid [80], [86], while similar reliability evaluation criterion for the natural gas network is to be developed and incorporated in the expansion planning of IENS for ensuring effective multi-energy delivery.

Moreover, various optimization techniques, such as stochastic programming and robust optimization, have also been applied to solve coordinated expansion planning problems with uncertainties. (i) Stochastic programming based expansion planning of the IENS generates multiple scenarios for simulating uncertainties of electricity/gas loads and gas prices, as well as random outages of system components [83]. Furthermore, as large numbers of scenarios would increase the computation burden, scenario reduction technique is often used to achieve a higher computational performance [89]-[90] for the coordinated expansion planning problem. (ii) Robust optimization-based tools [23], [91] have also been applied for the coordinated expansion planning of the IENS, to counter worst-case scenarios that result in the most severe damage to the interdependent infrastructures. Specifically, the worst-case scenarios can be identified through security checking subproblems and iteratively added into the master problem for deriving robust solutions.

The positive role of PtG investment for handling uncertainties has also been studied in [23], [92]-[93]. It is concluded in [23] that the investment of PtG can facilitate a deeper penetration of renewable energy and postpone the construction of expensive transmission lines. It is also shown in [92]-[93] that PtG can help reduce the operation cost with less wind curtailment, gas consumption, and carbon emission.

V. ENERGY MARKETS AND ENERGY HUB

A. *Energy Market Integration*

The energy industry continues to evolve, driven by various factors that may shape the future energy system operation, transaction, and management. The restructuring of electricity industry began in the 1990s to create competitive electricity markets for wholesale electricity [94]. It allows new players to play a role as market participants and have non-discriminatory access to the infrastructure. In addition, independent system operator (ISO) has the responsibility of ensuring the real-time energy balance and maintaining reliability of the bulk electric system. Locational marginal pricing (LMP) mechanism is widely used as wholesale electric energy price to reflect the value of electric energy at different times/locations, accounting for patterns of loads, generations, and physical limits of the transmission network. The major commodities traded in electric markets are energy, transmission service, and ancillary service.

In comparison, the natural gas industry structure has changed dramatically since 1980s, by unbundling the interstate pipeline transportation for a fully competitive wholesale market [95]. The price of natural gas is dependent on supply and demand interactions, which promote the development of market centers and hubs. Hubs are typically operated by several interstate pipeline companies and allow market participants to acquire natural gas from several independent sources through the gas network. Furthermore, deregulation of the natural gas industry has facilitated physical and financial gas markets with various trading options for producers, marketers, and distribution companies to better manage the cost and risk.

Indeed, the increasing role of natural gas in electricity generation has raised significant interests in coordinating natural gas and electricity in terms of energy market design and pricing in addition to market scheduling. The impacts of natural gas network on a unit commitment-based market scheduling model are thoroughly discussed in [29], [31], [54], [57], [65]. In addition, demand response, renewable energy, and flexible ramping could help relieve the reliance on natural gas availability, reduce the system operations cost, and mitigate the risk posed by natural gas shortage. Furthermore, interruptible-load based and coupon-based demand response resources are introduced in [96] as virtual power plants to trade in the market, which help stabilize electricity locational marginal prices and relieve the gas network congestion.

The references mentioned above adopt scheduling model to investigate coordination issues from the market operators' view. In comparison, [97] proposed a model from the perspective of gas-fired power plant, which optimizes operation cost in a competitive electricity market while taking into consideration of gas purchases, gas capacity contracting, and residual demand uncertainty induced by renewable energy sources. Similarly, [98] discussed a methodology that incorporates characteristics of both natural gas supply contracts and gas system congestion to support gas generator owner's decision-making process for participating in electricity market. Typically, an energy company that participants in electricity and gas markets usually have independent decision-making processes with two distinct optimization models. Reference [99] presents two methodologies for coupling electricity and gas market models to explore optimal coordinated solutions, which allow more synergies and result in a competitive advantage over traditional strategies.

In addition, with growing natural gas-fired generations in the market, strategic behaviors of gas producers may also influence the electricity market operation. A computational game theoretic investment model is discussed in [100] with intent to demonstrate and assess market power of gas producers in the electricity market. Furthermore, driven by strategic offering behaviors of producers, the equilibrium of the coupled gas and electricity markets is discussed in [101] using a special diagonalization algorithm. The unilateral equilibrium of the electricity or gas market is found in the inner loop given the rivals' strategies, while interactions of the two markets are tackled in the outer loop.

Currently, the electricity and natural gas pricing are independently settled with two separate markets, even though the impact exists as aforementioned. A combined natural gas and electricity network pricing mechanism is presented in [102], which applies the main wheeling charge methods, such as MW/gas-mile, invested related asset cost (IRAC) and Aumman-Shapley allocation to both electricity and gas network. A combined pricing will enable the synergies and derive more accurate economic signals for incentivizing effective coordinated operation scheduling and expansion planning of the IENS.

B. *Energy Hub -A New Model for Energy Infrastructure*

The fundamental difference between an energy hub and a traditional energy system for interconnecting multiple electricity and natural gas components is that, loads within an energy hub can be supplied by multiple carriers for minimizing the total cost. From the system's point of view, an energy hub features input, output, conversion, and storage of multiple energy systems in a functional unit. This feature provides a new view to reevaluate the interdependency issues between the electricity grid and the natural gas system.

The energy hub concept is first introduced in [103]-[104] to investigate combined economic dispatch and optimal power flow (OPF) problems pertaining to the multiple energy carriers system. Further discussions on future energy system are presented in [105]-[106]. Specifically, an energy hub represents an interface between energy participants (producers and consumers) and various energy system carriers. In addition, the introduction of energy storage, demand-side management, and renewable energy into the energy hub model further highlights the role of energy hub in improving efficiency of multiple energy carriers system [107]-[109]. An approach in [107] considers optimal couplings (i.e., an energy hub structure) among multiple energy networks consisting of electricity, natural gas, and district heating loads. Reference [108] aims to concentrate on the economic dispatch of multiple energy carriers at the presence of uncertain renewable energy resources. In addition, researchers demonstrate the value of applying the energy hub model in system expansion planning [88], [109]. A financial investment valuation method is proposed in [110] for energy hubs with conversion, storage, and demand-side management capabilities, which assesses the values added to individual infrastructures. A portfolio theory based integrated planning approach is discussed in [111], which calculates the optimal portfolio and relative shares of energy supplies.

The growing interests on energy hubs also bring discussions into the scope of advanced management strategy with emerging technologies, markets, and pricing mechanisms. A bi-level stochastic programming based decision-making model for an energy hub manager is presented in [112] for managing the hub operation cost under energy price uncertainties. A probabilistic optimization approach is proposed in [113] to operate a renewable-based residential energy hub deployed with plug-in hybrid electric vehicles and rooftop solar panels. A competitive equilibrium of energy hub interactions in a dynamic pricing energy market is presented in [114], which inspires the effort to determine the equilibrium using various algorithms.

VI. Conclusion and Future Research Directions

This paper discusses the key coupling components that connect the electricity grid and the natural gas network, and reviews the state-of-the-art coordination of interdependent electricity and natural gas systems in three major aspects. Based on the review, it is noticed that the following potential research opportunities could further benefit the secure, reliable, and economic operation and planning of future IENS.

A. *Nonlinearity of the Natural Gas Network*

Linear transportation model of the natural gas network could be implemented in the long-term expansion planning problem, such as decomposition-based security-constrained co-optimization planning [87] and robust optimization-based planning [91]. However, applying this simplified model to the coordinated short-term scheduling problems could lead to solutions of poor quality or even outside acceptable operational ranges of the IENS. On the other hand, the more accurate nonlinear Weymouth gas flow equation brings significant challenges to the decomposition-based and robust optimization-based algorithms, because efficiency of both algorithms highly depends on linearity of the natural gas operation subproblem [24], [62]. A conventional approach is to convexify the nonlinear Weymouth gas flow constraints, so that natural gas operation subproblems can feedback valid cutting planes for obtaining the coordinated optimal solution [29]-[30].

Future researches could include the following two aspects for handling nonlinearity of the natural gas network.

1) Convexification of nonlinear Weymouth equations. With convexified Weymouth equations for the natural gas network, more sophisticated algorithms such robust optimization can be implemented to consider uncertainties associated with gas demands and pipeline contingencies. Consequently, the influence of uncertainties of the gas network on the electric power system operation can be studied.

2) Improving linear energy consumption models of gas compressors. The linear energy consumption function of gas compressor stations presented in the paper loses the pressure information in the original nonlinear form. A more accurate linear model for energy consumption of compressor stations could further increase solution accuracy of the natural gas problem.

B. *Coordination in Other Aspects*

Future research on the coordination of the IENS would include the following four directions.

1) Heterogeneous components coupling the electricity grid and the natural gas network need to be accurately simulated for representing practical situations. Specifically, specific roles of combined-cycle gas turbines, dual-fuel generating units, and PtG facilities in the coordinated scheduling and planning of the IENS with respect to different load and renewable generation levels and under various uncertainties could been fully analyzed.

2) Demand response capabilities of electricity loads and

natural gas loads as well as their uncertainties would be included in the coordinated scheduling and planning of the IENS. Demand response resources in the electricity grid have been well recognized and are being deployed, while those of the natural gas system are still at the beginning stage. The wide development and deployment of demand response techniques in the natural gas system could further promote the growing integration of gas-fired units and enhance the coordinated optimal operation of future IENS.

3) The coordinated operation of electricity and natural gas distribution systems with gas-fired distributed generations, PtG, and distributed renewable energy resources needs to be investigated. Several studies have focused on the expansion planning of the electric power and natural gas distribution systems [37], [115]-[117]. However, with a deeper penetration of distributed renewable generations in the near future, the coordination of electricity and natural gas systems at the distribution level while considering the positive effect of PtGs needs further attentions.

4) Resilience enhancement of interdependent electricity and natural gas infrastructures plays a key role in energy resiliency of our modern society. Indeed, during a natural disaster, resilience of the electricity grid and the natural gas network are highly dependent on each other. That is, loss of a power line or shutdown of a pipeline can easily spread to the other system and further lead to cascading failures in the IENS. However, although coordinated scheduling of the IENS in normal situations has been extensively studied, studies of the IENS from the resilience perspective are rather limited.

5) With an integrated energy market model set up in the future, a comprehensive market framework that incorporates both electricity and gas into market clearing processes needs to be considered and designed. Currently, electricity and natural gas pricing are independently organized and determined with two separate markets. The coordination mechanism and integration of these two markets is still staying at a preliminary stage. Mutual impacts between these two systems have been studied largely from the perspective of impact of gas shortage on electric system operation cost. The role of ever-growing gas-fired generators on driving future natural gas price in gas market transaction process could be potential interests for both market participants. Advanced energy management strategies and market interaction involved in a multiple energy system are also worth investigating.

6) Energy hub is a prototype of integrating multiple forms of energy carrier into one single model for system operation and planning. In comparison to existing electric and natural gas network systems, energy hub is more applied as a tool to analyze a multi-energy networked system that is in research frame without much industry practice. Future interests can be considering a more practical multiple energy system to address the issues faced by real operations. Furthermore, most of the energy hub systems in previous works adopt simplified linear models for simulating devices in the hub as well as the network, while solution accurately could be significantly improved if the original non-linear models are used.

References

[1] IEA, World Energy Outlook, 2011, [Online]. Available: http://www.worldenergyoutlook.org/weo2011/.

[2] EIA, Monthly Energy Review, 2016, [Online]. Available: http://www.eia.gov/totalenergy/data/monthly/#naturalgas/.

[3] NERC. Accommodating an Increased Dependence on Natural Gas for Electric Power, 2013. [Online]. Available: http://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_PhaseII_FINAL.pdf.

[4] Gahleitner G. Hydrogen from renewable electricity: an international review of power-to-gas pilot plants for stationary applications. Int J Hydrogen Energy 2013;38:2039-2061.

[5] Guandalini G, Campanari S, Romano M. Power-to-gas plants and gas turbines for improved wind energy dispatchability: Energy and economic assessment. Appl Energy 2015;147:117-130.

[6] Shahidehpour M, Yong Fu, Wiedman T. Impact of natural gas infrastructure on electric power systems. Proc IEEE 2005;93:1042-1056.

[7] Tor O, Shahidehpour M. Crossroads of Power. IEEE Power Energy Mag 2014;12:49-62.

[8] Dai C, Wu L, Wu H. A multi-band uncertainty set based robust SCUC with spatial and temporal budget constraints. IEEE Trans Power Syst 2016;31:4988-5000.

[9] Liu Y, Li J, Wu L, Ortmeyer T. Chordal relaxation based ACOPF for unbalanced distribution systems with DERs and voltage regulation devices. IEEE Trans Power Syst 2017; (to appear).

[10] Liu C, Shahidehpour M, Wang J. Coordinated scheduling of electricity and natural gas infrastructures with a transient model for natural gas flow. Chaos 2011;21:1-12.

[11] Zhou Y, Gu C, Wu H, Song Y. An equivalent model of gas networks for dynamic analysis of gas-electricity systems. IEEE Trans Power Syst 2017; (to appear).

[12] Menon E, Gas pipeline hydraulics. Boca Raton, FL, USA: Taylor & Francis, 2005.

[13] Ríos-Mercado RZ, Borraz-Sánchez C. Optimization problems in natural gas transportation systems: A state-of-the-art review. Appl Energy 2015;147:536-555.

[14] Thompson M. Natural gas storage valuation, optimization, market and credit risk management. J Commod Mark 2016;2:26-44.

[15] Liu C, Shahidehpour M, Li Z, Fotuhi-Firuzabad M. Component and mode models for the short-term scheduling of combined-cycle units. IEEE Trans Power Syst 2009;24:976-990.

[16] Morales-Espana G, Correa-Posada C, Ramos A. Tight and compact MIP formulation of configuration-based combined-cycle units. IEEE Trans Power Syst 2016;31:1350-1359.

[17] Li T, Eremia M, Shahidehpour M. Interdependency of natural gas network and power system security. IEEE Trans Power Syst 2008;23:1817-1824.

[18] Lu B, Shahidehpour M. Unit commitment with flexible generating units. IEEE Trans Power Syst 2015;20:1022-1034.

[19] Zeng Q, Fang J, Li J, Chen Z. Steady-state analysis of the integrated natural gas and electric power system with bi-directional energy conversion. Appl Energy 2016;184:1483-1492.

[20] Zheng J, Wu Q, Jing Z. Coordinated scheduling strategy to optimize conflicting benefits for daily operation of integrated electricity and gas networks. Appl Energy 2017;192:370-381.

[21] Qadrdan M, Ameli H, Strbac G, Jenkins N. Efficacy of options to address balancing challenges: Integrated gas and electricity perspectives. Appl Energy 2017;190:181-190.

[22] Wu S, Ríos-Mercado R, Boyd E, Scott L. Model relaxations for the fuel

cost minimization of steady-state gas pipeline networks. Math Comput Model 2000;31:197-220.

[23] He C, Wu L, Liu T, Bie Z. Robust Co-optimization Planning of Interdependent Electricity and Natural Gas Systems with a Joint N-1 and Probabilistic Reliability Criterion. IEEE Trans Power Syst 2017;(to appear).

[24] He C, Liu T, Wu L, Shahidehpour M. Robust coordination of interdependent electricity and natural gas systems in day-ahead scheduling for facilitating volatile renewable generations via power-to-gas technology. J Mod Power Syst Clean Energy 2017;5:375-388.

[25] Götz M, Lefebvre J, Mörs F, McDaniel Koch A, Graf F, Bajohr S, Reimert R, Kolb T. Renewable Power-to-Gas: A technological and economic review. Renew Energy 2016;85:1371-1390.

[26] Jentsch M, Trost T, Sterner M. Optimal use of Power-to-Gas energy storage systems in an 85% renewable energy scenario. Energy Procedia 2014;46:254-261.

[27] Qadrdan M, Abeysekera M, Chaudry M, Wu J, Jenkins N. Role of power-to-gas in an integrated gas and electricity system in Great Britain. Int J Hydrogen Energy 2015;40:5763-5775.

[28] Sun G, Chen S, Wei Z, Chen S. Multi-period integrated natural gas and electric power system probabilistic optimal power flow incorporating power-to-gas units. J Mod Power Syst Clean Energy 2017;5:412-423.

[29] Liu C, Shahidehpour M, Fu Y, Li Z. Security-constrained unit commitment with natural gas transmission constraints. IEEE Trans Power Syst 2009;24:1523-1536.

[30] Alabdulwahab A, Abusorrah A, Zhang X, Shahidehpour M. Coordination of interdependent natural gas and electricity infrastructures for firming the variability of wind energy in stochastic day-ahead scheduling. IEEE Trans Sustain Energy 2015;6:606-615.

[31] Zhang X, Shahidehpour M, Alabdulwahab A, Abusorrah A. Hourly electricity demand response in the stochastic day-ahead scheduling of coordinated electricity and natural gas networks. IEEE Trans Power Syst 2016;31:592-601.

[32] Zhao B, Conejo AJ, Sioshansi R. Unit commitment under gas-supply uncertainty and gas-price variability. IEEE Trans Power Syst 2017;32:2394-2405.

[33] Chertkov M, Fisher M, Backhaus S, Bent R, Misra S. Pressure fluctuations in natural gas networks caused by gas-electric coupling. 48th Hawaii Int Conf Syst Sci 2015: 2738-2747.

[34] Hejazi A, Mashhadi H. Effects of natural gas network on optimal operation of gas-fired power plants. 6th Conf Therm Power Plants. 2016:105-110.

[35] Behrooz H, Boozarjomehry R. Dynamic optimization of natural gas networks under customer demand uncertainties. Energy 2017;134:968-983.

[36] Qadrdan M, Wu J, Jenkins N, Ekanayake J. Operating strategies for a GB integrated gas and electricity network considering the uncertainty in wind power forecasts. IEEE Trans Sustain Energy 2014;5:128-138.

[37] Odetayo B, MacCormack J, Rosehart W, Zareipour H. A sequential planning approach for distributed generation and natural gas networks. Energy 2017;127:428-437.

[38] Correa-posada C, Sánchez-martín P. Integrated power and natural gas model for energy adequacy in short-term operation. IEEE Trans Power Syst 2015;30:3347-3355.

[39] Zlotnik A, Roald L, Backhaus S, Chertkov M, Andersson G. Coordinated scheduling for interdependent electric power and natural gas infrastructures. IEEE Trans Power Syst 2017;32:600-610.

[40] Li G, Zhang R, Jiang T, Chen H, Bai L, Li X. Security-constrained bi-level economic dispatch model for integrated natural gas and electricity systems considering wind power and power-to-gas process. Appl Energy 2016;194:696-704.

[41] Liu C, Shahidehpour M, Wang J. Application of augmented Lagrangian relaxation to coordinated scheduling of interdependent hydrothermal power and natural gas systems. IET Gener Transm Distrib 2010;4:1314-1325.

[42] Alkano D, Scherpen J. Distributed supply coordination for Power-to-Gas facilities embedded in energy grids. IEEE Trans Smart Grid 2017; (to appear).

[43] He C, Wu L, Liu T, Shahidehpour M. Robust Co-optimization scheduling of electricity and natural gas systems via ADMM. IEEE Trans Sustain Energy 2017;8:658-670.

[44] Wen Y, Qu X, Li W, Liu X, Ye X. Synergistic operation of electricity and natural gas networks via ADMM. IEEE Trans Smart Grid 2017; (to appear).

[45] Qadrdan M, Chaudry M, Wu J, Jenkins N, Ekanayake J. Impact of a large penetration of wind generation on the GB gas network. Energy Policy 2010;38:5684-5695.

[46] Sahin C, Li Z, Shahidehpour M, Erkmen I. Impact of natural gas system on risk-constrained midterm hydrothermal scheduling. IEEE Trans Power Syst 2011;26:520-531.

[47] Wu L, Shahidehpour M. Optimal coordination of stochastic hydro and natural gas supplies in midterm operation of power systems. IET Gener Transm Distrib 2011;5:577-587.

[48] Behbahani-Nejad M, Bagheri A. The accuracy and efficiency of a MATLAB-Simulink library for transient flow simulation of gas pipelines and networks. J Pet Sci Eng 2010;70:256-265.

[49] Pambour K, Cakir Erdener B, Bolado-Lavin R, Dijkema G. SAInt-A novel quasi-dynamic model for assessing security of supply in coupled gas and electricity transmission networks. Appl Energy 2017;203:829-857.

[50] Clegg S, Mancarella P. Integrated modeling and assessment of the operational impact of Power-to-Gas (P2G) on electrical and gas transmission networks. IEEE Trans Sustain Energy 2015;6:1234-1244.

[51] Yang J, Zhang N, Kang C, Xia Q. Effect of natural gas flow dynamics in robust generation scheduling under wind uncertainty. IEEE Trans Power Syst 2017; (to appear).

[52] Fang J, Zeng Q, Ai X, Chen Z, Wen J. Dynamic optimal energy flow in the integrated natural gas and electrical power systems. IEEE Trans Sustain Energy 2017; (to appear).

[53] Kamalinia S, Wu L, Member S, Shahidehpour M. Stochastic midterm coordination of hydro and natural gas flexibilities for wind energy integration. IEEE Trans Sustain Energy 2014;5:1070-1079.

[54] Xiaping Zhang, Liang Che, Shahidehpour M. Impact of natural gas system on short-term scheduling with volatile renewable energy. 2015 IEEE Power Energy Soc Gen Meet 2015;2015:1-5.

[55] Qiao Z, Guo Q, Sun H, Pan Z, Liu Y, Xiong W. An interval gas flow analysis in natural gas and electricity coupled networks considering the uncertainty of wind power. Appl Energy 2017;201:343-353.

[56] Hu Y, Lian H, Bie Z, Zhou B. Unified probabilistic gas and power flow. J Mod Power Syst Clean Energy 2017;5:400-411.

[57] Zhang X, Che L, Shahidehpour M, Alabdulwahab A, Abusorrah A. Electricity-natural gas operation planning with hourly demand response for deployment of flexible ramp. IEEE Trans Sustain Energy 2016;7:996-1004.

[58] Correa-Posada C and Sanchez-Martion P. Gas network optimization: A comparison of piecewise linear models. 2014. [Online]. Available: http://www.optimization-online.org/DB_FILE/2014/10/4580.pdf

[59] Sirvent M, Kanelakis N, Geißler B, Biskas P. Linearized model for optimization of coupled electricity and natural gas systems. J Mod Power Syst Clean Energy 2017;5:364-374.

[60] Urbina M, Li Z. A combined model for analyzing the interdependency of electrical and gas systems. 39th North Am Power Symp NAPS 2007:468-472.

[61] Chen S, Wei Z, Sun G, Sun Y, Zang H, Zhu Y. Optimal power and gas flow with a limited number of control actions. IEEE Trans Smart Grid 2017; (to appear).

[62] Correa-Posada C, Sánchez-Martín P, Lumbreras S. Security-constrained model for integrated power and natural-gas system. J Mod Power Syst Clean Energy 2017;5:326-336.

[63] Correa-Posada C, Sánchez-Martin P. Security-constrained optimal power and natural-gas flow. IEEE Trans Power Syst 2014;29:1780-1787.

[64] Bai L, Li F, Cui H, Jiang T, Sun H, Zhu J. Interval optimization based operating strategy for gas-electricity integrated energy systems considering demand response and wind uncertainty. Appl Energy 2016;167:270-279.

[65] Liu C, Lee C, Shahidehpour M. Look ahead robust scheduling of wind-thermal system with considering natural gas congestion. IEEE

Trans Power Syst 2015;30:544-545.
[66] Bai L, Li F, Jiang T, Jia H. Robust scheduling for wind integrated energy systems considering gas pipeline and power transmission N-1 contingencies. IEEE Trans Power Syst 2017;32:1582-1584.
[67] Kou Y, Zheng J, Li Z, Wu Q. Many-objective optimization for coordinated operation of integrated electricity and gas network. J Mod Power Syst Clean Energy 2017;5:350-363.
[68] Sardou I, Khodayar M, Ameli M. Coordinated operation of natural gas and electricity networks with microgrid aggregators. IEEE Trans Smart Grid 2017; (to appear).
[69] Costa D, Nunes M, Vieira J, Bezerra U. Decision tree-based security dispatch application in integrated electric power and natural-gas networks. Electr Power Syst Res 2016;141:442-429.
[70] Ameli H, Qadrdan M, Strbac G. Value of gas network infrastructure flexibility in supporting cost effective operation of power systems. Appl Energy 2017;202:571-580.
[71] Devlin J, Li K, Higgins P, Foley A. A multi vector energy analysis for interconnected power and gas systems. Appl Energy 2017;192:315-328.
[72] Chen S, Wei Z, Sun G, Cheung K, Wang D. Identifying optimal energy flow solvability in electricity-gas integrated energy systems. IEEE Trans Sustain Energy 2017;8:846-854.
[73] Chen S, Wei Z, Sun G, Cheung K, Sun Y. Multi-linear probabilistic energy flow analysis of integrated electrical and natural-gas systems. IEEE Trans Power Syst 2017;32:1970-1979.
[74] Qadrdan M, Chaudry M, Jenkins N, Baruah P, Eyre N. Impact of transition to a low carbon power system on the GB gas network. Appl Energy 2015;151:1-12.
[75] Unsihuay C, Marangon-Lima J, de Souza A. Integrated power generation and natural gas expansion planning. 2007 IEEE Lausanne Power Tech. 2007: 1404-1409.
[76] Chaudry M, Jenkins N, Qadrdan M, Wu J. Combined gas and electricity network expansion planning. Appl Energy 2014;113:1171-1187.
[77] Unsihuay-Vila C, Marangon-Lima J, De Souza A, Perez-Arriaga I, Balestrassi P. A model to long-term, multiarea, multistage, and integrated expansion planning of electricity and natural gas systems. IEEE Trans Power Syst 2010;25:1154-1168.
[78] Barati F, Seifi H, Sepasian M, Nateghi A, Shafie-khah M, Catalao J. Multi-period integrated framework of generation, transmission, and natural gas grid expansion planning for large-scale systems. IEEE Trans Power Syst 2015;30:2527-2537.
[79] Qiu J, Dong Z, Zhao J, Meng K, Zheng Y, Hill D. Low carbon oriented expansion planning of integrated gas and power systems. IEEE Trans Power Syst 2015;30:1035-1046.
[80] Qiu J, Yang H, Dong Z, Zhao J, Meng K, Luo F, Wang K. A linear programming approach to expansion co-planning in gas and electricity markets. IEEE Trans Power Syst 2016;31:3594-3606.
[81] Sanchez C, Bent R, Backhaus S, Blumsack S, Hijazi H, Hentenryck P Van. Convex optimization for joint expansion planning of natural gas and power systems. 49th Hawaii Int Conf Syst Sci. 2016: 2536-2545.
[82] Barati F, Seifi H, Nateghi A, Sepasian M, Shafie-khah M, Catalao J. An integrated generation, transmission and natural gas grid expansion planning approach for large scale systems. IEEE Power Energy Soc Gen Meet 2015; 30: 1-5.
[83] Hu Y, Bie Z, Ding T, Lin Y. An NSGA-II based multi-objective optimization for combined gas and electricity network expansion planning. Appl Energy 2016;167:280-93.
[84] Leite da Silva A, Rezende L, Manso L, Anders G. Transmission expansion planning: A discussion on reliability and N-1 security criteria. IEEE 11th Int. Conf. Probabilistic Methods Appl to Power Syst. 2010: 244-251.
[85] Qiu J, Dong Z, Zhao J, Meng K, Luo F, Chen Y. Expansion co-planning for shale gas integration in a combined energy market. J Mod Power Syst Clean Energy 2015;3:302-311.
[86] Wang D, Qiu J, Meng K, Gao X, Dong Z. Coordinated expansion co-planning of integrated gas and power systems. J Mod Power Syst Clean Energy 2017;5:314-325.
[87] Zhang X, Shahidehpour M, Alabdulwahab A, Abusorrah A. Security-constrained co-optimization transportation infrastructures. IEEE Trans Power Syst 2015;30:2984-2993.
[88] Zhang X, Che L, Shahidehpour M, Alabdulwahab A, Abusorrah A. Reliability-based optimal planning of electricity and natural gas interconnections for multiple energy hubs. IEEE Trans Smart Grid 2017;8:1658-1667.
[89] Qiu J, Dong Z, Zhao J, Xu Y, Zheng Y, Li C, Wang K. Multi-stage flexible expansion co-planning under uncertainties in a combined electricity and gas market. IEEE Trans Power Syst 2015;30:2119-2129.
[90] Ding T, Hu Y, Bie Z. Multi-Stage stochastic programming with nonanticipativity constraints for expansion of combined power and natural gas systems. IEEE Trans Power Syst 2017; (to appear).
[91] Shao C, Shahidehpour M, Wang X, Wang X, Wang B. Integrated planning of electricity and natural gas transportation systems for enhancing the power grid resilience. IEEE Trans Power Syst 2017; (to appear).
[92] Zeng Q, Fang J, Chen Z, Li J, Zhang B. A multistage coordinative optimization for sitting and sizing P2G plants in an integrated electricity and natural gas system. 2016 IEEE Int Energy Conf. 2016:1-6.
[93] Zeng Q, Zhang B, Fang J, Chen Z. A bi-level programming for multistage co-expansion planning of the integrated gas and electricity system. Appl Energy 2017;200:192-203.
[94] Illinois Institute of Technology, White Paper: Long-term Electric and Natural Gas Infrastructure Requirements, 2014, [Online]. Available: https://pubs.naruc.org/.
[95] Juris A. The emergence of markets in the natural gas industry. World Bank Policy Res Working Paper 1998: 1-37.
[96] Cui H, Li F, Hu Q, Bai L, Fang X. Day-ahead coordinated operation of utility-scale electricity and natural gas networks considering demand response based virtual power plants. Appl Energy 2016;176:183-195.
[97] Dueñas P, Leung T, Gil M, Reneses J. Gas-electricity coordination in competitive markets under renewable energy uncertainty. IEEE Trans Power Syst 2015;30:123-131.
[98] Dueñas P, Barquín J, Reneses J. Strategic management of multi-year natural gas contracts in electricity markets. IEEE Trans Power Syst 2012;27:771-779.
[99] Gil M, Duenas P, Reneses J. Electricity and natural gas interdependency: Comparison of two methodologies for coupling large market models within the European regulatory framework. IEEE Trans Power Syst 2016;31:361-369.
[100] Spiecker S. Modeling market power by natural gas producers and its impact on the power system. IEEE Trans Power Syst 2013;28:3737-3746.
[101] Wang C, Wei W, Wang J, Liu F, Mei S. Strategic offering and equilibrium in coupled gas and electricity markets. IEEE Trans Power Syst 2017; (to appear).
[102] Morais M, Marangon Lima J. Combined natural gas and electricity network pricing. Electr Power Syst Res 2007;77:712-719.
[103] Geidl M, Andersson G. Operational and structural optimization of multi-carrier energy systems. Eur Trans Electr Power 2006;16:463-477.
[104] Geidl M, Andersson G. Optimal power flow of multiple energy carriers. IEEE Trans Power Syst 2007;22:145-155.
[105] Kienzle F, Favre-Perrod P, Arnold M, Andersson G. Multi-energy delivery infrastructures for the future. 2008 First Int Conf Infrastruct Syst Serv Build Networks a Bright Futur. 2008: 1–5.
[106] Favre-Perrod P, Kienzle F, Andersson G. Modeling and design of future multi-energy generation and transmission systems. Eur Trans Electr Power 2010;20:994-1008.
[107] Geidl M, Andersson G. Operational and structural optimization of multi-carrier energy systems. Eur Trans Electr Power 2006;16:463-477.
[108] Moeini-Aghtaie M, Dehghanian P, Fotuhi-Firuzabad M, Abbaspour A. Multiagent genetic algorithm: An online probabilistic view on economic dispatch of energy hubs constrained by wind availability. IEEE Trans Sustain Energy 2014;5:699-708.
[109] Zhang X, Shahidehpour M, Alabdulwahab A, Abusorrah A. Optimal expansion planning of energy hub with multiple energy infrastructures. IEEE Trans Smart Grid 2015;6:2302-2311.
[110] Kienzle F, Ahcin P, Andersson G. Valuing investments in multi-energy conversion, storage, and demand-side management systems under uncertainty. IEEE Trans Sustain Energy 2011;2:194-202.
[111] Adamek F, Arnold M, Andersson G. On decisive storage parameters for minimizing energy supply costs in multicarrier energy systems. IEEE

Trans Sustain Energy 2014;5:102-109.
[112] Najafi A, Falaghi H, Contreras J, Ramezani M. A Stochastic bilevel model for the energy hub manager problem. IEEE Trans Smart Grid 2017;8:2394-2404.
[113] Rastegar M, Fotuhi-Firuzabad M, Zareipour H, Moeini-Aghtaie M. A probabilistic energy management scheme for renewable-based residential energy hubs. IEEE Trans Smart Grid 2016;8:2217-2227.
[114] Bahrami S, Toulabi M, Ranjbar S, Moeini-Aghtaie M, Ranjbar A. A decentralized energy management framework for energy hubs in dynamic pricing markets. IEEE Trans Smart Grid 2017; (to appear).
[115] Saldarriaga C, Hincapie R, Salazar H. An integrated expansion planning model of electric and natural gas distribution systems considering demand uncertainty. 2015 IEEE Power Energy Soc Gen Meet. 2015: 1-5.
[116] Saldarriaga C, Hincapié R, Salazar H. A holistic approach for planning natural gas and electricity distribution networks. IEEE Trans Power Syst 2013;28:4052-4063.
[117] Odetayo B, MacCormack J, Rosehart W, Zareipour H. A chance constrained programming approach to integrated planning of distributed power generation and natural gas network. Electr Power Syst Res 2017;151:197-207.