Investment Equilibria Involving Gas-Fired Power Units in Electricity and Gas Markets

Sheng Chen, Member, IEEE, Antonio J. Conejo, Fellow, IEEE, Ramteen Sioshansi, Senior Member, IEEE, and Zhinong Wei

Abstract—We study investment equilibria in electricity and gas markets wherein electricity producers and natural gas suppliers behave strategically. We consider also hybrid producers that own both generating units and gas sources. Each strategic producer determines its investment decisions in gas-fired units, and its offering and bidding strategies to maximize its own profit, anticipating electricity and gas market-clearing outcomes. Producers owning gas-fired units submit bids to the gas market to procure fuel and offers to the electricity market to sell electricity. The resulting model is recast as an equilibrium problem with equilibrium constraints that we solve using a direct approach. Numerical results from two test systems illustrate the proposed methodology.

Index Terms—Electricity market, gas market, investment, strategic offering and bidding, equilibria

NOMENCLATURE

Indices and Sets

- \( C_m \): set of gas compressors connected to node \( m \)
- \( d/D \): index/set of electricity demands
- \( e/E \): index/set of gas demands
- \( E_i \): set of electric buses connected directly to bus \( i \)
- \( F/G \): set of candidate gas-fired units
- \( G_m \): set of gas nodes connected directly to node \( m \)
- \( I \): indices/set of electric power system buses
- \( i(u/d) \): power system bus where power unit \( u \) is connected to node \( d \)
- \( K/k \): index/set of gas compressors
- \( L/l \): index/set of producers
- \( M_m \): indices/set of gas system nodes
- \( m(w/e) \): gas system node where gas source \( w \) is located
- \( REF \): reference bus of the power system
- \( T/t \): index/set of operating conditions
- \( V/v \): index/set of existing power units
- \( W/w \): index/set of gas sources
- \( \Omega^{GE} \): set of existing gas-fired units owned by producer \( l \)
- \( \Omega^{GC} \): set of candidate gas-fired units for producer \( l \)

Parameters and Constants

- \( b_{i,j} \): susceptance of transmission line \( i,j \) (p.u.)
- \( C_{d,t} \): marginal utility of demand \( d \) in operating condition \( t \) ($/p.u.)
- \( C_{e,t} \): marginal utility of gas demand \( e \) in operating condition \( t \) ($/Mm^3)$
- \( C_g \): marginal cost of non-gas-fired unit \( v \) ($/p.u.)
- \( C_O \): operation and maintenance (O&M) cost of candidate gas-fired unit \( f \) ($/p.u.)
- \( C_{OE} \): O&M cost of existing gas-fired unit \( v \) ($/p.u.)
- \( C_S \): marginal production cost of gas source \( w \) ($/Mm^3)$
- \( F_{c,max} \): gas-transportation limit of compressor \( k \) (Mm$^3$/h)
- \( F_{e,max} \): maximum demand of gas demand \( e \) (Mm$^3$/h)
- \( F_{f,max} \): capacity of gas source \( w \) (Mm$^3$/h)
- \( F_{GE,max} \): maximum fuel consumption by candidate gas-fired unit \( f \) (Mm$^3$/h)
- \( F_{G,max} \): maximum fuel consumption by existing gas-fired unit \( v \) (Mm$^3$/h)
- \( K_f \): annualized capital cost of candidate unit \( f \) ($/p.u.)
- \( K_{f,max} \): investment budget ($) 
- \( P_{G,max} \): capacity of power unit \( v \) (p.u.)
- \( P_{max} \): capacity of power line \( i,j \) (p.u.)
- \( P_{L,max} \): maximum load of electricity demand \( d \) (p.u.)
- \( W_{m,n} \): Weymouth constant of pipeline \( m,n \) ($/(Mm^3$/h)/bar)
- \( \chi \): maximum capacity of candidate gas-fired unit \( f \) (p.u.)
- \( \eta_v \): heat rate of existing gas-fired unit \( v \) (Mm$^3$/p.u.)
- \( \eta_f \): heat rate of candidate gas-fired unit \( f \) (Mm$^3$/p.u.)
- \( \sigma_t \): weight on operating condition \( t \) (h)
- \( \delta_k \): conversion efficiency of gas compressor \( k \) (p.u.)
- \( \rho_{C,min} \): minimum squared ratio of compressor \( k \) (p.u.)
- \( \rho_{C,max} \): maximum squared ratio of compressor \( k \) (p.u.)
- \( \rho_{f} \): maximum squared gas pressure at node \( m \) (bar$^2$)
- \( \rho_{m} \): minimum squared gas pressure at node \( m \) (bar$^2$)
The strategic investments in gas-fired units, and the strategic offering and bidding decisions made by each producer are represented by a bi-level problem. The upper-level subproblem seeks to maximize producers’ profits, while the lower-level subproblems represent the electricity market clearing (EMC) and gas market clearing (GMC) in a set of operating conditions.

The bi-level problem of each producer is transformed into a mathematical program with equilibrium constraints (MPEC) by replacing the lower-level subproblems with their optimality conditions. Jointly considering the MPECs of all the producers yields an equilibrium problem with equilibrium constraints (EPEC). We use a direct solution approach [11–15] that replaces the MPECs with their KKT conditions to compute generalized Nash equilibria.


The models that are proposed in these works take the perspective of a central planner under perfectly competitive markets, which may be unrealistic. Moreover, these works do not represent strategic behavior in electricity and gas markets when modeling investment in gas-fired generation. Given this context, our work makes the following two formative contributions to the existing literature.

1) It develops an EPEC framework to represent the interactions between strategic investors and producers in electricity and gas markets.
2) It identifies a range of investment equilibria. This is done by converting the EPEC into a computationally tractable mixed-integer linear optimization problem.

The remainder of this paper is organized as follows. Section II provides the mathematical formulation of each producer’s bi-level model. Section III details the MPECs, the EPEC, and the proposed solution methodology. Sections IV

---

**I. INTRODUCTION**

Replacing coal-fired and other power units with gas-fired ones is increasingly attractive. On one hand, low gas prices make investment in gas-fired power units economically attractive. On the other hand, the net-load fluctuations caused by renewable energy sources call for the flexibility provided by gas-fired power units.

Because power-generation-investment decisions are made often within a market framework, investment models pertaining to gas-fired power units should represent the gas market and fuel-procurement cost. The electricity market also should be represented to capture revenues from electricity sales.

Thus, we propose an equilibrium model that captures strategic investment in gas-fired units and strategic offering and bidding in both electricity and gas markets.

We consider stand-alone power and gas producers and hybrid producers that own both power units and gas sources.
and \( \mathbf{V} \) summarize numerical results of two test systems. Section \( \mathbf{VI} \) concludes.

II. Model Formulation

Fig. 1 depicts the structure of the proposed problem. The upper level includes a set of power, gas, and hybrid producers. The lower level represents EMC and GMC under different operating conditions. Poncelet et al. [13] provide an approach to select representative operating conditions. Producers that own gas-fired units behave strategically in both markets through electricity-supply offers and fuel-procurement bids. The lower-level EMC and GMC are interrelated indirectly by producers that participate in both markets. We assume that the two markets clear simultaneously. Sequential market clearing can yield efficiency losses. The upper- and lower-level problems are interrelated in the following two ways.

1) Electricity locational marginal prices (ELMPs) and gas locational marginal prices (GLMPs), which are obtained from the lower-level EMC and GMC problems, respectively, affect producer profits in the upper-level problems.

2) Strategic investment and offering and bidding decisions, which are determined in the upper-level problem, affect the lower-level EMC and GMC problems.

Formulations of the upper- and lower-level problems are provided below.

A. Upper-Level Problem

Upper-level objective function (1) represents the profit of strategic producer \( l \). Specifically, the terms, \( \eta_v u_m(v,t) \) and \( \eta_f u_m(f,t) \), in (1) represent the variable fuel cost of existing gas-fired unit \( v \) and candidate gas-fired unit \( f \) in operating condition \( t \), respectively. \( i(v) \) and \( i(f) \) denote the electric buses where existing and candidate units \( v \) and \( f \), respectively, are located. \( m(v) \) and \( m(f) \) denote the gas nodes where gas-fired units \( v \) and \( f \) are located. \( m(w) \) denotes the gas node where gas source \( w \) is located.

Objective function (1) is optimized subject to the constraints:

\[
\begin{align*}
\sum_{f \in \mathcal{F}} X_f + \sum_{v \in \mathcal{V}} P_{v}^{G_{\text{max}}} & \geq (1 + \chi) \sum_{d \in \mathcal{D}} D_{d_{\text{max}}} \quad (2c) \\
\alpha_{v,t} & \geq 0, \forall v \in \{ \Omega_{l}^{E}, \Omega_{l}^{G} \}; \forall f \in \mathcal{T} \\
\alpha_{f,t} & \geq 0, \forall f \in \Omega_{l}^{G}; \forall t \in \mathcal{T} \\
\beta_{w,t} & \geq 0, \forall w \in \Omega_{l}^{S}; \forall t \in \mathcal{T} \\
\gamma_{v,t}^{G} & \geq 0, \forall v \in \Omega_{l}^{G}; \forall t \in \mathcal{T} \\
\gamma_{f,t}^{G} & \geq 0, \forall f \in \Omega_{l}^{G}; \forall t \in \mathcal{T}.
\end{align*}
\]

Constraints (2a) limit the capacity of candidate gas-fired units that can be built by producer \( l \). Regulatory constraint (2b) is a generic investment budget limit affecting all of the investors. Regulatory constraint (2c) imposes a planning-reserve margin, which is defined relative to the maximum demand \( \mathcal{D} \), which is assumed to occur in operating condition \( t = 1 \). Constraints (2d) and (2e) require generating offers to be non-negative. Similarly, constraints (2f) require gas-supply offers to be non-negative. Finally, constraints (2g) and (2h) require fuel-procurement bids for gas-fired units to be non-negative.

B. Lower-Level EMC

The EMC for operating condition \( t \) is:

\[
\min \sum_{v \in \mathcal{V}} \eta_v \cdot I_{v,t} \cdot P_{v,t}^{E} + \sum_{f \in \mathcal{F}} \alpha_{f,t} \cdot I_{f,t} \cdot P_{f,t}^{G} - \sum_{d \in \mathcal{D}} C\text{EL}_{d_{\text{max}}} \cdot P_{d_{\text{max}}}^{L} \quad (3)
\]

subject to:

\[
\begin{align*}
\sum_{d \in \Theta_{p}^{D}} P_{d_{\text{max}}}^{L} & - \sum_{v \in \Theta_{v}^{D}} \sum_{f \in \Theta_{f}^{G}} P_{v,t}^{G} \leq \sum_{d \in \mathcal{D}} P_{d_{\text{max}}}^{G} \quad (2a) \\
0 & \leq P_{d_{\text{max}}}^{L} \leq P_{d_{\text{max}}}^{L} \quad (2b) \\
0 & \leq P_{v_{\text{max}}}^{G} \leq P_{v_{\text{max}}}^{G} \quad (2c) \\
0 & \leq P_{f_{\text{max}}}^{G} \leq P_{f_{\text{max}}}^{G} \quad (2d) \\
0 & \leq P_{f_{\text{max}}}^{L} \leq X_f \cdot \rho_{\text{min}}^{f,t} \cdot \rho_{\text{max}}^{f,t} \forall f \in \mathcal{F} \\
\theta_{\text{REF},t} & = 0 : \rho_{\text{min}}^{f,t} \forall t \in \mathcal{T}.
\end{align*}
\]

The dual variable that is associated with each constraint is indicated after the colon. The primal-variable set of the EMC problem of operating condition \( t \) is \( \mathcal{E}_{t}^{\text{ip}} = \{ P_{v}^{E}, P_{f}^{G}, P_{d_{\text{max}}}^{L}, \theta_{t} \} \), while the dual-variable set is \( \mathcal{E}_{t}^{\text{ip}} = \{ \lambda_{i,t}, \rho_{1,i,t}, \rho_{2,i,t}, \rho_{3,i,t}, \rho_{4,i,t}, \rho_{5,i,t}, \rho_{6,i,t}, \rho_{7,i,t}, \rho_{8,i,t} \} \).

Objective function (3) is the negative social welfare (SW) that is engendered by the electricity markets. Its first two terms represent the production cost of existing and candidate power units, respectively. The last term represents the utility of power demands. We use single-block offers and bids for each production unit and demand, respectively. Offering and bidding quantities are not variables of our model. However, our model can be extended to include multiple quantity blocks to represent a desired offer or bid curve.

Constraints (4) pertain to power system operations. Specifically, (4a) and (4b) represent active power-flow balance at each bus. Its dual variable, \( \lambda_{i,t} \), is the ELMP of bus \( i \) in operating condition \( t \). Constraints (4c) and (4d) enforce the transmission capacity of each power line. Constraints (4e) and (4f) bound electricity demands.
The primal-variable set of the GMC problem for operating condition \( t \) is:

\[
\min_{\Xi^{O}} \sum_{\Xi \in \Omega^{GC}} K_{f} X_{f} - \sum_{t \in T} \sigma_{t} \left( \sum_{\Xi \in \Omega^{GC}} \sum_{v \in \Omega_{v}^{E}} P_{r}^{GE} \cdot \left( \lambda_{(\Xi,v),t} - C_{v}^{GE} \right) + \sum_{\Xi \in \Omega^{GC}} \sum_{v \in \Omega_{v}^{E}} P_{r}^{GE} \cdot \left( \lambda_{(\Xi,v),t} - C_{v}^{GE} - \eta_{f} u_{m(v),t} \right) \right) - \sum_{t \in T} \sigma_{t} \sum_{\Xi \in \Omega^{GC}} P_{f,t}^{GC} \cdot \left( \lambda_{(\Xi),t} - C_{f}^{GC} - \eta_{f} u_{m(f),t} \right) \right) - \sum_{t \in T} \sigma_{t} \sum_{w \in \Omega_{w}^{E}} F_{w,t}^{S} \cdot \left( u_{m(w),t} - C_{w}^{S} \right)
\]

Constraints (44) and (48) impose output bounds on existing power units and candidate gas-fired units, respectively. Constraint (41) sets the phase angle at the reference bus to zero.

### C. Lower-Level GMC

The GMC for operating condition \( t \) is:

\[
\min_{\Xi^{O}} \sum_{\Xi \in \Omega^{E}} \sum_{v \in \Omega_{v}^{E}} \beta_{w,t}^{F} F_{w,t}^{S} - \sum_{\Xi \in \Omega^{E}} \sum_{v \in \Omega_{v}^{E}} C_{v}^{GE} F_{v,t}^{L} - \sum_{\Xi \in \Omega^{E}} \sum_{v \in \Omega_{v}^{E}} \gamma_{t}^{GE} F_{v,t}^{L} - \sum_{\Xi \in \Omega^{E}} \sum_{v \in \Omega_{v}^{E}} \gamma_{t}^{GC} F_{v,t}^{GC} \quad (5)
\]

subject to:

\[
\begin{align*}
&\sum_{\Xi \in \Omega^{E}} F_{w,t}^{L} + \sum_{\Xi \in \Omega^{E}} F_{w,t}^{S} = \sum_{\Xi \in \Omega^{E}} F_{v,t}^{L} - \sum_{\Xi \in \Omega^{E}} F_{v,t}^{S} \quad (6a) \\
&+ \sum_{n \in \Omega_{n}^{E}} F_{m,n,t} + \sum_{k \in \Omega_{k}^{E}} \left( 1 - \theta_{k} \right) F_{k,t}^{E} = 0 : u_{m,t} \forall m \in \mathcal{M} \\
&F_{m,n,t} | F_{m,n,t} | W_{m,t} : \Pi_{m,n,t} - \Pi_{n,m,t} : \Phi_{2,m,n,t}^{E} \in \mathcal{M}, n \in \mathcal{G} \\
&0 \leq F_{k,t}^{C} \leq F_{k,t}^{C_{\max}} = \phi_{m,k,t}^{C_{\max}} = \phi_{m,k,t}^{C_{\max}} \forall k \in \mathcal{K} \\
&0 \leq F_{w,t}^{S} \leq F_{w,t}^{S_{\max}} \forall w \in \mathcal{W} \\
&0 \leq F_{w,t}^{L} \leq F_{w,t}^{L_{\max}} \forall w \in \mathcal{W} \\
&0 \leq F_{m,n,t}^{C_{\min}} \leq F_{m,n,t}^{C_{\max}} : \phi_{m,n,t}^{C_{\min}} = \phi_{m,n,t}^{C_{\max}} \\
&0 \leq F_{m,n,t}^{C_{\min}} \leq F_{m,n,t}^{C_{\max}} : \phi_{m,n,t}^{C_{\min}} = \phi_{m,n,t}^{C_{\max}} \\
&0 \leq F_{f,t}^{C_{\max}} \leq F_{f,t}^{C_{\min}} \forall f \in \mathcal{F} \\
&\text{Objective function} (5) \text{ is the negative } \mathcal{SW} \text{ derived from the gas market. The first term represents gas-production costs. The second term represents the utility of non-electricity-related gas demands, while the last two terms represent the utility of electricity-related gas demands.}
\end{align*}
\]

Constraints (64) pertain to the operation of the gas system. Specifically, (6a) represent nodal gas-flow balance, which includes non-electricity-related gas demands, gas consumption from existing and candidate gas-fired units, gas-source production, and the gas flow through pipelines and compressors. The dual variable, \( u_{m,t} \), that is associated with (6a) represents the GLMP of node \( m \) in operating condition \( t \). Constraints (65) relate the gas flow to the squared pressure drop at the two ends of each pipeline. Constraints (66) represent the transport capacity of compressors, which limit the power consumption of these compressors. Constraints (67) represent the production capacity of gas sources. Constraints (68) bound the non-electricity-related gas demands served. Constraints (69) limit the nodal gas pressures. Constraints (6a) impose minimum and maximum compression ratios on compressors. The inlet and outlet pressures of gas compressors and gas nodal pressures are related as:

\[
\Pi_{m,t}^{\text{in}} = \Pi_{m,t}^{\text{out}} : \Pi_{m,t} : \mathcal{C}(m)^{\text{in}}, \Pi_{m,t}^{\text{out}} : \Pi_{m,t} : \mathcal{C}(m)^{\text{out}}
\]

where \( \mathcal{C}(m)^{\text{in}} \) and \( \mathcal{C}(m)^{\text{out}} \) denote, respectively, the set of compressors which have their inflow to and outflow from node \( m \).

Constraints (6a) and (6b) limit the fuel consumption of existing and candidate gas-fired units, respectively.

Constraints (64) are nonlinear, which complicates the solution of problem (5)–(6). For simplicity and tractability, we linearize (6a) using the first-order Taylor expansion [16] as:

\[
\text{sgn} \left( F_{0}^{0}, t \right) \left( 2 F_{m,n}^{0}, t F_{m,n,t} - F_{m,n,t}^{0} \right) = W_{m,n}^{2} \\
\times \left( \Pi_{m,n,t} - \Pi_{n,m,t} : \Phi_{2,m,n,t}^{E} \forall m \in \mathcal{M}, n \in \mathcal{G} \right.
\]

The nonlinear term, \( F_{m,n,t} | F_{m,n,t} | \), on the left-hand side of (6a) is linearized around a given operating condition, \( F_{0}^{0}, t \). First, we solve a bi-level model that neglects (6a), and the solution obtained (i.e., the value of \( F_{0}^{0}, t \) for each operating scenario, \( t \)) is used as the linearization point in (7).

Both EMC (3)–(4) and GMC (5), (6a), (6c)–(7) are linear programming (LP) problems, for which the strong-duality theorem holds.

The variable set of upper-level problem (14)–(15) is \( \Xi^{UL} = \{ X_{f,t}, \alpha_{w,t}, \alpha_{f,t}, \beta_{w,t} : \Xi_{w,t}^{GE}, \Xi_{w,t}^{GC}, \Xi_{l} \} \), which includes the decision variables of producers and the primal variables of the EMC and GMC problems.

Our model allows one producer simultaneously to own gas sources and gas-fired power units. Depending on where a producer’s gas sources and gas-fired power units are located, its participation in the markets differs.

1) If the gas source and gas-fired power unit are not located at the same gas node, the producer uses the gas-pipeline network to transfer the gas from gas production nodes
to its gas-fired unit. In this case, the gas-fired power unit buys fuel from the gas market.

2) If a producer’s gas source and gas-fired power unit are located at the same gas node, the solution obtained from our model should have the strategic bid (to procure fuel) that is provided by the gas-fired power unit equal to the strategic offer provided (to supply gas) by the gas source. This is because our model maximizes the producer’s profit.

III. Solution Methodology

For each strategic producer, bi-level model (3)–(5), (6a), (6b)–(7) can be transformed into an MPEC by replacing the lower-level EMM and GMC problems with their optimality conditions (primal constraints, dual constraints, and the strong-duality equality). The resulting MPEC for producer \( i \) is:

objective:

\[
\sum_{j \in E_i} b_{i,j} \cdot (\lambda_{i,t} - \lambda_{j,t}) + \sum_{j \in E_i} b_{j,i} \cdot (\rho_{i,j,t}^{\max} - \rho_{i,j,t}^{\min}) = 0 \forall i \in I, i \neq REF, t \in T \tag{11d}
\]

\[
\sum_{j \in E_{REF}} b_{REF,j} \cdot (\lambda_{REF,t} - \lambda_{j,t}) + \sum_{j \in E_{REF}} b_{j,REF} \cdot (\rho_{1,REF,j,t}^{\max} - \rho_{1,REF,j,t}^{\max}) + \rho_{5,t} = 0 \forall \theta \in T 
\]

\[
\rho_{i,j,t}^{\max} \geq 0 \forall i \in I, j \in E_i, t \in T \tag{11f}
\]

\[
\rho_{2,d,t}^{\max} \geq 0 \forall d \in D, t \in T \tag{11g}
\]

\[
\rho_{3,v,t}^{\max} \geq 0 \forall v \in V, t \in T \tag{11h}
\]

\[
\rho_{4,f,t}^{\max} \geq 0 \forall f \in F, t \in T \tag{11i}
\]

4) strong duality for the EMM problems (one set for each operating condition, \( t \)):

\[
\sum_{v \in V} a_{v,t} P_{v,t}^{E} + \sum_{f \in F} a_{f,t} P_{f,t}^{GC} - \sum_{d \in D} c_{d,t}^{E} p_{d,t}^{E} = 0 \tag{12}
\]

\[
- \sum_{j \in I, j \in E_i} \rho_{i,j,t}^{\max} p_{i,j,t}^{\max} - \sum_{d \in D} \rho_{2,d,t}^{\max} p_{2,d,t}^{\max} - \sum_{v \in V} \rho_{3,v,t}^{\max} p_{v,t}^{\max} \geq 0 \forall v \in V, t \in T
\]

\[
\sum_{d \in D} \rho_{4,f,t}^{\max} p_{f,t}^{\max} \geq 0 \forall f \in F, t \in T
\]

5) primal constraints of the GMC problems (one set for each operating condition, \( t \)):

\[
\sum_{e \in \Phi_m} F_{e,t}^{C} + \sum_{v \in \Phi_{v,t}^{GC}} F_{v,t}^{GC} + \sum_{f \in \Phi_{f,t}^{GC}} F_{f,t}^{GC} = 0 \forall \theta \in T
\]

\[
F_{v,t}^{GC} = 0 \forall v \in V, t \in T
\]

\[
\sum_{k \in K} F_{k,t}^{C} \geq 0 \forall k \in K, t \in T
\]

\[
\sum_{v \in V} \Phi_{v,t}^{C} = 0 \forall \theta \in T
\]

\[
\sum_{m} \rho_{m,t}^{\min} \leq \sum_{k} \rho_{k,t}^{\max} \forall m \in M, t \in T
\]

\[
\rho_{k,t}^{\max} \leq \rho_{k,t}^{\max} \forall k \in K, t \in T
\]

\[
\rho_{k,t}^{\min} \leq 0 \forall k \in K, t \in T
\]

\[
\sum_{v \in V} \Phi_{v,t}^{C} = 0 \forall \theta \in T
\]

6) dual constraints for the GMC problems (one set for each operating condition, \( t \)):

\[
\beta_{w,t} - u_{m(w),t} + \Phi_{4,w,t}^{\max} - \Phi_{4,w,t}^{\min} = 0 \forall \theta \in T
\]

\[
u \in V, t \in T
\]

\[
u \in E, t \in T
\]

\[
u \in M, n \in G_m, t \in T
\]

\[
u \in \Phi_m, t \in T
\]

\[
u \in V, t \in T
\]

\[
u \in M, n \in G_m, t \in T
\]

\[
u \in M, t \in T
\]
− Φ_{m,t}^{\min} + \sum_{k \in \mathcal{G}(m)^n} \left( \Phi_{T,k,t}^{\min} - \Phi_{T,k,t}^{\max} \right)
+ \sum_{k \in \mathcal{G}(m)^n} \left( \Phi_{k,t}^{\max} - \Phi_{k,t}^{\min} \right) = 0 \forall m \in \mathcal{M}, t \in T \quad (14e)

\text{KKT conditions of producer } l \text{'s MPEC should satisfy the following sets of equations:}

\min_{\Phi} \Phi_e - \sum_{T \in \mathcal{E}} \Phi_{T,e} \quad (14a)

\min_{\Phi} \Phi_{S,e} \quad (14b)

\min_{\Phi} \Phi_{f,t} \quad (14c)

\min_{\Phi} \Phi_{g,t} \quad (14d)

\min_{\Phi} \Phi_{l,t} \quad (14e)

\min_{\Phi} \Phi_{k,t} \quad (14f)

\min_{\Phi} \Phi_{m,t} \quad (14g)

\min_{\Phi} \Phi_{n,t} \quad (14h)

\min_{\Phi} \Phi_{o,t} \quad (14i)

\min_{\Phi} \Phi_{p,t} \quad (14j)

\min_{\Phi} \Phi_{q,t} \quad (14k)

\min_{\Phi} \Phi_{r,t} \quad (14l)

\min_{\Phi} \Phi_{s,t} \quad (14m)

\min_{\Phi} \Phi_{t,t} \quad (14n)

7) and strong duality for the GMC problems (one for each operating condition, t):

\sum_{w \in \mathcal{W}} \beta_{w,t} F_{w,t} - \sum_{v \in \mathcal{E}} C_{e,t} F_{e,t} - \sum_{v \in \mathcal{L}} G_{e,t} F_{e,t} \quad (15)

− \sum_{f \in \mathcal{F}} \Phi_{f,t} = \sum_{m \in \mathcal{M}} \left( \sum_{j \in \mathcal{G}(m)^n} \left( F_{j,m,t} \right)^2 \Phi_{2,m,n,t} \right)

− \sum_{e \in \mathcal{E}} \left( \sum_{w \in \mathcal{W}} \Phi_{w,t} \right)

− \sum_{m \in \mathcal{M}} \left( \sum_{e \in \mathcal{E}} \Phi_{e,m,t} \right)

− \sum_{v \in \mathcal{E}} \left( \sum_{f \in \mathcal{F}} \Phi_{f,v,t} \right)

\kappa_{l,t} \forall t \in T,

where \( m^{\text{in}} \) and \( m^{\text{out}} \) denote inflow and outflow nodes of compressor \( k \), respectively.

Constraints (10)–(12) represent the optimality conditions of EMC problems for all of the operating conditions, while (13)–(15) represent the optimality conditions of GMC problems for all of the operating conditions. Thus, producer \( l \)’s MPEC is (8)–(15).

Generalized Nash equilibria can be computed by solving simultaneously all of the producers’ MPECs. This can be done efficiently by combining the KKT conditions for each MPEC, which gives an EPEC \( \text{[3]} \). The KKT conditions of producer \( l \)’s MPEC, which we denote KKT\( l \), consist of the following three sets of conditions.

1) Primal equality constraints of producer \( l \)’s MPEC, which consist of (10a), (10b), (10c), (10d), (11a), (11b), (12), (13a), (13b), (14a)–(14g), and (15).

2) Stationarity conditions, which are obtained by setting the gradient of the Lagrangian of producer \( l \)’s MPEC equal to zero.

3) Complementarity conditions that are associated with the inequality constraints that are in producer \( l \)’s MPEC.

For sake of simplicity, we do not list the KKT conditions here. Deriving KKT conditions is a relatively simple exercise. For example, the solver EMPS \( \text{[4]} \) which is available in GAMS, derives KKT conditions automatically.

In addition to these KKT conditions, a generalized Nash equilibrium should satisfy the following sets of equations:

\begin{align}
F_{e,t}^{\Phi} &= \eta_{e} F_{e,t}^{\Phi} \forall e \in \mathcal{E}, t \in T \\
F_{f,t}^{\Phi} &= \eta_{f} F_{f,t}^{\Phi} \forall f \in \mathcal{F}, t \in T,
\end{align}

which ensure that fuel that is consumed by each gas-fired unit in the EMC solution equals fuel that is supplied in the GMC solution. Constraints (16) assume that the gas consumption of each gas-fired unit is linear in its active-power output. Thus, the resulting EPEC is:

KKT\( l \forall l \in \mathcal{L} \) and (16). (17)

Because system of equalities and inequalities (17) is nonlinear, we linearize it using the following three steps \( \text{[3]} \).

1) Strong-duality equalities (12) and (15) are replaced by the equivalent complementarity conditions, (4b)–(4e) and (6c)–(6o) of the EMC and GMC problems, respectively.

2) The complementary-slackness conditions in KKT\( l \) are linearized using the technique that is proposed by Fortuny-Amat and McCarl \( \text{[17]} \), which requires binary variables.

3) Bilinear terms involving \( \gamma_{l,t} \) and \( \kappa_{l,t} \), i.e., the dual variables that are associated with (12) and (15), are linearized using binary expansion (which is an approximation) or by fixing them to values that are obtained using trial-and-error.

The big-M values that are used in linearization step 2 are obtained using trial-and-error. We denote the linearized version of (17) as LKKT\( \text{all} \).

Because EPEC (17) may have multiple solutions \( \text{[2]} \), we use the following auxiliary optimization problem:

\begin{align}
\min \sum_{f \in \mathcal{F}} K_{f} X_{f} - \sum_{t \in \mathcal{E}} \sigma_{t} F_{t}^{\Phi} \cdot (\lambda_{t} + C_{t} - C_{t}^{G}) \quad (18)
\end{align}

s.t. LKKT\( \text{all} \),

which maximizes the total profit (TP) of all producers, to search for equilibria in which producers maximize the joint exercise of market power. Objective function (18) can be

https://www.gams.com/latest/docs/UG_EMP.html
linearized \([1, 2]\). Alternative objectives, such as maximizing social welfare or the profit of an individual producer, can be used to search for other equilibria.

The resulting EPEC model is a mixed-integer LP (MILP) problem, which can be solved using branch-and-cut solvers, such as CPLEX or GUROBI.

We use a diagonalization algorithm \([13]\) to check whether or not an EPEC solution is a generalized Nash equilibrium.

IV. ILLUSTRATIVE EXAMPLE

To illustrate the proposed model, this section presents results from a simple example. The assumed topologies of the networks are shown in Fig. 2. The coupling between the gas and power systems includes an existing gas-fired unit at bus 3 (node 3) and two candidate gas-fired units at bus 1 (node 1) and bus 3 (node 3). Producer 1 owns existing power unit 1 and candidate gas-fired unit 1, while producer 3 owns gas source 1. Producer 2 owns existing gas-fired unit 2, candidate gas-fired unit 2, and gas source 2. The two candidate gas-fired units have maximum capacities of 200 MW each. Their annualized capital costs are $7600/MW and $9000/MW, respectively, while their heat rates are 0.005 Mm\(^3\)/MWh and 0.0045 Mm\(^3\)/MWh, respectively. We consider three operating conditions with weights of 0.4380, 0.3285, and 0.2105, during which the total electricity demands are 300 MW, 225 MW, and 150 MW, respectively, and the total gas demands are 2.0 Mm\(^3\)/h, 1.5 Mm\(^3\)/h, and 1.0 Mm\(^3\)/h, respectively. Table I summarizes the marginal utilities of electricity and natural gas demands in the three operating conditions.

To investigate the impact of power system congestion on investment equilibria, we consider cases in which the transmission capacity of the line connecting buses 2 and 3 is 200 MW, 160 MW, 140 MW, and 100 MW. Tables II–IV summarize results for the example. These tables demonstrate the following three findings.

1) Reducing the capacity of the line connecting buses 2 and 3 results in less capacity of the candidate gas-fired unit at bus 3 being built. This increases the profits of producers 1 and 3 while reducing that of producer 2.

2) There is no congestion in the case with 200 MW of transmission capacity between buses 2 and 3. Congestion surpluses with 160 MW, 140 MW and 100 MW of transmission capacity between buses 2 and 3 are $0.88 million, $0.77 million, and $0.55 million, respectively. The reduced transmission surplus is due to reduced ELMP differences and less flow between buses 2 and 3, as shown in Table II (the ELMP during \(t = 3\) is always $20/MWh, which is why it is not shown in the table).

3) Table IV summarizes GLMPs in the peak-demand operating condition. It shows that as transmission capacity between buses 2 and 3 is reduced, nodes 3 and 4 (which fuel primarily the gas-fired units at bus 3) becomes less stressed, with a commensurate drop in their GLMPs. Conversely, the GLMP at node 1 increases, due to greater fuel demand from gas-fired unit 1.

These types of findings can be used by a market regulator or policymaker to promote investments that increase SW.

V. CASE STUDY

This section summarizes the results from a case study that is based on a Belgian 24-node power system\([5]\) and 20-node gas system\([20]\), which are shown in Fig. 3. The power system includes 7 candidate gas-fired units at buses 2, 6, 8, 14, 15, 21, and 22. We consider three producers including producer 1, which owns the power units in area 1, producer 3, which owns the gas sources in area A, and producer 2, which owns the power units in area 2 and the gas sources in area B. To illustrate the proposed model, eight cases are considered.

---

**TABLE I**

Example: Marginal Utilities of Electricity and Natural Gas Demands in the Three Operating Conditions

<table>
<thead>
<tr>
<th>Electricity Demand Utility ($/MWh)</th>
<th>Gas Demand Utility ($/Mm(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(t)</td>
<td>(i = 1)</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>1</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>23</td>
</tr>
<tr>
<td>3</td>
<td>21</td>
</tr>
</tbody>
</table>

**TABLE IV**

Example: GLMPs in Operating Condition 1 (Peak Demand) ($/Mm\(^3\))

<table>
<thead>
<tr>
<th>(P_{\text{max}})</th>
<th>(m = 1)</th>
<th>(m = 2)</th>
<th>(m = 3)</th>
<th>(m = 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>2678</td>
<td>2800</td>
<td>2900</td>
<td>2900</td>
</tr>
<tr>
<td>160</td>
<td>2795</td>
<td>2800</td>
<td>2803</td>
<td>2803</td>
</tr>
<tr>
<td>140</td>
<td>2800</td>
<td>2800</td>
<td>2800</td>
<td>2800</td>
</tr>
<tr>
<td>100</td>
<td>2800</td>
<td>2800</td>
<td>2800</td>
<td>2800</td>
</tr>
</tbody>
</table>

https://doi.org/10.5281/zenodo.999150
TABLE II
EXAMPLE: INVESTMENT RESULTS

<table>
<thead>
<tr>
<th>Investment Cost ($ million)</th>
<th>Added Capacity (MW)</th>
<th>Profit ($ million)</th>
<th>Total Profit ($ million)</th>
<th>Social Welfare ($ million)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{max}}^{1,2}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>2.12</td>
<td>42</td>
<td>200</td>
<td>0.71</td>
</tr>
<tr>
<td>160</td>
<td>1.97</td>
<td>37</td>
<td>188</td>
<td>1.42</td>
</tr>
<tr>
<td>140</td>
<td>2.10</td>
<td>40</td>
<td>200</td>
<td>1.78</td>
</tr>
<tr>
<td>100</td>
<td>2.05</td>
<td>80</td>
<td>160</td>
<td>3.49</td>
</tr>
</tbody>
</table>

TABLE III
EXAMPLE: ELMPs AND POWER FLOWS

<table>
<thead>
<tr>
<th>ELMPs ($/\text{MWh}$)</th>
<th>$P_{\text{max}}^{1,2}$ (MW)</th>
<th>$P_{\text{max}}^{3,2}$ (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t = 1$</td>
<td>$i = 1$</td>
<td>$i = 2$</td>
</tr>
<tr>
<td>200</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>160</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>140</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>100</td>
<td>25</td>
<td>25</td>
</tr>
</tbody>
</table>

B. Gas-Pressure Limits

We consider two cases, in which the operation ranges of nodal gas pressures are between 30 bar and 70 bar and between 35 bar and 65 bar, respectively. Table VII and Fig. 4 summarize the results for these cases. These results indicate that stricter gas-pressure limits result in a) lower TP and SW (cf. Table VII), b) higher ELMPs (cf. Fig. 4), and c) lower profits for producers 1 and 2 from the electricity market due to higher fuel costs for gas-fired units (cf. Table VII).

TABLE VII
CASE STUDY: PRODUCERS’ PROFITS, TP, AND SW FOR TWO GAS-PRESSURE RANGES

<table>
<thead>
<tr>
<th>Range</th>
<th>$l = 1$ (Electricity)</th>
<th>$l = 3$ (Gas)</th>
<th>$l = 3$ Total</th>
<th>Social Welfare ($ million)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-70</td>
<td>1083</td>
<td>1044</td>
<td>151</td>
<td>984</td>
</tr>
<tr>
<td>35-65</td>
<td>1066</td>
<td>1019</td>
<td>195</td>
<td>941</td>
</tr>
</tbody>
</table>

These results could translate into policy action to reinforce the gas network, which may stimulate investments in gas-fired units and increase SW.

C. Error of the Gas-Flow Model

To measure the accuracy of linearized natural gas flow model (7), we solve an exact gas-flow model, consisting of nonlinear constraints (6a) and (6b), using Newton’s method to obtain a gas-flow solution that satisfies all the equality constraints pertaining to the gas system. We set a slack gas node, the gas pressure of which is fixed while its gas supply is unknown prior to solving the exact gas-flow model. Specifically, we fix the variables that pertain to natural gas supply is unknown prior to solving the exact gas-flow model. Additionally, the power flow from area 2 to area 1 increases, and, consequently, for each operating condition, the ELMPs in area 2 increase, while the ELMPs in area 1 decrease (cf. Table VI).

TABLE VI
CASE STUDY: LOAD-WEIGHTED ELMPs ($/\text{MWh}$) OF AREAS 1 AND 2 FOR TWO TIE-LINE CAPACITIES

<table>
<thead>
<tr>
<th>$P_{\text{max}}^{1,2,3}$ (MW)</th>
<th>Area 1</th>
<th>Area 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1720</td>
<td>60.0</td>
<td>50.0</td>
</tr>
<tr>
<td>3000</td>
<td>60.0</td>
<td>47.2</td>
</tr>
</tbody>
</table>

Fig. 3. Case Study: Belgian 24-node power system and 20-node gas system.

A. Tie-Line Transmission Capacity

We investigate the impact of the capacity of the line connecting bus 24, which is in area 1, to bus 14, which is in area 2. We consider cases in which the capacity of this line is 1720 MW and 3000 MW. Tables V and VI provide results for these cases. Table V shows that greater transmission capacity results in higher generation investment in area 2 and higher profit for producer 2 from the electricity market. Additionally, the power flow from area 2 to area 1 increases, and, consequently, for each operating condition, the ELMPs in area 2 increase, while the ELMPs in area 1 decrease (cf. Table VI).
Then, we define the following index:

\[ E_{m,t} = \sqrt{\Pi^L_{m,t}} - \sqrt{\Pi^E_{m,t}} \cdot 100\% \forall m \in \mathcal{M}, t \in T, \]  

where \( \Pi^L_{m,t} \) and \( \Pi^E_{m,t} \) denote the squared pressure of node \( m \) during operating condition \( t \) that is obtained from the linearized and exact natural gas flow models, respectively.

Fig. 5 shows \( E_{m,t} \) for all nodes under three operating conditions. We observe from this figure that the linearization errors under operating condition \( t = 1 \) are larger than under the other two operating conditions. However, these linearization errors \( (E_{m,t} \leq 1.6\% \forall m \in \mathcal{M}, t \in T) \) are acceptable for practical applications. These results indicate that the linearized gas-flow model is sufficiently accurate.

### D. Investment Equilibria under Perfect Competition

We compare investment equilibria under perfect and imperfect competition. Specifically, we consider the case in which all producers are non-strategic and offer at their marginal production costs, but remain strategic in their investment decisions. Tables VIII and IX summarize the results with a tie-line capacity of 3000 MW (i.e., \( P_{14,24}^{\text{max}} = 3000 \text{ MW} \)).

The outcomes indicate that perfect competition results in 1) lower ELMPs and GLMPs and 2) equal total newly built capacity, but higher capacity built in Area 2. In addition, the SW under imperfect and perfect competition are similar. However, the producers’ profits under imperfect and perfect competition differ significantly. This is because the perfect-competition case allows firms to exercise market power through their investment decisions only. Conversely, the firms have greater purview to exercise market power through their investment, offering, and bidding strategies under imperfect competition. Fig. 6 summarizes the producers’ profit in each operating condition under perfect and imperfect competition. The results in Table IX and Fig. 6 indicate that the market outcomes under perfect and imperfect competition are relatively close during operating condition \( t = 1 \), but are largely different under the other two operating conditions.

### E. Computation of Multiple Equilibria

We search for multiple equilibria by selecting different values of \( \Upsilon_{l,t} \) and \( \kappa_{l,t} \). Three equilibria, which are summarized in Table X, are found. The third equilibrium, in which the fixed values of \( \Upsilon_{l,t} \) and \( \kappa_{l,t} \) are larger than those in the other two equilibria, results in the highest TP and SW. The EPEC does...
TABLE VIII
CASE STUDY: INVESTMENT RESULTS UNDER PERFECT AND IMPERFECT COMPETITION WITH $P_{14,24}^{\text{max}} = 3000$ MW

<table>
<thead>
<tr>
<th>Type of Investment</th>
<th>Cost Added Capacity (GW)</th>
<th>Profit ($ million)</th>
<th>Social Welfare ($ million)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comp. (area 1)</td>
<td>$l=1$</td>
<td>$l=2$ (Electricity)</td>
<td>$l=2$ (Gas)</td>
</tr>
<tr>
<td>Imperfect</td>
<td>1.74</td>
<td>959</td>
<td>1074</td>
</tr>
<tr>
<td>Perfect</td>
<td>1.05</td>
<td>684</td>
<td>812</td>
</tr>
</tbody>
</table>

F. Electricity and Gas Demands

We consider three cases. The first two cases have 5% higher electricity demands and 5% higher gas demands, respectively, relative to the base case. The third case has 5% higher marginal utility for gas demands relative to the base case. Table X summarizes the equilibria that are obtained from the base case and cases with different demands. These results show the interaction between the electricity and gas markets. Increasing the electricity demands results in higher profits for both electricity and gas producers. However, increasing the gas demands or the utilities of the gas demands results in higher gas-producer profits but lower electricity-producer profits. This is because these two cases yield higher gas prices, which increases the fuel cost of gas-fired units. Higher electricity demand leads to increased investment in area 2, which is required to supply the added electricity demand.

G. Number of Producers

Table XII reports the impact of the number of producers on the computational complexity of the EPEC. Clearly, a larger number of producers results in higher computational burden. However, the EPEC model is solved in a reasonable amount of time.

H. Number of Operating Conditions

The number of operating conditions is increased to six, nine, and 12 in the case of 3000 MW of transmission capacity between buses 14 and 24. Equilibria that are obtained with different numbers of operating conditions are provided in Table XIII. This table shows that TP decreases gradually with the number of operating conditions. On the other hand, the EPEC remains computationally tractable, even with 12 operating conditions.

VI. CONCLUSION

This paper develops an EPEC to characterize investment equilibria that are reached by power, gas, and hybrid strategic producers. Our results show that transmission-capacity constraints in the power system and gas-pressure limits in the gas system impact the equilibria that are obtained, the profits of the competing producers, and both ELMPs and GLMPs. On the computational side, the MILP problem representing the EPEC is tractable for realistic power and gas systems. Our work highlights the importance of representing the gas-market and its associated network constraints in generation-investment problems that include gas-fired units. Our work can help a regulator (and other policymakers) to gain insight into 1) the coupling between electricity and gas markets, 2) the investment behaviors of strategic producers, and 3) how supply-side market power impacts the investment decisions and profits of each producer. Our model also may help a
TABLE XI  
CASE STUDY: INVESTMENT RESULTS WITH DIFFERENT ELECTRICITY AND GAS DEMANDS

<table>
<thead>
<tr>
<th>Case</th>
<th>Added Capacity (GW)</th>
<th></th>
<th>Profit ($ million)</th>
<th></th>
<th>Social Welfare ($ million)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Case Area 1</td>
<td>Area 2</td>
<td>l = 1</td>
<td>l = 2 (Electricity)</td>
<td>l = 2 (Gas)</td>
</tr>
<tr>
<td>Base</td>
<td>2.40</td>
<td>2.39</td>
<td>1083</td>
<td>1044</td>
<td>151</td>
</tr>
<tr>
<td>High Electricity Demand</td>
<td>2.40</td>
<td>3.32</td>
<td>1096</td>
<td>1046</td>
<td>176</td>
</tr>
<tr>
<td>High Gas Demand</td>
<td>2.40</td>
<td>2.39</td>
<td>1071</td>
<td>1042</td>
<td>183</td>
</tr>
<tr>
<td>High Gas Utility</td>
<td>2.40</td>
<td>2.39</td>
<td>1053</td>
<td>1035</td>
<td>171</td>
</tr>
</tbody>
</table>

TABLE XIII  
CASE STUDY: EQUILIBRIUM RESULTS WITH DIFFERENT NUMBERS OF OPERATING CONDITIONS

<table>
<thead>
<tr>
<th>[T]</th>
<th>Profit ($ million)</th>
<th>Social Welfare ($ million)</th>
<th>Binary Variables</th>
<th>Columns</th>
<th>Rows</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>l = 1</td>
<td>l = 2</td>
<td>l = 3</td>
<td>Total</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1083</td>
<td>1195</td>
<td>984</td>
<td>3262</td>
<td>3723</td>
<td>2912</td>
</tr>
<tr>
<td>6</td>
<td>1068</td>
<td>1181</td>
<td>973</td>
<td>3222</td>
<td>3650</td>
<td>6275</td>
</tr>
<tr>
<td>9</td>
<td>1076</td>
<td>1166</td>
<td>970</td>
<td>3212</td>
<td>3683</td>
<td>8892</td>
</tr>
<tr>
<td>12</td>
<td>1078</td>
<td>1125</td>
<td>991</td>
<td>3194</td>
<td>3672</td>
<td>11573</td>
</tr>
</tbody>
</table>

regulator to design better rules for both electricity and gas markets.

Our modeling framework can be extended to consider uncertainty in renewable generation by introducing a larger number of operating conditions. This might result in intractability, which can be addressed by decomposition [21].

REFERENCES

Sheng Chen (M’19) received his B.S. and Ph.D. degrees from the College of Energy and Electrical Engineering, Hohai University, Nanjing, China, in 2014 and 2019, respectively. From January 2018 to January 2019 he was a visiting scholar at The Ohio State University, Columbus, OH. He is currently an associate professor in the College of Energy and Electrical Engineering, Hohai University, Nanjing, China. His research interests include integrated energy systems, operations research, and electricity markets.

Antonio J. Conejo (F’04) received the M.S. degree from the Massachusetts Institute of Technology, Cambridge, MA, in 1987, and the Ph.D. degree from the Royal Institute of Technology, Stockholm, Sweden, in 1990. He is currently a professor in the Department of Integrated Systems Engineering and the Department of Electrical and Computer Engineering, The Ohio State University, Columbus, OH. His research interests include control, operations, planning, economics and regulation of electric energy systems, as well as statistics and optimization theory and its applications.

Ramteen Sioshansi (M’11–SM’12) holds the B.A. degree in economics and applied mathematics and the M.S. and Ph.D. degrees in industrial engineering and operations research from the University of California, Berkeley, and an M.Sc. in econometrics and mathematical economics from The London School of Economics and Political Science. He is a professor in the Department of Integrated Systems Engineering at The Ohio State University, Columbus, OH. His research focuses on renewable and sustainable energy system analysis and the design of restructured competitive electricity markets.

Zhinong Wei received the B.S. degree from Hefei University of Technology, Hefei, China, in 1984, the M.S. degree from Southeast University, Nanjing, China, in 1987, and the Ph.D. degree from Hohai University, Nanjing, China, in 2004. He is now a professor of electrical engineering with the College of Energy and Electrical Engineering, Hohai University, Nanjing, China. His research interests include integrated energy systems, power system state estimation, smart distribution systems, and integration of distributed generation into electric power systems.