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Steady-state analysis of the integrated natural gas and electric power system with bi-directional energy conversion

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HIGHLIGHTS

- The integrated gas and electrical system with bi-directional energy conversion is formulated.
- The unified unit system is proposed to enhance the computational efficiency.
- Numerical simulations are carried out to validate the proposed method.
- Transmission loss reduction and increasing renewable integration by P2G.

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ABSTRACT

Nowadays, the electric power system and natural gas network are becoming increasingly coupled and interdependent. A harmonized integration of natural gas and electricity network with bi-directional energy conversion is expected to accommodate high penetration levels of renewables in terms of system flexibility. This work focuses on the steady-state analysis of the integrated natural gas and electric power system with bi-directional energy conversion. A unified energy flow formulation is developed to describe the nodal balance and branch flow in both systems and it is solved with the Newton–Raphson method. Both the unification of units and the per-unit system are proposed to simplify the system description and to enhance the computation efficiency. The applicability of the proposed method is demonstrated by analyzing an IEEE-9 test system integrated with a 7-node natural gas network. Later, time series of wind power and power load are used to investigate the mitigation effect of the integrated energy system. At last, the effect of wind power and power demand on the output of Power to Gas (P2G) and gas-fired power generation (GPG) has also been investigated.

1. Introduction

Due to the broad public attention of the climate change and fossil resource depletion, renewable sources such as wind and solar are developed rapidly in recent years. Taking Denmark for example, by the end of 2014, the wind power capacity in Denmark has reached 4855 MW. Furthermore, a long-term goal has been put forwarded by a political agreement in Denmark that a 100% renewable energy should be implemented in 2050 [1]. The design of the future 100% renewable energy systems has also been documented in general terms in [2,3]. Though the renewable has been developed in recent years with great potential, its intermittent and unpredictable nature raises the difficulty to balance the energy production and consumption [4]. Existing options to accommodate the renewables include: increasing deployment of the fast-ramping sources such as pumped hydro power plants [5] and electrical energy storages [6,7], coordinating wind and solar across wide spatial diversities [8], optimal managing the demands to meet the renewable generation profiles [9,10].

Natural gas is another environmentally-friendly energy source in accommodating the intermittent renewable energy. Firstly, natural gas-fired power generation (GPG) plays a critical role in peak regulation in the absence of hydropower, because it can respond rapidly to changes in demand and supply [11]. So the natural gas network becomes increasingly important for providing backup to the growing supplies of intermittent renewable energy. Secondly, the P2G technology provides an opportunity to convert surplus renewables to a gas fuel. It shows a big potential to store renewables in the natural gas network in large-scale and long duration way [12]. It works by using the surplus wind power or other renewable sources to produce gas fuel that can be stored in the

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Nomenclature

Indices

s, d, g	supply, demand, generation
GPG, P2G, GC	gas-fired power generation, power to gas, gas compressor

Parameter

C	constant
CR	compression ratio
C_{GPG}	the proportional relationship of energy conversion from gas to power in GPG, $\mathrm{m^3/MW\,h}$
C_{P2G}	the energy conversion from electricity to the natural gas in P2G system, $\mathrm{m^3/MW\,h}$
C_{km}	the overall transmission coefficient for an individual pipeline, $(\mathrm{m^3/h})/\mathrm{kPa}$
c_k	specific heat ratio for the natural gas
D_{km}, L_{km}	the inside diameter of pipe in meter, the pipe length in km
$E_{p,km}$	the pipeline efficiency, a decimal value no larger than 1.0
E_c	compressors parasitic efficiency, 0.99 for centrifugal units
f_{km}	the friction factor
G_{ij}, B_{ij}, Y	electrical conductance, electrical susceptance, line admittance matrix
G_k, $G_{s,k}$, $G_{d,k}$	the gas flow, the gas supply, the gas demand at node k, $\mathrm{m^3/h}$
HR	the heat rate, MJ/MW h
J	Jacobian matrix of partial derivatives
K_{GC}	constant of compressor
LHV	lower heating value, $\mathrm{MJ/m^3}$
p_b	gas pressure at base condition, kPa
$P_{g,i}$, $P_{d,i}$	the active power generated of bus i, the active power demand of bus i, MW
$Q_{g,i}$, $Q_{d,i}$	the reactive power generated of bus i, the reactive power demand of bus i, MVar
R_{km}	$R_{km} = 1/C_{km}^2$, the hydraulic resistance coefficient of the pipeline, $\mathrm{kPa^2/(m^3/h)^2}$
$S_{s,k}$, $S_{d,k}$	gas supply and demand at node k, MW
T_s	suction temperature of compressor, R
T_b	gas temperature at base condition, K (273+ °C)
$T_{a,km}$	average absolute temperature of pipeline, K (273 +°C)
V, Y	bus voltage, nodal admittances matrix
Z_{km}	the resistance coefficient of the pipeline, $\mathrm{kPa^2/(MW)^2}$
Z_a	average compressibility factor
γ_G	the natural gas specific gravity, dimensionless
η_c, η_{GPG}, η_{P2G}	compression efficiency, the energy efficiency of GPG, the energy efficiency of P2G

Variables

BHP_{km}	brake horsepower consumed by the gas compressor, horsepower
$G_{d,\mathrm{GPG}}$, $G_{s,\mathrm{P2G}}$	gas consumption in GPG, gas generation in P2G, $\mathrm{m^3/h}$
$P_{d,\mathrm{P2G}}$, $P_{\mathrm{GC},km}$, $P_{g,\mathrm{GPG}}$	power consumed by P2G system, by gas compressor, power generated by GPG, MW
$G_{\mathrm{gas},km}$	standard gas flow rate in the pipeline, measured at base temperature and pressure, $\mathrm{m^3/h}$
$G_{\mathrm{GC},km}$	natural gas flow in the compressor, $\mathrm{m^3/h}$
p_m, p_k	the Nodal gas pressure at both ends of the pipeline, kPa
Π_k, Π_m	$\Pi_k = p_k^2$, $\Pi_m = p_m^2$, $\mathrm{kPa^2}$
$S_{\mathrm{gas},km}$	gas flow rate in the pipeline from the node k to m, measured in MW
$S_{d,\mathrm{GPG}}$, $S_{g,\mathrm{P2G}}$	gas consumption in GPG, gas generation in P2G, MW
$\lvert V\rvert$, θ	magnitude of voltage, angle of voltage

existing natural gas networks, and the stored energy can then be injected back into electricity system through GPG when needed. Thus, the electric power system and natural gas network are becoming increasingly coupled and interdependent. The extensive development and application of GPG and P2G will significantly enhance the interaction between the gas and electrical systems.

While extensive studies have been conducted in natural gas and electric power systems individually, a coordinated analysis of the integrated gas and electric power system is still insufficient [13]. The state of the art reviews on the integrated natural gas and power system can be found in [14,15]. Literatures on this topic can be classified into two general perspectives: the economic perspective and the technical perspective. The economic or market perspective mainly aims at the interaction of the pricing mechanisms between different systems [16,17]. Building a feasible economic model is an important step in economic assessment. However, the influence of the technical constraints is often overlooked or given in a simplified way. For example, the network constraints are often neglected in such studies. The technical perspective focuses on the secure and efficient operation and planning of the integrated energy systems [15]. Different approaches have been proposed in terms of the time horizon. A multi-time period combined gas and electricity network optimization model was developed in [18], which takes into account the varying nature of gas flows, network support facilities. Qiu et al. [19] proposed a multi-stage co-planning model to identify the optimal co-expansion plan in the integrated energy systems. The reliability is another important issue of the integrated energy systems [20]. It aims at analyzing the interdependence of the integrated electricity and gas system under abnormal conditions, such as cascading failures propagating from one system to another [21].

In these studies mentioned above, the GPG has been widely considered as the single-directional linkage between the natural gas and electricity networks. However, P2G, which enables bi-directional energy conversion, has only recently appeared in the investigation of the integrated natural gas and electric power system. Qadrdan et al. [22] investigated the impacts and benefits of employing P2G in the integrated operation of the electricity and gas networks. It showed that the introduction of P2G not only reduced the wind curtailment but also improved the optimal dispatch for electricity and gas. To further analyze the steady state energy flow in the integrated energy system with bi-directional energy conversion, a comprehensive method is needed including both P2G and GPG. The main objective of this paper is to provide a unified formulation for the steady state analysis of the integrated energy system with bi-directional energy conversion. A set of non-linear equations representing the gas and power systems are obtained based on the nodal balance of the gas and power flows, respectively. The integrated formulation of the natural gas and electric power system is obtained by combining the stated flow models through links of the gas compressor, P2G and gas-fired power plants. A case study has been conducted to demonstrate the feasibility of the proposed approach on the IEEE-9 test system connected with a 7-node natural gas network. The effect of the fluctuant power supply and power demand on the integrated natural gas and electric power system has been studied with historical data. The effect of wind power and power demand on the output of the GPG and P2G has also been investigated. The major contributions of this work are:

- A harmonized integration of natural gas and electric power system with bi-directional energy conversion is formulated, including the gas compressors, the power-to-gas and the gas-fired power plants.
- Both the unification of units and the per-unit system are proposed to simplify the system description and to enhance the computational efficiency.
- Numerical simulations are carried out to validate and demonstrate the feasibility, efficiency and accuracy of the proposed method and results are analyzed.

The remainder of the paper is organized as follows: Section 2 introduces the formulation of the integrated gas and power system; Section 3 presents a unified gas and power flow solution for analyzing the steady-state energy distribution; Section 4 illustrates a verification of the unified solution for the integrated system; Finally, case studies are described in Section 5, and the conclusion is provided in Section 6.

2. Modeling of the integrated gas and power system

2.1. Power flow in the electric power system

Power flow studies are of great importance in planning and operation of power systems. The goal of a power-flow study is to obtain voltage angle and magnitude information for each bus in a power system for specified load and generator power and voltage conditions [23]. The problem can be formulated as follows. The bus voltage V and nodal admittances matrix Y of the system are given in polar coordinates by

$$V_i = |V_i|\angle\theta_i = |V_i|(\cos\theta_i + j\sin\theta_i) \tag{1}$$

$$Y_{ij} = |Y_{ij}|\angle\theta_{ij} = |Y_{ij}|(\cos\theta_{ij} + j\sin\theta_{ij}) = G_{ij} + jB_{ij} \tag{2}$$

Then the real power and reactive power injection at different buses are given by

$$P_i = |V_i|\sum_{j=1}^{N}|V_j|(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) \tag{3}$$

$$Q_i = |V_i|\sum_{j=1}^{N}|V_j|(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) \tag{4}$$

where $\theta_{ij} = \theta_i - \theta_j$. Eqs. (3) and (4) constitute the polar form of the power flow equations. The net active power P_i and reactive power Q_i entering bus i are calculated. Let $P_{g,i}$ and $P_{d,i}$ denote the power generation and consumption at bus i. Then the nodal power balance equations are given as

$$\Delta P_i = P_{g,i} - P_{d,i} - |V_i|\sum_{j=1}^{N}|V_j|(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) \tag{5}$$

$$\Delta Q_i = Q_{g,i} - Q_{d,i} - |V_i|\sum_{j=1}^{N}|V_j|(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) \tag{6}$$

2.2. Wind power output

For each wind-power unit, the active power for a variable speed wind turbine ($P_{g,var}$) is calculated based on [24]

$$P_{g,var}(v) = \begin{cases} 0 & \text{if } v < V_{ci} \text{ or } v > V_{co} \\ a + bv^3 & \text{if } V_{ci} \leqslant v \leqslant V_r \\ P_r & \text{if } V_r \leqslant v \leqslant V_{co} \end{cases} \tag{7}$$

where $P_{g,var}(v)$ is the wind power for a variable speed wind turbine at wind speed v. P_r is the rated power output of the wind-power unit., V_{ci}, V_r and V_{co} are the cut-in, rated and cut-out wind speeds, respectively. The coefficient a is the bias value, and b is the gradient value.

2.3. Gas flow in the natural gas system

The steady-state modelling of the natural gas system is formulated by the gas flow equations, compression power calculation and nodal mass balance. In this work, the elevation deviation in the gas pipelines is neglected. Besides, the assumption of isothermal flow is good enough for most practical purposes, since the gas temperature reaches constant values in long transmission lines [25]. Therefore, the temperature deviation in the gas pipelines is neglected in this work. We concentrate on the steady-state isothermal flow of gas in pipelines. With these assumptions, the flow equations and nodal balance equations can be formulated as follows.

2.3.1. Pipeline flow equation

For the steady-state isothermal flow in a gas pipeline, the flow rate is related to the pressure drop. Based on the assumptions that there is no elevation change in the pipeline, and the condition of flow is isothermal [25], the pipeline flow equation is expressed by

$$G_{gas,km} = C\left(\frac{T_b}{p_b}\right)D_{km}^{2.5}\left(\frac{p_k^2 - p_m^2}{L_{km}\gamma_G T_{a,km} Z_a f_{km}}\right)^{0.5} E_{p,km} \tag{8}$$

In the flow equation, the friction factor f_{km} is determined by different formulas based on different flow regimes. Note that in high-pressure gas transmission pipelines with high flow rates, only two types of flow regimes are observed: partially turbulent flow and fully turbulent flow [26]. Under this situation, f_{km} is given in SI units as

$$f_{km} = \frac{0.009407}{\sqrt[3]{D_{km}}} \tag{9}$$

where the friction factor f_{km} is determined only by the pipe diameter as mentioned above.

The physical characteristics of each pipeline with fixed gas composition in Eq. (8) can be summarized by a single constant C_{km} [27]:

$$C_{km} = C\left(\frac{T_b}{p_b}\right)D_{km}^{2.5}\left(\frac{1}{L_{km}\gamma_G T_{a,km} Z_a f_{km}}\right)^{0.5} E_{p,km} \tag{10}$$

And then a more compact form of Eq. (8) depicting the gas flow from node k to m can be given as

$$\Pi_k - \Pi_m = R_{km}G_{gas,km}^2 \tag{11}$$

where $\Pi_k = p_k^2$, $\Pi_m = p_m^2$ and $R_{km} = 1/C_{km}^2$, R_{km} represents the hydraulic resistance coefficient of the pipeline whose meaning is similar to the line impedance of the power system.

2.3.2. Compression power calculation

The brake horsepower of the gas compressor is related to the compression ratio (CR) and gas flow rate from the compressor. Compression ratio (CR) is the ratio of absolute discharge pressure to the absolute suction pressure [28].

$$CR = \frac{p_m}{p_k} = \left(\frac{\Pi_m}{\Pi_k}\right)^{0.5} \tag{12}$$

$$\mathrm{BHP}_{km} = K_{\mathrm{GC}} Z_a G_{\mathrm{GC},km} \left[\frac{T_s}{E_c \eta_c}\right] \left[\frac{c_k}{c_k - 1}\right] \left[\left(\frac{p_m}{p_k}\right)^{\frac{c_k-1}{c_k}} - 1\right] \tag{13}$$

$$\mathrm{BHP}_{km} = K_{\mathrm{GC}} Z_a G_{\mathrm{GC},km} \left[\frac{T_s}{E_c \eta_c}\right] \left[\frac{c_k}{c_k - 1}\right] \left[\left(\frac{\Pi_m}{\Pi_k}\right)^{\frac{c_k-1}{2c_k}} - 1\right] \tag{14}$$

where K_{GC} is a constant, the value depends on the units of the $G_{\mathrm{GC},km}$ in the equation, for MMscfd, the value of K_{GC} is 0.0854; It should be mentioned that 1 MMscfd of gas flow at 15 °C equals 1177 m^3/h in flow rate. So the value of K_{GC} is 7.26×10^{-5} if the unit of $G_{\mathrm{GC},km}$ is given as m^3/h.

2.3.3. Nodal gas balance equation

The nodal gas balance equations simply indicate that the sum of the inflows and outflows at the node should be zero:

$$G_{s,k} - G_{d,k} - \sum_{m \in k} G_{gas,km} = 0 \tag{15}$$

Considering a natural gas network consisting of N nodes and M branches, a reference node is pre-set with given nodal pressure. The unknown variables include $(N-1)$ nodal pressures and M pipeline flow rates.

2.4. Integrated natural gas and power flow formulation

The energy conversion between the gas and electric power system primarily takes place in the GPG units and P2G.

2.4.1. Gas-fired power generation

For the Gas-fired power generation, heat rate (HR) is a term used to indicate the power plant efficiency, which is the ratio of heat given up by the natural gas, regarding its lower heating value (LHV), to the power available at the GPG [29]. It has the SI unit of MJ/MW h. Therefore, a lower heat rate gives higher energy efficiency. And the relationship between the heat rate and efficiency can be found in [30] as

$$\eta_{\mathrm{GPG}} = \frac{3600}{HR} \tag{16}$$

The relationship between the power generation and the natural gas network is mathematically formulated by the heat rate curve,

$$HR = \alpha + \beta P_{g,\mathrm{GPG}} + \gamma P_{g,\mathrm{GPG}}^2 \tag{17}$$

where the coefficients α, β, γ define the efficiency in this energy conversion process.

Then the gas consumption, $G_{d,\mathrm{GPG}}$ (m^3/h), can be calculated approximately from

$$G_{d,\mathrm{GPG}} = \frac{HR \cdot P_{g,\mathrm{GPG}}}{\mathrm{LHV}} \tag{18}$$

The gas flow required for the energy demanded can also be computed by the following equation if the power plant efficiency is known.

$$G_{d,\mathrm{GPG}} = \left(\frac{3600}{\eta_{\mathrm{GPG}} \mathrm{LHV}}\right) P_{g,\mathrm{GPG}} \tag{19}$$

where LHV represents the lower heating value of the natural gas, the value is from 35.40 to 39.12 MJ/m^3 [31]. An average value of 37.26 MJ/m^3 is used in this paper.

2.4.2. Power to gas

Power to gas (P2G) system can produce hydrogen, and the produced hydrogen can also be injected into the gas network. But the amount of hydrogen to be fed into the gas system is limited since there are still many impacts and uncertainties on injecting hydrogen into the gas system. Firstly, blending hydrogen into natural gas pipeline reduces the thermal energy due to the lower energy density of the hydrogen gas. Secondly, blending hydrogen gas gives bad effects on pipe material including embrittlement, which decreases material strength. Thirdly, the leakage rate of hydrogen is greater than methane since hydrogen is a much smaller molecule, a large leakage of hydrogen may also cause economic and safety concerns [32]. Besides, blending hydrogen in gas network gives adverse effects on the gas appliance, such as burners, boilers or gas engines. Therefore, there are still many mandatory restrictions for injecting hydrogen into gas network. For example, the maximum level of hydrogen content that is allowed in the UK is 0.1% (by volume) [22]. Considering the main composition of natural gas is methane, the target product of P2G is methane in this paper. Thus, the production chain of P2G consists of two steps: electrolysis and methanation. Electrolysis is a process of using electricity to split water into hydrogen and oxygen. The chemical reaction [33] in the electrolyzer is elaborated by

$$2\mathrm{H_2O(l)} \leftrightarrow 2\mathrm{H_2(g)} + \mathrm{O_2(g)} \quad \Delta\mathrm{H} = +571.6\ \mathrm{kJ} \tag{20}$$

Methanation is the synthesis of hydrogen and carbon dioxide to methane. This process is based on the Sabatier reaction

$$\mathrm{CO_2(g)} + 2\mathrm{H_2(g)} \leftrightarrow \mathrm{CH_4(g)} + \mathrm{O_2(g)} \quad \Delta\mathrm{H} = +318.7\ \mathrm{kJ} \tag{21}$$

The methane is then compressed, metered and injected into the natural gas system. Combine both of the reaction (20) and (21), an overall reaction P2G can be given as

$$\mathrm{CO_2(g)} + 2\mathrm{H_2O(l)} \leftrightarrow \mathrm{CH_4(g)} + 2\mathrm{O_2(g)} \quad \Delta\mathrm{H} = +890.3\ \mathrm{kJ} \tag{22}$$

From the overall Eq. (22), theoretically, with every 890.3 kJ of energy consumed, 1 mol of CO_2 can be turned into 1 mol of methane. In practice, the energy conversion efficiency (η_{P2G}) should also be considered. In this work, η_{P2G} is defined as the ratio of the absorbed energy density by the produced gas to the power consumed by P2G, per unit volume of gas produced. The same as GPG, the energy density of natural gas is given regarding its lower heating value (LHV). Thereby the energy conversion relationship between the gas generation rate $G_{s,\mathrm{P2G}}$ and the consumed power $P_{d,\mathrm{P2G}}$ can be given as

$$\eta_{\mathrm{P2G}} = \frac{(G_{s,\mathrm{P2G}}/3600) \cdot \mathrm{LHV}}{P_{d,\mathrm{P2G}}} \times 100\% \tag{23}$$

where $G_{s,\mathrm{P2G}}$ is gas generation rate of the P2G system, m^3/h, which can be calculated from

$$G_{s,\mathrm{P2G}} = \left(\frac{3600\eta_{\mathrm{P2G}}}{\mathrm{LHV}}\right) \times P_{d,\mathrm{P2G}} \tag{24}$$

The physical characteristics of each P2G system in Eq. (24) can be expressed by a single constant C_{P2G} given by

$$C_{\mathrm{P2G}} = \frac{3600\eta_{\mathrm{P2G}}}{\mathrm{LHV}} \tag{25}$$

This leads to a simpler equation for the P2G system,

$$G_{s,\mathrm{P2G}} = C_{\mathrm{P2G}} P_{d,\mathrm{P2G}} \tag{26}$$

where C_{P2G} denotes the energy conversion from electricity to the natural gas in P2G system, the value of C_{P2G} is in proportion to the energy efficiency of the P2G system.

This is a simplified model for showing the relationship between the amount of used electricity and the amount of gas production in P2G. In this model, the amount of used electricity is determined by the amount of gas production and the efficiency of the P2G system, which is similar to the model in [22].

3. A unified gas and power flow solution

The integrated natural gas and electric power system is composed of a gas network and a power grid. The formulation of the integrated natural gas and electricity infrastructures is obtained by combining the stated flow models. The bi-directional energy flow is formed by considering the links between both infrastructures via the gas compressor, GPG and P2G. For simplification of analysis, the unit of the gas flow rate is converted to power unit as MW and then per-unit conversion is carried out in the integrated system. Finally, a unified modelling and solution framework is described to solve the coupled gas and power flow equations.

3.1. Unification of units and the per-unit system

The integrated gas and power system is composed of a gas network and a power system. For simplification of analysis in the integrated energy system, the unit of the gas flow rate is converted to power unit as MW by introducing the energy density of natural gas. For natural gases, the energy density is its lower heating value (LHV) in MJ/m^3. Thus, the novel gas flow rate (S_{gas}) can be calculated by

$$S_{\text{gas}} = \frac{G_{\text{gas}} \times \text{LHV}}{3600} \tag{27}$$

where S_{gas} is the converted form of gas flow rate in MW.

Thus, Eq. (11) can be rewritten as

$$\Pi_k - \Pi_m = Z_{km} S^2_{\text{gas},km} \tag{28}$$

where Z_{km} in kPa^2/(MW)^2 represents the resistance coefficient of the pipeline whose meaning is similar to the line impedance of the power system.

Accordingly, Eqs. (15), (19) and (24) can be rewritten as the following equations.

$$\Delta S_k = S_{s,k} - S_{d,k} - \sum_{m \in k} S_{\text{gas},km} \tag{29}$$

$$S_{d,\text{GPG}} = \frac{P_{g,\text{GPG}}}{\eta_{\text{GPG}}} \tag{30}$$

$$S_{g,\text{P2G}} = \eta_{\text{P2G}} P_{d,\text{P2G}} \tag{31}$$

The unit of BHP is also converted to the power unit (MW), it is known that one horsepower equals to 745.7 Watts. Thus, the converted form of power consumption in compressor can be given as

$$P_{\text{GC},km} = 745.7 \times 10^{-6} \times \text{BHP}_{km} \tag{32}$$

$$P_{\text{GC},km} = K'_{\text{GC}} Z_a S_{\text{gas},km} \left[\frac{T_s}{E_c \eta_c}\right] \left[\frac{c_k}{c_k - 1}\right] \left[\left(\frac{\Pi_m}{\Pi_k}\right)^{\frac{c_k-1}{2c_k}} - 1\right] \tag{33}$$

where K'_{GC} is a constant, the value depends on the units of the $S_{\text{gas},km}$ in the equation. If the unit of $S_{\text{gas},km}$ is given as MW, and the energy density of natural gas is set as 37.26 MJ/m^3, the value of K'_{GC} is 5.23×10^{-6}.

Thereby, both of gas flow and power flow are measured by MW in this paper.

Furthermore, for simplicity, a per-unit system is applied to describe the integrated gas and power system which is widely adopted in the power systems analysis. In this paper, we consider that the base value of voltage is 110 kV, the base value of gas pressure is 1 MPa and the base value of power is 100 MW. Then the rest of the units can be derived from the independent based values. Finally, all the related coefficients are adjusted to meet the per-unit system accordingly.

3.2. Unified gas and power flow solution

In order to analyze the steady state energy distribution in the integrated energy system, the integrated energy flow is formed by gathering the stated flow models of both natural gas and electric power system. A set of nonlinear equations representing the gas and power systems are obtained based on the nodal balance of gas and power flows, respectively.

$$\Delta P_i = P_{g,i} - P_{d,i} - |V_i| \sum_{j=1}^{N} |V_j| (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) \tag{5}$$

$$\Delta Q_i = Q_{g,i} - Q_{d,i} - |V_i| \sum_{j=1}^{N} |V_j| (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) \tag{6}$$

$$\Delta\Pi_{km} = \Pi_k - \Pi_m - Z_{km} S^2_{\text{gas},km} \tag{34}$$

$$\Delta S_k = S_{k,s} - S_{k,d} - \sum_{m \in k} S_{\text{gas},km} \tag{35}$$

$$\Delta P_{\text{GC}} = P_{\text{GC}} - K'_{\text{GC}} Z_a S_{\text{gas},km} \left[\frac{T_s}{E_c \eta_c}\right] \left[\frac{c_k}{c_k - 1}\right] \left[\left(\frac{\Pi_m}{\Pi_k}\right)^{\frac{c_k-1}{2c_k}} - 1\right] \tag{36}$$

The Newton–Raphson method is popular for solving the nonlinear equations. Concretely, consider a point X close to the exact solution, the linearization of all the nonlinear equations at X can be given by the Taylor series expansion [34] as

$$F(X) = -J \times \Delta X \tag{37}$$

The above equation forms the basis for the iterative procedure to calculate the solution. Where X represents all the unknown variables and $F(X)$ represents all of the mismatches, thus

$$X = [\theta \quad |V| \quad P_{\text{GPG}} \quad P_{\text{P2G}} \quad P_{\text{GC}} \quad \Pi \quad S_{\text{gas}}]^{\text{T}} \tag{38}$$

$$F(X) = [\Delta P \quad \Delta Q \quad \Delta\Pi \quad \Delta S \;\; \Delta P_{\text{GC}}]^{\text{T}} \tag{39}$$

and J is a Jacobian matrix of partial derivatives which is given by

$$J = \begin{bmatrix} \frac{\partial \Delta P}{\partial \theta} & \frac{\partial \Delta P}{\partial |V|} & \frac{\partial \Delta P}{\partial P_{\text{GPG}}} & \frac{\partial \Delta P}{\partial P_{\text{P2G}}} & \frac{\partial \Delta P}{\partial P_{\text{GC}}} & 0 & 0 \\ \frac{\partial \Delta Q}{\partial \theta} & \frac{\partial \Delta Q}{\partial |V|} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{\partial \Delta\Pi}{\partial \Pi} & \frac{\partial \Delta\Pi}{\partial S_{\text{gas}}} \\ 0 & 0 & \frac{\partial \Delta S}{\partial P_{\text{GPG}}} & \frac{\partial \Delta S}{\partial P_{\text{P2G}}} & \frac{\partial \Delta S}{\partial P_{\text{GC}}} & \frac{\partial \Delta S}{\partial \Pi} & \frac{\partial \Delta S}{\partial S_{\text{gas}}} \\ 0 & 0 & 0 & 0 & \frac{\partial \Delta P_{\text{GC}}}{\partial P_{\text{GC}}} & \frac{\partial \Delta P_{\text{GC}}}{\partial \Pi} & \frac{\partial \Delta P_{\text{GC}}}{\partial S_{\text{gas}}} \end{bmatrix} \tag{40}$$

According to the practical operation situation of the power system and gas network, every parameter has an available solution domain that provides a setting range of the initial values. In the available solution domain, the convergence of Newton–Raphson method has been verified in this work by comparing various calculation results under differing initial iterative values.

4. Numerical verification of the unified solution

In this section, we establish several cases to verify our proposed unified modelling and solution. The convergence of Newton–Raphson method has been verified in this work by comparing various calculation results under differing initial iterative values. The simulation results are summarized in Tables 1–4.

Cases for comparison: (1) In Case 1, the unit of the gas network has not been converted to the power unit, we consider that the unit of gas flow rate is m^3/h and the unit of gas pressure is kPa; the unit for voltage is kV, and the unit of power is MW. (2) Case 2 is a per-unit system, the unit of the gas flow rate is converted to power unit

Table 1
The nodal parameters of natural gas network.

No.	Case 1			Case 2		
	Gas supply (m^3/h)	Gas demand (m^3/h)	Gas pressure (kPa)	Gas supply (p.u.)	Gas demand (p.u.)	Gas pressure (p.u.)
1	60,000	12012.09	969.98	6.210	1.243	0.97
2	0	10,000	500	0	1.035	0.50
3	0	12,000	438.63	0	1.242	0.44
4	10012.1	0	1000	1.036	0	1
5	0	20,000	860.69	0	2.070	0.86
6	0	16,000	814.86	0	1.656	0.81
7	0	0	1000	0	0	1

as MW. Furthermore, in the per-unit system, the base value of voltage is 110 kV, the base value of gas pressure is 1 MPa, and the base value of power is 100 MW.

4.1. The structure of the integrated gas and electricity system

An IEEE-9 test system combined with a 7-node natural gas network is applied to illustrate the proposed approach as shown in Fig. 1. The 7-node gas network is not a real gas network, but a simplified version of a gas system. It is composed of six pipelines and seven nodes. The node of N7 is connected with gas storage which is considered the reference node where the nodal pressure is specified as 1 MPa shown in Table 1. Its parameters are taken from the real gas system as shown in Table 2. On the other hand, the electricity infrastructure has three generators at B1, B2 and B3, and has three load buses at B5, B6 and B8. B1 is defined as a gas-fired generator that is connected to N1. B2 and B3 are set as a wind farm and a coal-fired power plant, respectively. Finally, there are three links between the 7-nodes gas network and IEEE-9 system, which are gas-fired generator, gas compressor and P2G. There are four kinds of parameters in this integrated system: the pipeline's hydraulic resistance coefficient given in Table 2; the impedance of the transmission lines in electricity system; the energy efficiency of GPG which is given as 0.8 in this case study; the last one is the energy efficiency of P2G, which is expected in the region of 55–80% [35]. In this study, the energy efficiency of P2G is set as 0.8.

4.2. Initialization and comparison

Newton–Raphson method begins with initial guesses of all unknown variables (such as voltage magnitudes and angles at load buses and voltage angles at generator buses, nodal pressures at the gas network, and pipeline flow rates). It is common to use a "flat start" in which all pipeline flow rates, nodal pressures and voltage angles are set to zero. The initial guesses of the unknown voltage magnitudes are set as 1. The pre-set tolerance is 10^{-10}. The detailed simulation results are summarized in Tables 1–4.

Table 1 summarizes the results for the natural gas network associated with the natural gas source, gas demanded by the gas-fired plant, gas supplied by P2G, as well as the nodal pressures. Table 2 summarizes the pipeline's parameters and gas flow rates. The data of electric network are summarized in Table 3, which includes active power supplies, active power demands, voltage magnitudes, as well as voltage phase angles. The comparison results indicate that the calculation of the unified solution in Case 2 agreed well with that in Case 1. Thus, the testing results prove that this unified solution with the per-unit system is feasible and sufficiently accurate.

Furthermore, Table 4 gives the comparison of calculation results in terms of power loss (*PL*), energy loss (*EL*) and power consumption in the gas compressor (BHP or P_{GC}) under differing initial iterative values. It shows that all the calculations can converge to a stable value even though the initial value of all the unknown voltage magnitude $|V_i|$ vary from 1 to 4. This illustrates that the Newton–Raphson method has good convergence when used in the integrated gas and power system. Further, the iteration in Case 2 is faster than the iteration in Case 1 as shown in Table 4. This indicates that the unified solution with the per-unit system has a better computational efficiency. It also helps to extend this method to the real-word implementations.

5. Numerical simulations

5.1. The mitigation effect of the integrated natural gas and electricity system

5.1.1. The mismatch of wind power and power demand

In order to investigate the impact of the fluctuant power supply and demand on the integrated natural gas and electricity system, a stochastic data of wind power and power demand is injected into the electric network. The data of wind power and power demand is obtained from Energinet.dk, the power transmission system operator in Denmark. These data measured with a time interval of one hour. The data in the first two weeks of January 2014 is adopted in this study. Fig. 2 shows the time series of the wind power and power load. It shows that the overall power demand is usually lower during the night hours while the wind blows. And there are peak demands in the morning and later in the evening. Compared with the electricity demand, the output of wind power is more unpredictable and intermittent. It shows that sometimes the fluctuation of wind power has a reverse trend to electricity

Table 2
The branch parameters of natural gas network.

Branch	From	To	Case 1		Case 2	
			$R_{km}(\text{kPa}^2/(\text{m}^3/\text{h})^2)$	$G_{km}(\text{m}^3/\text{h})$	Z_{km}(p.u.)	S_{km}(p.u.)
1	6	1	0.0003	47987.9	0.0280	4.967
2	1	2	0.0004	12,000	0.0373	1.242
3	2	3	0	25987.9	0.0000	2.689
4	4	3	0.00025	0	0.0233	0
5	5	4	0.0002	36,000	0.0187	3.726
6	6	5	0.0003	16,000	0.0280	1.656

Table 3
The electric parameters of power system.

Bus	Case 1				Case 2			
	$\lvert V_i\rvert$(kV)	$\theta_i(rad)$	P_g(MW)	P_d(MW)	$\lvert V_i\rvert$(p.u.)	θ_i(p.u.)	P_g(p.u.)	P_d(p.u.)
1	112.97	−0.054	99.5	0	1.027	−0.054	0.995	0
2	109.89	−0.112	90	0	0.999	−0.112	0.9	0.000
3	111.32	−0.075	160	0.6	1.012	−0.075	1.6	0.006
4	112.75	−0.031	0	0	1.025	−0.031	0	0
5	111.32	−0.056	0	125	1.012	−0.056	0	1.250
6	113.41	0.033	0	90	1.031	0.033	0	0.900
7	112.75	0.022	0	129.5	1.025	0.022	0	1.295
8	112.75	0.121	0	0	1.025	0.121	0	0.000
9	114.4	0.000	0	0	1.040	0.000	0	0.000

Table 4
The comparison of calculation results under differing initial iterative values.

Case 1					Case 2				
Initial values of all $\lvert V_i\rvert$(kV)	Iterations (times)	*PL* (MW)	BHP (Horsepower)	*EL* (MW)	Initial values of all $\lvert V_i\rvert$(p.u.)	Iterations (Times)	*PL* (p.u.)	P_{GC} (p.u.)	*EL* (p.u.)
110	11	4.33	847.1	55.64	1	6	0.043	0.0064	0.556
220	12	4.33	847.1	55.64	2	8	0.043	0.0064	0.556
330	16	4.33	847.1	55.64	3	9	0.043	0.0064	0.556
440	14	4.33	847.1	55.64	4	10	0.043	0.0064	0.556

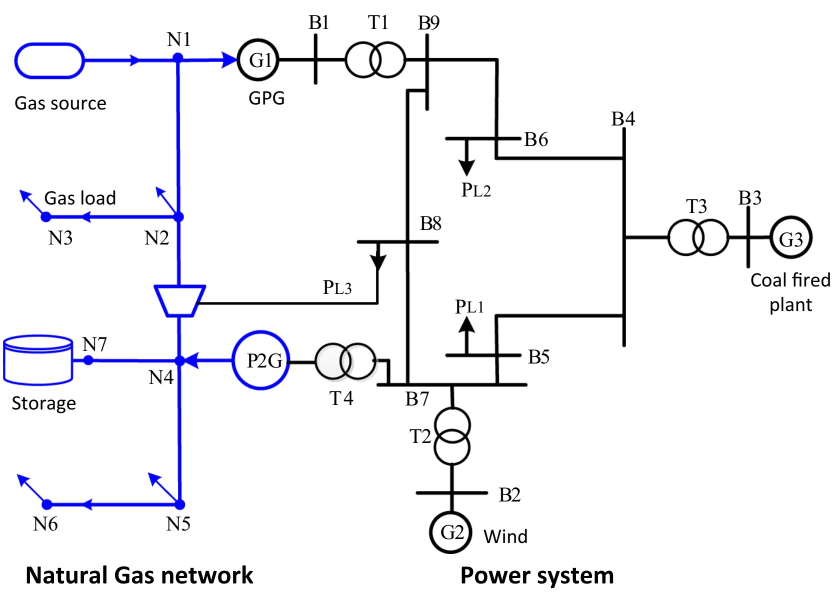

Fig. 1. Structure of an integrated gas and electricity system.

demand. Thus, a backup capacity such as GPG is required to provide peak regulation, while a large scale storage technology such as P2G is increasingly needed to store the surplus wind power to accommodate the growing supplies of intermittent renewable energy.

5.1.2. The mitigation effect of using P2G in the integrated system

In order to investigate the mitigation effect of using P2G in the integrated natural gas and electric power system, the comparison of the integrated energy system with P2G and without P2G is carried out in the context of power loss, power consumption in the gas compressor and the total energy loss as shown in Figs. 3–5. The total energy loss is defined as the difference between the total energy supply in the integrated system and the total energy demand. Similar to voltage in the power system, the nodal gas pressure is a vital factor for the security operation of the gas network, the effect of P2G on the nodal gas pressure is another issue investigated as shown in Fig. 6.

The stochastic wind power is injected into the electric power system through B2, and the time-series of power load is distributed to B5 and B6 in the power system. The gas demand in the gas network is also set as a time series which is obtained from Energinet.dk. It should be noted that the gas injection from the gas source is generally assumed to be a flat profile which means it is a constant injection rate. We set the gas injection rate from the gas source as 4 p.u. in this study. Thereby the fluctuation of the gas demand will be balanced by the linepack of the gas network. To be specific, the change of gas load will result in linepack variation. Especially, in the peak hour, the increased gas demand from GPG will lead to a rapid linepack reduction, which brings a great challenge to the linepack maintenance. Thus, a sufficient linepack is critical for the reliability of gas supply. The effect of using P2G on the variation of linepack is shown in Fig. 7.

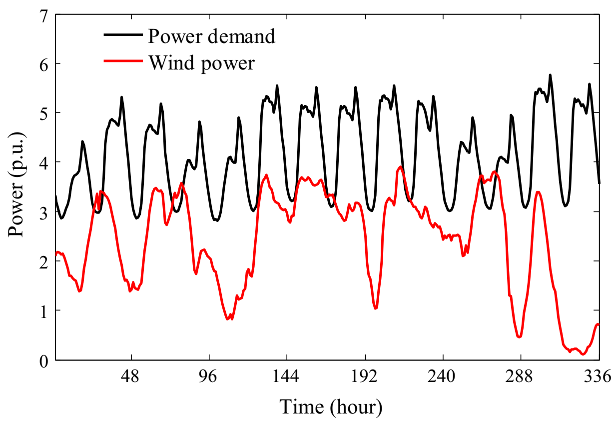

Fig. 2. The fluctuation of wind power and power demand.

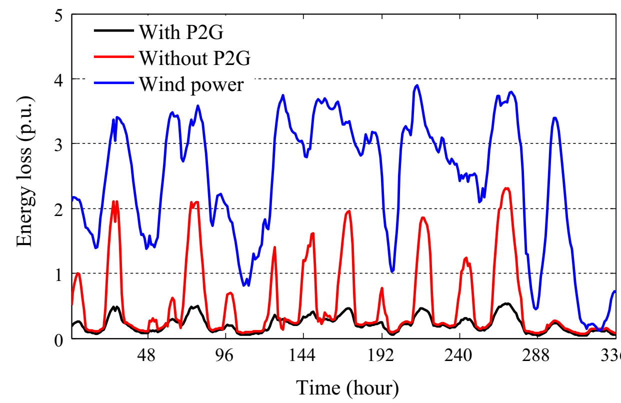

Fig. 5. Comparing the total energy loss in the integrated system with P2G versus without P2G.

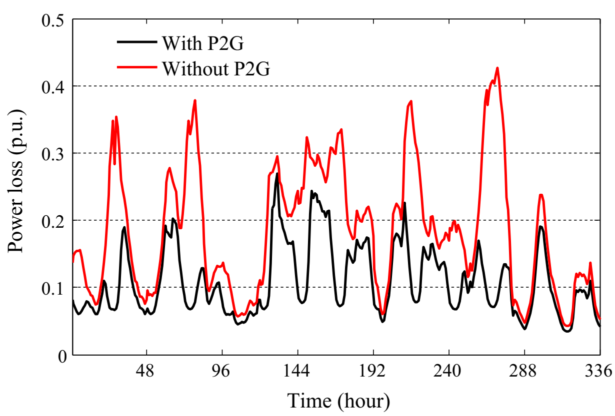

Fig. 3. Comparing the power loss in the integrated system with P2G versus without P2G.

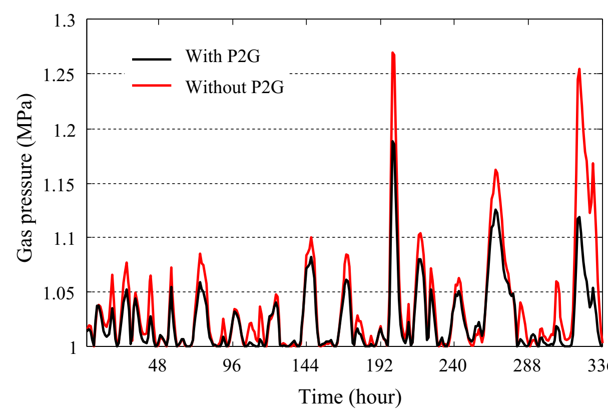

Fig. 6. Comparing the fluctuation of the nodal gas pressure in the integrated system with P2G versus without P2G.

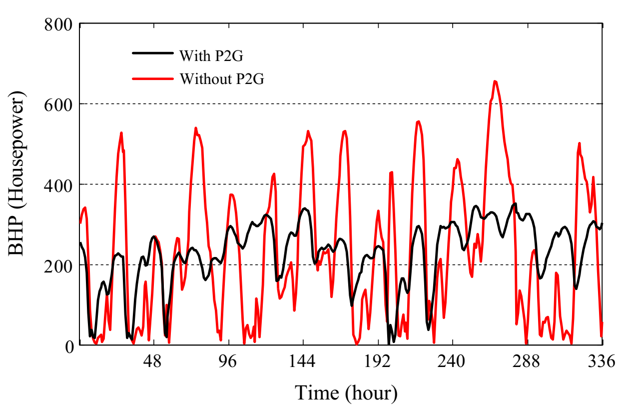

Fig. 4. Comparing the brake horsepower in the integrated system with P2G versus without P2G.

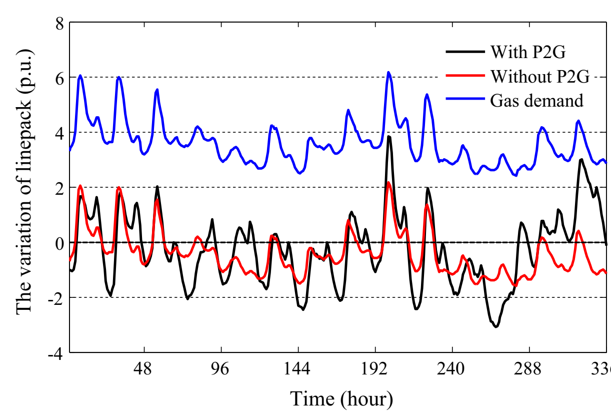

Fig. 7. Comparing the variation of linepack in the integrated system with P2G versus without P2G.

The power loss in the power system is illustrated in Fig. 3. It shows that power loss can be reduced by the integration of P2G in the coupled natural gas and power system. Without P2G, the power loss fluctuates significantly from 0.05 p.u. to 0.43 p.u. The total power loss accounts for 5.6% of the total power demand. While, in the integrated systems with P2G, the power loss is reduced, it just fluctuates between 0.04 and 0.28 p.u. Within the given time horizon, 27.5% total power loss is reduced by using P2G. The reason is that the P2G, located at B7, can help with the local balance of the wind power. Part of the surplus wind power produced at B2 can be consumed by P2G at B7 so that it would not need to transmit long distances to other buses such as B6. Thus, from the perspective of reducing power loss, it is preferred to locate P2G near a wind farm.

Similar to the power system, there is energy loss in the transmission of natural gas. The transmission loss in the natural gas network is mainly consumed by the gas compressor. Fig. 4 shows the brake horsepower (BHP) in the gas compressor. Compared with the integrated system without P2G, the BHP fluctuation is dampened when P2G is introduced to the integrated energy system. Without P2G, the BHP fluctuates significantly from 0 to 660 horsepower.

Whereas in the integrated systems with P2G, the BHP is decreased, it just fluctuates between 0 and 340 horsepower. As some gas fuel can be produced by P2G and then injected into the gas network from N4, the local gas consumption can be balanced by gas supplies from P2G, which helps to reduce the natural gas flow in the compressor. From Eq. (13), it is seen that BHP is proportional to the gas flow rate in the compressor. That's why P2G has mitigation effect on the BHP.

Fig. 5 shows the comparison of the total energy loss that is defined as the difference between the total energy generation in the integrated system and the total energy demand. It should be mentioned that the wind generation is taken into account. It is seen that when there is a lower penetration level of wind power, there is not much difference in the total energy loss between the integrated systems with P2G and without P2G. But the difference increases with the penetration level of wind power. The reason is that without P2G, surplus wind power is curtailed when there is a high penetration level of wind power but low power demand. Whereas, as a part of surplus wind power can be converted to gas fuel by using P2G, the wind curtailment is decreased, and the total energy loss can also be reduced. Further analysis shows that the total energy loss in the given horizon is reduced 62 percent by using P2G if the wind curtailment is regarded as a part of the total energy loss.

The effect of using P2G on the natural gas network is another issue of concern. The simulation results of the nodal gas pressure at N4 and the linepack of the gas network are illustrated in Figs. 6 and 7, respectively.

Just like the voltage stability, which is an important factor on the reliability of electric power system, the nodal gas pressure is a vital factor for the security operation of the gas network. Fig. 6 shows the fluctuation of the gas pressure at N4. It can be seen that the gas pressure fluctuation is dampened when P2G is introduced to the integrated gas and power system. In this figure, the gas pressure fluctuates within a range of 1–1.27 MPa if the integrated system is operated without P2G. When the integrated system is operated with P2G, it is limited in a narrower range between 1 MPa and 1.18 MPa. This indicates that the integrated gas and electricity system with GPG and P2G has more flexibility to help accommodate the fluctuation of the power system. It can preserve high stabilization in the gas network when a sufficient linepack is considered in the operational process.

It should be noted that the gas injection from the gas source are assumed to be flat which means the gas supply is at a constant rate. So linepack plays an important role in providing flexibility to meet the load fluctuation. When the gas demand exceeds gas supply, it is consumed. When there is more gas injection than gas demand, it is replenished. Fig. 7 shows the variation of linepack. It should be mentioned that the linepack is consumed when the variation value is positive, and the linepack is replenished when the variation value is a minus. It can be seen that the variation of linepack constantly changes with gas demand. And linepack plays a more critical role in the integrated system with P2G. From Fig. 7, the variation of the integrated system with P2G is larger than that without P2G. The reason is that the surplus wind power can be converted to gas fuel through the using of P2G, which can increase the replenishing speed of the linepack, accordingly it makes a more rapid variation on the linepack. It also illustrates that the linepack plays a more important role in the integrated system with P2G than that without P2G.

5.2. The effect of the wind power and power demand on the integrated gas and power system

The fluctuation and mismatch of wind power and power demand have been described above. We also concern the effect of wind power and power demand on the energy converters (P2G and GPG). In order to investigate the effect of wind power and power demand on P2G and GPG, a time series of wind power is injected into the electric network through bus 2, and the load at bus 5 and 6 are also set as a stochastic time-series. One year's data of 2014 is adopted in this study that is obtained from Energinet.dk.

Fig. 8 shows the relationship of the wind power, power demand and the output of P2G. It's clear that there is much higher gas produced by P2G when the power consumption is lower and the penetration of wind power is higher. Which can be attributed to the energy storage property of P2G: when the production of wind power increases, the surplus electricity power will be used to produce gas fuel that can be stored in the existing natural gas networks and the stored energy can then be injected back into electricity system through GPG. This indicates that the P2G technology has a potential to provide flexibility to the growing intermittent renewable energy.

The effect of the wind power and power demand on the output of gas-fired power plant is shown in Fig. 9. As we can see, the electricity generation in GPG increases with power demand and decreases with the wind power. When there is lower in wind power supply and higher in power consumption, the GPG will increase electricity production to meet the power balance. This result provides a clear exhibit of the ability of peak regulation of the gas-fired power generation. Thus, the required flexibility to meet the fluctuation of power load and renewables can be managed by the GPG.

Fig. 10 shows the relationship among the wind power, power demand and the reducing ratio of the total energy loss, where the reducing ratio of the total energy loss is defined as the decrease of the total energy loss by using integrated energy system with P2G divided by the total energy loss generated in the system without P2G. As we can see, this reducing ratio of the total energy loss

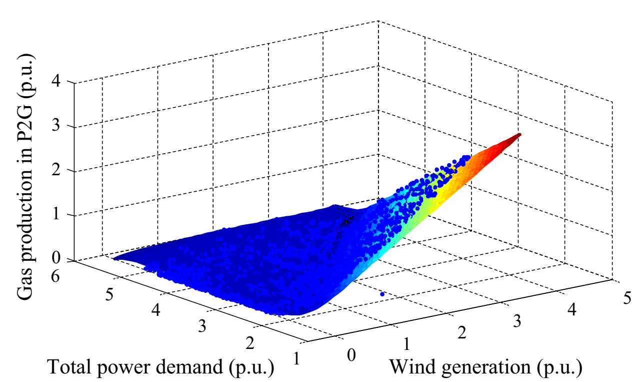

Fig. 8. The effect of the wind power and power demand on the output of P2G.

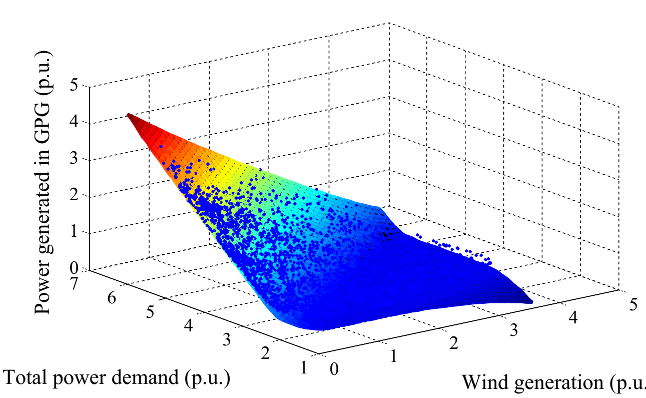

Fig. 9. The effect of the wind power and power demand on the output of gas-fired power plant.

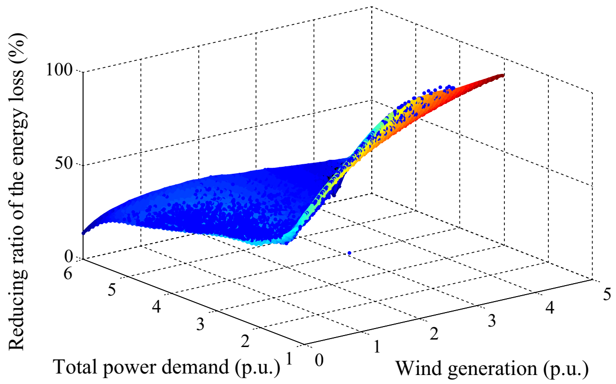

Fig. 10. The reducing ratio of energy loss in the integrated energy system.

increases with wind power and decreases with power demand, which indicates that the integrated energy system has a more notable influence on reducing the power loss when there is a larger output of wind power and lower power demand.

6. Conclusion

In this paper, a harmonized integration of natural gas and electric power system with bi-directional energy conversion is formulated as a set of non-linear equations. And a unified modelling and solution framework is developed to solve the coupled gas and power flow equations. The unification of units and per-unit system are proposed to simplify the system description and to enhance the computation efficiency. Case studies on an IEEE-9 test system combined with a 7-node natural gas network are carried out to demonstrate the applicability of the proposed approach. The testing results indicate that this unified solution with the per-unit system is feasible and sufficiently accurate. Furthermore, the unified solution with the per-unit system has a better computational efficiency. After that, time series of wind power and power load are introduced to investigate the mitigation effect of using P2G in the integrated natural gas and electric power system. Simulation results show that all the power loss, BHP and the total energy loss can be reduced by using P2G in the integrated energy system. It also indicates that the integrated gas and power system with P2G can maintain a stable level due to its network flexibility. Besides, a sufficient line-pack is more critical for the integrated energy system with P2G. At last, the effect of wind power and power demand on the output of the P2G and GPG is also investigated, the result provides an exhibit of the ability of peak regulation of GPG and P2G.

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