https://doi.org/10.1016/j.energy.2019.03.154

Game-Theoretic Planning for Integrated Energy System with Independent Participants Considering Ancillary Services of Power-to-Gas Stations

Xian Zhang, K. W. Chan, Huaizhi Wang*, Jiefeng Hu, Bin Zhou, Yan Zhang, Jing Qiu

Abstract— **The emergence of power-to-gas stations (P2GSes) has provided opportunities to make an efficient use of surplus power generated from intermittent renewable energy, thus linking the natural gas and electricity networks as an integrated energy system. To build new P2GSes, new electricity feeders and natural gas pipelines should also be planned coordinately to support the operation of P2GSes. This paper presents a game-theoretic planning model for the integrated energy system (IES) consisting of the natural gas system, electricity system, and P2GSes. P2GSes are assumed to be independent participants in the IES in a deregulated market environment. The Nash bargaining theory is employed to formulate this cooperative planning model for the first time. In addition, the profitability potential of P2GSes to provide emission reduction and secondary reserve services is innovatively and thoroughly evaluated in the proposed planning model. The proposed Nash bargaining planning model considering ancillary service is then applied to the IES comprising a coupled 24-bus electricity and 20-bus natural gas system. Case studies validate its effectiveness and we have compared the proposed model with two typical planning models including the traditional centralized planning and sequential planning models. The simulation results show that the proposed planning model can achieve the most fair and Pareto-efficient payoff allocation for the three independent participants and also achieve a good IES system performance. It can be concluded that our model can not only help to promote the popularization of P2G technology, but also enhance the cooperation among the P2GSes, the electricity system and the natural gas system.**

Index Terms—**Power-to-gas, integrated energy system, Nash bargaining, cooperative planning, secondary reserve, energy storage.**

This work was jointly supported by Natural Science Foundation of China (51507103, 51477104), Natural Science Foundation of Guangdong Province (No. 2016A030313041), the Foundations of Shenzhen Science and Technology Committee (JCYJ20150525092941041, JCYJ20160422165525693), and X. Zhang's Ph.D. studentship.

* Corresponding author.

H. Z. Wang is with the College of Mechatronics and Control Engineering, Shenzhen University, Shenzhen, 518060, China (e-mail: wanghz@szu.edu.cn, wanggb@szu.edu.cn).

X. Zhang, K. W. Chan and J. Hu are with the Department of Electrical Engineering, The Hong Kong Polytechnic University, Hong Kong, 999077, China (e-mail: eexianzhang@outlook.com, eekwchan@polyu.edu.hk, jerry.hu@polyu.edu.hk).

B. Zhou is with the College of Electrical and Information Engineering, Hunan University, Changsha, 410082, China (e-mail: binzhou@hnu.edu.cn).

Y. Zhang is with the State Grid Energy Research Institute, Beijing, 102209, China (e-mail: zhangyan@sgeri.sgcc.com.cn)

J. Qiu is with School of Electrical and Information Engineering, the University of Sydney (e-mail: qiujing0322@gmail.com)

NOMENCLATURE

A. *Abbreviations*

P2G power-to-gas
IES integrated energy system
P2GS power-to-gas station
DG distribution generator
BESS battery energy storage system
DE differential evolution
FPSO fuzzy particle swarm optimization
NSGA-II non-dominated sorting genetic algorithm II
NGFP natural gas fired plant
AMPL a modeling language for mathematical programming
AE alkaline electrolysis
PEM polymer electrolyte membrane electrolysis
CM chemical methanation
BM biological methanation
NBS Nash bargaining solution
DC direct current

B. *Sets*

Ω^{P2G}, Ω^{EP2G} set of candidate and existing P2GS
Ω^{ECL}, Ω^{EL} set of candidate and existing electricity feeders
Ω^{GT}, Ω^{TG} set of gas turbines and thermal generators
Ω^{EB}, Ω^{GB} set of electricity buses and gas system buses
Ω^{GP}, Ω^{GCP} set of candidate and existing gas pipelines
Ω^{C} set of compressors

C. *Parameters*

Y planning period
$\lambda_{p,t}^{P2G,SA}$ gas price per unit volume of P2GS p at time t
$\lambda_{p,t}^{CAR}$ the unit price for energy conversation of P2GS p at time t.
$\lambda_{p,t}^{CA,UP}$, $\lambda_{p,t}^{CA,DW}$ the prices for the available upward and downward secondary reserve.
$E_{ru,t}$ binary variable corresponding to the upward secondary reserve deployment at time t.
$E_{rd,t}$ binary variable corresponding to the downward secondary reserve deployment at time t.
$P_p^{CA,UP}$, $P_p^{CA,DW}$ the available capacities to provide upward and downward reserve.
$\lambda_{p,t}^{AC,UP}$, $\lambda_{p,t}^{AC,DW}$ the prices for energy delivered as secondary upward and downward reserve of P2GS p at time t.
$\lambda_p^{P2G,IN}$ the price of constructing P2GS p (per capacity)
$P_p^{P2G,RAT}$ the rated capacity of P2GS p
$\lambda_{p,t}^{ETP}$ the price of active power bought by P2GS p at time t.
$\lambda_{i,t}^{ELE}$ the price of electricity of bus i at time t
λ_{ij}^{LINE} unit cost to construct a new feeder ij
λ_{mn}^{PIPE} unit cost to construct a new pipeline mn
l_{mn}^{PIPE} the length of the pipeline mn
λ_p^{PIPE} unit cost to construct a new pipeline to connect P2GS p with the gas system
l_p^{PIPE} the length of the pipeline connecting P2GS p with the gas system
l_{ij}^{LINE} the length of the feeder ij
λ_p^{LINE} unit cost to construct a new feeder to connect P2GS p with the electricity system
a_v, b_v, c_v cost coefficients for thermal generator v
r^{P2G} the disagreement point of P2GSes
r^{E} the disagreement point of electricity system
r^{G} the disagreement point of the gas system
$P_p^{P2G,MIN}$ the minimum operating power of P2GS p
S_p^{MAX} the maximum capacity of the pipeline connecting P2GS p with the gas system
P_p^{MAX} the maximum power magnitude of the P2GS p
μ_p^{EFF} the efficiency of P2GS p
$P_{ij}^{EL,MAX}$ the maximum transmission capacity of existing electricity feeder ij
$P_{ij}^{ECL,MAX}$ the maximum transmission power of candidate feeder ij
$P_u^{GT,MIN}$ the lower power limits of uth gas turbine
$P_u^{GT,MAX}$ the upper power limits of uth gas turbine
$P_v^{TG,MIN}$ the lower limits of vth thermal generator
$P_v^{TG,MAX}$ the upper limits of vth thermal generator
$S_{mn}^{GP,MAX}$ the maximum gas flow of the candidate pipeline mn at time t
$S_{mn}^{GCP,MAX}$ the maximum gas flow of the existing pipeline mn at time t
$f_{mn,t}$ the gas flow of the pipeline mn at time t
$S_{m,t}^{GAS,INJ,MAX}$ the maximum volume magnitude of imported natural gas provided by the gas source on bus m at time t
$S_{m,t}^{GAS,INJ,MIN}$ the minimum volume magnitude of imported natural gas provided by the gas source on bus m at time t
$S_{m,t}^{GAS,INJ}$ the volume magnitude of imported natural gas provided by the gas source on bus m at time t
$S_{m,t}^{GAS,SAL}$ the volume magnitude of natural gas demand on bus m at time t.
$S_{m,t}^{GT}$ the volume magnitude of natural gas on bus m supplied to the gas turbine
π_m^{MIN} the minimum air pressure of bus m
π_m^{MAX} the maximum air pressure of bus m
x_{ij}^{EL}, x_{ij}^{ECL} the reactance of the existing and candidate feeders
x_{ij} the reactance of the feeder ij
r yearly discount rate
N the number of P2GSes
$\lambda_{m,t}^{GAS}$ unit price of natural gas of bus m at time t
$\lambda_{u,t}^{GT}$ unit price of natural gas bought by the gas turbine u at time t

D. *Variables*

R^{P2G}	the payoff of P2GSes
R^{E}	the payoff of the electricity system
R^{G}	the payoff of the natural gas system
η_{p}^{P2G}	the decision variable for candidate P2GS *p*
$R^{\text{P2G,PR}}$	the profit of P2GSes
$C^{\text{P2G,IN}}$	investment cost of P2GSes
$C^{\text{P2G,OP}}$	operation cost of P2GSes
$R^{\text{P2G,SA}}$	the income of P2GSes from selling natural gas
$R^{\text{P2G,FR}}$	the revenue of P2GSes from providing secondary reserve service
$R^{\text{P2G,EN}}$	the income of P2GSes for providing secondary reserve energy
$R^{\text{P2G,CA}}$	the income of P2GSes for having upward and downward secondary reserve capacity available
$R^{\text{P2G,CAR}}$	the revenue of P2GSes earned from carbon reduction
$S_{p,t}^{\text{P2G,SA}}$	the volume of sold natural gas of P2GS *p* at time *t*
$P_{p,t}^{\text{ETP}}$	the active power bought by P2GS *p* at time *t* in the day-ahead market
$P_{p,t}^{\text{AC,UP}}$, $P_{p,t}^{\text{AC,DW}}$	the actual power of providing upward and downward secondary reserve by P2GS *p* at time *t*.
$P_{p,t}^{\text{AC}}$	actual consumed electric energy by the P2GS at time *t*
$R^{\text{E,PR}}$	the profit of electricity system
$C^{\text{E,IN}}$	investment cost of electricity system
$C^{\text{E,OP}}$	operation cost of electricity system
$R^{\text{G,PR}}$	the profit of the gas system
$C^{\text{G,IN}}$	investment cost of electricity system
$C^{\text{G,OP}}$	operation cost of electricity system
$P_{i,t}^{\text{ELE,SAL}}$	the active power demand of bus *i* at time *t*
η_{ij}^{LINE}	the decision variable to invest a new feeder *ij*
l_{p}^{LINE}	the length of the new electricity feeder to connect P2GS *p* with the power grid
$S_{u,t}^{\text{GT}}$	the volume magnitude of natural gas bought by gas turbine *u* at time *t*
$P_{u,t}^{\text{GT}}$	the output active power of gas turbine *u* at time *t*
$P_{v,t}^{\text{TG}}$	the output active power of thermal generator *v* at time *t*
η_{mn}^{PIPE}	decision variable to invest a new pipeline *mn*
$S_{p,t}$	the volume magnitude of natural gas in the pipeline connecting P2GS *p* with the gas system at time *t*
$P_{p,t}$	the transmission power of the electricity feeder linking P2GS *p* with the electricity system at time *t*
$S_{p,t}^{\text{P2G,SAL}}$	the volume magnitude of natural gas exported by P2GS *p* at time *t*
$P_{ij,t}^{\text{EL}}$	the transmission power of existing feeder *ij* at time *t*
$P_{ij,t}^{\text{ECL}}$	the transmission power of candidate feeder *ij* at time *t*
$\theta_{i,t}$, $\theta_{j,t}$	phase angle of bus *i* and *j* at time *t*
$S_{mn,t}^{\text{GP}}$	the gas flow of the candidate pipeline *mn* at time *t*
$S_{mn,t}^{\text{GCP}}$	the gas flow of the existing pipeline *mn* at time *t*
$f_{mn,t}$	gas flow in the feeder *mn* at time *t*
$\tau_{mn,t}$	the gas withdrawn to operate the compressor on the feeder *mn* at time *t*
$\pi_{m,t}$, $\pi_{n,t}$	the air pressure of bus *m* and bus *n* at time *t*
$H_{mn,t}$	the actual horsepower for the compressor on the feeder *mn*

I. INTRODUCTION

A. Motivation

Integrated energy system (IES) is defined as a multi-network that incorporates generation, storage, transportation, and conversion of coal, natural gas, electricity, et al. in a single framework [1]. The integration of natural gas and electricity systems are the main existing form of IES in many countries for the long distance transmission of a large amount of energy [2]. A natural gas-fired plant (NGFP) is the major component coupling natural gas with electricity systems by using natural gas to produce electricity in a low-emission way [13]. In recent years, power-to-gas (P2G) stations (P2GSes), serving as another linkage between natural gas and electricity systems, have drawn many researchers' attention [49], but the development of P2Gses is still in the initial stage. The P2G technology presents a possible solution for electricity storage through methane production by converting excess electricity into natural gas, and introduces high flexibility in the energy balance of the grid [16][50]. The pilot, demo and lab P2GS for the flexible storage of electricity have been constructed and operated in Europe, USA and Japan. P2G is considered to be one of the most promising energy storage technologies in the mid-term [17]. P2GSes could be used for storing the excess renewable energy including photovoltaic, wind or hydro power by the methanation process [18][51][52]. From the remuneration point of view, P2G is considered to be most suitable for seasonal storage such as long-term renewable output levelling [19]. Study results obtained in [25] indicate that the construction of more P2GS could reduce the costs of network expansion with cables, but the profitability of P2GS is highly related to the surplus in the grid and the full load hours of P2G electrolyzing. It is also revealed that the integrated management of P2GSes and the IES could reduce the overall system operation cost by reducing power losses [20] or system line congestions [21]. Due to the great potential of the P2G application, there is an urgent requirement for planning more P2GSes. Furthermore, the electricity feeders and gas pipelines should be co-planned simultaneously to transmit electricity to the P2GS and transfer the generated natural gas to the gas system. Therefore, it is of interest to develop a co-planning strategy of IES consisting of P2GSes, the natural gas and the electricity systems in order to promote the application of the P2G technology. However, research on this important issue is rare.

B. Relative background

In most of the previous research the distribution generators (DGs) or the P2GS planning is conducted individually neglecting the interdependence with the IES [9, 25, 26]. DG and battery energy storage system (BESS) constructions are considered in the co-planning of IES to accelerate the cost recovery process in the coupled gas and electricity systems in [9]. The optimal size of the grid balancing system based on gas turbines and P2GS is determined by a scenario based statistical approach in [26], and the operation hours, carbon emissions and wind power curtailment are taken as the main performances indexes. However, the investigations of coordinated planning of P2GSes, the natural gas and the electricity systems remain rare. A two-level multi-stage programming model is studied to co-ordinately expand the IES considering both the NGFP and P2GS in [24]. Nevertheless, this co-planning model is carried out by a single entity in a centralized manner. This approach is quiet contrary to the reality that in a deregulated competitive environment, the coupled natural gas system, electricity system and P2GSes are independent IES participants and responsible for their own planning and operation with different or even conflicting interests and objectives.

Game-theoretic models, which have been applied in electricity system and generation planning problems [27, 28], are efficient tools to analyze such kind of situations in which the planning decision variables of different participants are independently controlled. A Stackelberg game is modeled in [27] between the transmission line and renewable generation investment, and the results show that the game-theoretic tools can help both investors to implement their projects and achieve required distribution of the profit with proper transmission charges. The Aumann-Shapley approach is adopted in [28] to distribute the benefits produced by individual network uses from expansion projects, and is proved to be a more accurate and sound method to allocate the cost of new investments. However, so far the application of game theory in co-planning of the P2GS and IES is still absent from a systematic investigation.

Additionally, the application of P2G used as a flexible storage of electricity [17]- [21] can hardly bring enough profits, and the current high costs of P2G restraint its widespread development. P2GSes have economic potentials to provide ancillary services, given that the ancillary service price is sometimes much higher than the energy price in an IES with high penetration of renewables or intermitted loads. Nevertheless, the research on this subject is relatively insufficient [22]-[23]. Offsetting carbon emission, providing demand response and selling hydrogen to the fuel cell vehicles are considered as the major P2G ancillary and environmental services in [22] and the simulation results indicate that the participation of the ancillary service could significantly shorten the payback periods of P2G investment. The potential of P2G to provide secondary control reserve in Germany is investigated in [23], and the results demonstrate that the reserve service is economically viable but highly dependent on the IES's configuration and operation strategies.

Furthermore, the planning of IES is a typical nonconvex mixed integer nonlinear programming (MINLP) problem and cannot be solved by the conventional mathematical techniques. The heuristic algorithms [53-60], such as backtracking search algorithm [53], multi-objective particle swarm optimization (PSO) [54], rain-fall optimization algorithm [55], PSO-DQ [56], gene expression programming (GEP)-based method [57], optimized gene expression programming [58], artificial cooperative search algorithm [59], an expression-driven approach [60], etc., have been widely used on solving similar problems. The modified differential evolution (DE) algorithm [11], the fuzzy particle swarm optimization (FPSO) [12], and the elitist non-dominated sorting genetic algorithm II (NSGA-II) [13] have been used in the IES planning problems. Due to the prominent uncertainties existed in the IES planning, the stochastic optimization [14] and the chance-constrained programming [15] are applied in the solving process and they demonstrate good effectiveness in avoiding risks and improving the robustness of the planning schemes. However, there are many drawbacks related to these applied algorithms [63]. The performance of these algorithms highly depends upon the stability between their exploration and exploitation capabilities, which requires heavily diversified population based on the multi-dimensional search space of the problem to be solved. Additionally, the equality constraints can make the search space even more complex. BONMIN is a useful solver for solving nonconvex MINLP [61]. Its superiority has been demonstrated in [62] and [63]. In [62], a proposed probabilistic under frequency load shedding (UFLS) is optimized using the BONMIN solver. In [63], Hydro-Thermal Unit Commitment co-ordination system is solved in MINLP environment by BONMIN solver and the performance of the solver is shown in terms of convergence and better quality of solutions.

After thoroughly reviewing literatures, it becomes evident that all the aforementioned studies do not consider a cooperative planning model for IES consisting of P2GSes, natural gas and electricity systems in the deregulated market which considers the ancillary service of P2GSes.

C. Contribution and organization of the paper

Given the aforementioned considerations, this paper presents a cooperative planning model for IES consisting of P2GSes, natural gas and electricity systems. The model considers the ancillary service of P2GSes and is solved by the highly efficient commercial AMPL/BONMIN solver. The proposed model is compared with the centralized planning model and the sequential planning model to demonstrate its effectiveness in coping with the practical cooperative IES and P2GSes planning problem in the future deregulated competitive environment. The novel contributions of this paper can be summarized as follows.

a) To promote the development of P2G technology and the cooperation among P2GSes, natural gas and electricity systems, the proposed game-theory based cooperative planning model reflects the realistic planning process of natural gas system, electricity system and P2GSes in the deregulated competitive environment. In the proposed model, the natural gas system, the electricity system and P2GSes are independent decision makers and responsible for their own planning and operation with different or even conflicting interests and objectives, which is in accordance with the reality. The Nash bargaining theory is innovatively employed to formulate this planning model to obtain a negotiated planning solution called the Nash Bargaining Solution (NBS) for profit sharing, cost recovery, and nondiscriminatory benefits. The significance of the proposed algorithm is the bargaining and NBS fairness that result in the fair individual performance and the overall system performance [67].

b) The options to improve the investment recovery ability of P2GSes are explored including carbon reduction, secondary reserve energy and capacity provisions, aiming to promote the popularization of P2G technology and increase the possibility of the cooperation among those participants.

The remainder of this paper is organized as follows. Section II presents the key mathematical models in the IES. In Section III, the proposed Nash bargaining planning model is formulated. Besides, the centralized planning model and the sequential planning model are introduced as benchmarks in Section III. Section IV gives case studies and discussions. Section V concludes this paper.

II. MATHEMATICAL MODELS OF IES

P2GSes can convert excess electricity generated by renewable energy to natural gas. Gas can then be stored in an economic way on a large-scale. On the contrary, gas turbines of NGFPs in the gas system firstly convert natural gas to thermal energy and afterward convert it to electrical energy. P2GSes and gas turbines interconnect the power system with the gas system, thus achieving bi-directional flows of energy between the natural gas and electricity systems. With the increasing demand of P2GSes, it is necessary to comprehensively plan the natural gas and electricity systems with P2GSes. In this section, the general models of P2GSes and natural gas system are briefly introduced.

A. P2G Technology

P2G technology is a two-step process that converts excess electricity generated from renewable sources (such as wind or solar energy) into a grid compatible gas [29], the process of which is shown in Fig.3 [30]. The first step is *electrolysis*, in which hydrogen (H_2) is produced by water electrolysis as below:

$$2H_2O \xlongequal{\text{electrolysis}} 2H_2\uparrow + O_2\uparrow \tag{1}$$

At present, two technologies are applied to electrolysis, which are Alkaline electrolysis (AE) and Polymer electrolyte membrane electrolysis (PEM). In the second step, namely *methanation*, the produced hydrogen with an external carbon monoxide (CO) or carbon dioxide source (CO_2) is converted into methane (CH_4), which is described as

$$4H_2 + CO_2 \xlongequal{\text{catalysis}} CH_4 + 2H_2O \tag{2}$$

In the step of methanation, two technologies named chemical methanation (CM), and biological methanation (BM) are used. Although the conversion losses are inevitable in the two-step process, P2GSes still bring profit opportunities. For example, P2GSes can make a profit from gas market if the gap between gas price and electric energy price is large enough. Besides, P2GSes can also profit from participation in ancillary service markets such as giving secondary reserve service thanks to the quick response ability of electrolysis. This will be further discussed in this work.

B. Natural Gas System Models

The models of electricity systems are well established [31]. Similar to electricity systems, models of the natural gas system [32] consist of three basic parts: flow equation, compressor modeling and conservation of flow, in which lines (including compressors on lines) and interconnection points are mathematically represented by *pipelines* and *buses*.

1) Flow equation: The general steady-state flow rate f_{mn} of the pipeline, which starts at bus *m* and ends at bus *n*, can be expressed by the Weymouth flow equation as follows.

$$f_{mn} = \mathrm{sgn}(\pi_m, \pi_n) \cdot C_{mn} \cdot \sqrt{\left|\pi_m^2 - \pi_n^2\right|} \tag{3}$$

$$\mathrm{sgn}(\pi_m, \pi_n) = \begin{cases} 1 & \pi_m \geq \pi_n \\ -1 & \pi_m < \pi_n \end{cases} \tag{4}$$

where π_m and π_n represent gas pressures at buses m and n, respectively; C_{mn} is the pipeline constant; and sgn(π_m, π_n) corresponds to the flow direction. If the value is 1, the flow is from bus m to bus n. If sgn(π_m, π_n) equals -1, the flow is from bus n to bus m.

2) Compressor Model: As shown in Fig.2, compressor stations installed in the network are powered by the gas engine to offset the pressure loss, compensate the energy loss, and move the gas. Assuming that the compressor is located on the pipeline between bus m and n, the horsepower consumption H_{mn} is the crucial factor for the compressor, which expresses the relation between the gas flow rate f_{mn} through the compressor, and the pressures of π_m and π_n.

$$H_{mn} = B_{mn} \cdot f_{mn} \cdot \left[\left(\frac{\pi_m}{\pi_n} \right)^{Z_{mn}} - 1 \right] \tag{5}$$

where B_{mn} is a constant associated with compressor suction temperature and compressor efficiency; Z_{mn} corresponds to a constant associated with specific heat ratio and gas compressibility factor at compressor inlet. The gas withdrawn to generate electricity by a gas turbine to power the compressor, denoted as τ_{mn}, can be expressed as

$$\tau_{mn} = \alpha_{mn} + \beta_{mn} \cdot H_{mn} + \gamma_{mn} \cdot H_{mn}^2 \tag{6}$$

where α_{mn}, β_{mn}, γ_{mn} are conversion factors between H_{mn} and τ_{mn}.

C. Conservation of the Flow

The mass-flow balance equation [32] means that the overall gas entering the bus equals to the overall gas leaving the bus, and could be descripted as

$$(\boldsymbol{A} + \boldsymbol{U})\, \boldsymbol{f} + \boldsymbol{\omega} - \boldsymbol{T\tau} = 0 \tag{7}$$

where A_{mk} is the element of the branch-nodal incidence matrix $\boldsymbol{A}$ representing the interconnection of pipelines and buss; U_{mk} is the element of the matrix $\boldsymbol{U}$ describing the connection of compressors and buses; T_{mk} denotes the element of compressor-nodal incidence matrix $\boldsymbol{T}$, which shows whether the gas consumed to operate the compressor k is from the bus m; and the compressor will withdraw a part of gas, τ_{mn}, to power the gas turbine to run the compressor k; $\omega = \omega_S - \omega_L$ in the matrix $\boldsymbol{\omega}$ corresponds to the vector of gas injection while ω_S and ω_L are vectors of gas supplies and gas demands, respectively.

III. Nash Bargaining Model for Cooperative Planning of Electricity System, Natural gas System and P2GSes

In the deregulated competitive environment, the electricity, the natural gas systems and P2GSes are independent market participants in the IES. They are individual decision makers responsible for their own profits and have planning objectives conflicting to each other. The centralized planning model for the IES used in most previous literature assumes that all participants in the IES [5, 10-15, 24] belong to one entity, but this is quite contrary to the reality.

Game theory [64] is a powerful tool to investigate the situations of conflict and cooperation. It concerns ways to obtain the best actions for individual decision maker and recognize stable outcomes [65]. Games can be categorized as non-cooperative and cooperative games. The non-cooperative game explicitly models the decision-making process for each rational but selfish player to maximize his individual payoff in a self-interested manner without considering the impact of his strategies on other players. The Nash equilibrium (NE) is a typical solution of a non-cooperative game, which is proven to be not always socially optimal. This is because individually-rational strategies always lead to worse results than the theoretical possibility of an enforceable agreement among rational players.

Unlike non-cooperative models, the players in a cooperative game can make binding agreements. The cooperative game emphasizes collective rationality and social optimality. To determine the plan scheme of the IES and simulate cooperation among these three players in the IES, Nash bargaining game is innovatively introduced here. A solution method for the IES planning model based on a bargaining game is given combing the essence of the bargaining game. Nash bargaining game [66] is a kind of cooperative game, which has the bargaining solution called the Nash Bargaining Solution (NBS). Nash bargaining theory provides an effective method to study how these three selfish players interact and cooperate with each other, coming to binding agreements in essence a jointly generated surplus sharing problem [36]. The NBS scheme can result in *the fair individual performance and good overall system* [67]. Research on bargaining game has found extensive real applications [42-44], such as contract negotiation [37], trading promotion [38], risk aversion [39], reactive power compensation [44] and resource allocation for wireless cooperative networks [65] [67] [68].

In this paper, the locations of new P2GSes, selections of power feeders and gas pipelines are simultaneously determined using the Nash bargaining theory. The proposed planning model aims to obtain the plan scheme of the IES which maintains a good tradeoff between the fairness and the overall system performance. It means that the NBS can maximize the system performance (the overall system payoff) while keeping the NBS fairness. The NBS will be compared and analyzed with solutions obtained by other two benchmark models including the centralized planning model and the sequential planning model.

In this section, the general formulation of Nash bargaining planning model is first introduced. Then the proposed Nash bargaining planning model for the IES and other two benchmark models are described.

A. General Formulation of Nash Bargaining Model

In the Nash bargaining game with h players $(1, 2, \ldots, h)$, each player demands a portion of surplus they jointly create, which could only be obtained if the negotiation that satisfies every player could be reached. This can be modeled that game players are in a negotiation to identify an agreement outcome (u_1, …, u_h) from the payoff possibility set χ. (u_1^0, …, u_h^0) is called the players' disagreement point, which is the outcome that the players can expect to receive if negotiations break down. The problem has solutions if agreements in χ are better for every player than the disagreement point. A Nash bargaining solution (u_1^*, …, u_h^*) should satisfy four axioms, which reflects its *fairness and efficiency properties*: Pareto efficiency, symmetry, independence of irrelevant alternatives, and invariance under positive linear-affine transformation [40]. The detailed explanation of these axioms can be found in [69]. Furthermore, it is proved by John Nash that under mild conditions, the payoff (u_1^*, …, u_h^*) is exactly a Nash bargaining solution (NBS) obtained by solving the following optimization problem [40, 41]:

$$\max \quad (u_1 - u_1^0) \times \ldots \times (u_h - u_h^0) \tag{8}$$

$$\text{subject to} \quad (u_1, \ldots, u_h) \in \chi \qquad (u_1^0, \ldots, u_h^0) \in \chi^0 \tag{9}$$

$$(u_1, \ldots, u_h) \geq (u_1^0, \ldots, u_h^0) \tag{10}$$

where χ and χ^0 are the set of possible payoffs and the set of disagreement outcome, respectively. The optimization in (8)-(10) makes the acquisition process of the NBS very simple, intuitive, and efficient. Moreover, the details of bargaining process could be neglected, and the four axioms will be satisfied automatically by solving the proposed optimization model.

B. Nash Bargaining of the Cooperative Planning

The electricity system, natural gas system, and P2GSes are considered as three game players in the deregulated market environment. According to the general model, the Nash bargaining solution for the planning of the IES with P2GS can be obtained by solving the following optimization problem with three participants, and the disagreement point (r^{P2G}, r^{E}, r^{G}) of the proposed model is assumed to be (0, 0, 0), which indicates no benefits will be obtained if the negotiation between the participants is failed.

$$max \;\; \left(R^{\mathrm{P2G}} - r^{\mathrm{P2G}}\right)\left(R^{\mathrm{E}} - r^{\mathrm{E}}\right)\left(R^{\mathrm{G}} - r^{\mathrm{G}}\right) \tag{11}$$

Equation (11) is subject to the constraints (33) – (58), the details of which can be seen in the appendix; where R^{P2G}, R^{E}, R^{G} are the total payoff of P2GSes, electricity and natural gas systems, respectively. The NBS ensures that 1) The essence of the bargaining game is that participants can reach an agreement after multiple bargaining, and an equilibrium solution is obtained, where each participant cannot obtain greater returns by changing the planning strategy; 2) The overall system performance and the fair individual performance are considered simultaneously.

1) The Total Payoff of P2GSes

The total payoff of P2GSes, namely the total net profit, comes from the operation profits $R^{\mathrm{P2G,PR}}$ minus the investment costs $C^{\mathrm{P2G,IN}}$ and operation costs $C^{\mathrm{P2G,OP}}$.

$$R^{\mathrm{P2G}} = R^{\mathrm{P2G,PR}} - (C^{\mathrm{P2G,IN}} + C^{\mathrm{P2G,OP}}) \tag{12}$$

Playing the roles of both the electric power load and the natural gas source, P2GSes convert the electricity energy to the natural gas and participate in electricity energy market as the buyer. Besides, P2GSes could obtain revenues from providing auxiliary services by participating in the secondary reserve market due to the fast response nature of the P2G process and the energy storage ability of natural gas [23] [33]. Moreover, P2GSes could reduce the curtailed electric power by converting excess electricity generated from renewable energy to natural gas. This energy conversion improves the efficiency of energy utilization, and mitigates carbon emission [34, 35]. This carbon emission reduction function could also generate extra income for P2GS. Because the P2G technology is still in the stage of initial development, the construction cost of a P2GS is relatively high, which hinders the popularization of P2GSes to some extent. Therefore, to increase the profits of P2GSes, in the paper, in addition to the income from selling natural gas $R^{\text{P2G,SA}}$, the profits from providing ancillary service are taken into consideration, which include the revenue from providing secondary reserve service $R^{\text{P2G,FR}}$, and profits of carbon emission reduction $R^{\text{P2G,CAR}}$. The operation profits of P2GSes are described as follows:

$$R^{\text{P2G,PR}} = R^{\text{P2G,SA}} + R^{\text{P2G,CAR}} + R^{\text{P2G,FR}} \tag{13}$$

The $R^{\text{P2G,FR}}$ in (14) is divided in two parts: The income for having upward and downward secondary reserve capacity available $R^{\text{P2G,CA}}$, as shown in (15); and the income for providing secondary reserve energy $R^{\text{P2G,EN}}$ as shown in (16).

$$R^{\text{P2G,FR}} = R^{\text{P2G,EN}} + R^{\text{P2G,CA}} \tag{14}$$

where

$$R^{\text{P2G,CA}} = \sum_{y=1}^{Y} \frac{365}{(r+1)^{y-1}} \left(\sum_{t=1}^{T} \sum_{p \in \Omega^{\text{P2G}}} \eta_p^{\text{P2G}} \cdot (\lambda_{p,t}^{\text{CA,UP}} \cdot P_p^{\text{CA,UP}} + \lambda_{p,t}^{\text{CA,DW}} \cdot P_p^{\text{CA,DW}}) \right) \tag{15}$$

$$R^{\text{P2G,EN}} = \sum_{y=1}^{Y} \frac{365}{(r+1)^{y-1}} \sum_{t=1}^{T} \sum_{p \in \Omega^{\text{P2G}}} \eta_p^{\text{P2G}} \cdot (\lambda_{p,t}^{\text{AC,UP}} \cdot P_{p,t}^{\text{AC,UP}} E_{ru,t} - \lambda_{p,t}^{\text{AC,DW}} \cdot P_{p,t}^{\text{AC,DW}} E_{rd,t}) \tag{16}$$

More detailed, (16) indicates that the upward reserve bid includes offering a decrease in the energy consumption, which means a positive income. However, the downward reserve bid consists in offering an increase in the energy consumption and means a negative income.

The profit of selling natural gas $R^{\text{P2G,SA}}$ and carbon reduction $R^{\text{P2G,CAR}}$ can be expressed as

$$R^{\text{PtG,SA}} = \sum_{y=1}^{Y} \frac{365}{(r+1)^{y-1}} \sum_{t=1}^{T} \sum_{p \in \Omega^{\text{PtG}}} \eta_p^{\text{P2G}} \cdot \lambda_{p,t}^{\text{P2G,SA}} \cdot S_{p,t}^{\text{P2G,SA}} \tag{17}$$

$$R^{\text{P2G,CAR}} = \sum_{y=1}^{Y} \frac{365}{(r+1)^{y-1}} \sum_{t=1}^{T} \sum_{p \in \Omega^{\text{PtG}}} \eta_p^{\text{P2G}} \cdot \lambda_{p,t}^{\text{CAR}} \cdot P_{p,t}^{\text{ETP}} \tag{18}$$

and the costs for the construction and operation of P2GSes are as follows

$$C^{\text{P2G,IN}} = \frac{1}{(1+r)^{Y-1}} \sum_{p \in \Omega^{\text{P2G}}} \eta_p^{\text{P2G}} \cdot \lambda_p^{\text{P2G,IN}} \cdot P_p^{\text{P2G,RAT}} \tag{19}$$

$$C^{\text{P2G,OP}}=\sum_{y=1}^{Y}\frac{1}{(1+r)^{y-1}}\cdot(\sum_{p\in\Omega^{\text{P2G}}}\eta_p^{\text{P2G}}\cdot\lambda_p^{\text{P2G,IN}}\cdot P_p^{\text{P2G,RAT}}\cdot 0.05+365\cdot\sum_{t=1}^{T}\sum_{p\in\Omega^{\text{P2G}}}\eta_p^{\text{P2G}}\cdot\lambda_{p,t}^{\text{ETP}}\cdot P_{p,t}^{\text{ETP}}) \tag{20}$$

In (20), the operation costs of P2GSes consist of the P2GS maintenance cost, which is assumed to be 5% of the investment cost, and the total P2GS electricity energy purchase cost.

2) The Payoff of Electricity System

The payoff of the electricity system R^{E} is computed by (21), where $R^{\text{E,PR}}$, $C^{\text{E,IN}}$ and $C^{\text{E,OP}}$ are the profit, investment cost and operation cost of the electricity system, respectively.

$$R^{\text{E}}=R^{\text{E,PR}}-(C^{\text{E,IN}}+C^{\text{E,OP}}) \tag{21}$$

where
$$R^{\text{E,PR}}=\sum_{y=1}^{Y}\frac{1}{(1+r)^{y-1}}\sum_{t=1}^{T}(\sum_{i\in\Omega^{\text{EB}}}\lambda_{i,t}^{\text{ELE}}\cdot P_{i,t}^{\text{ELE,SAL}}+\sum_{p\in\Omega^{\text{P2G}}}\eta_p^{\text{P2G}}\cdot\lambda_{p,t}^{\text{ETP}}\cdot P_{p,t}^{\text{ETP}}) \tag{22}$$

$$C^{\text{E,IN}}=\frac{1}{(1+r)^{Y-1}}(\sum_{ij\in\Omega^{\text{ECL}}}\eta_{ij}^{\text{LINE}}\cdot\lambda_{ij}^{\text{LINE}}\cdot l_{ij}^{\text{LINE}}+\sum_{p\in\Omega^{\text{P2G}}}\eta_p^{\text{P2G}}\cdot\lambda_p^{\text{LINE}}\cdot l_p^{\text{LINE}}) \tag{23}$$

$$C^{\text{E,OP}}=\sum_{y=1}^{Y}\frac{365}{(1+r)^{y-1}}\sum_{t=1}^{T}(\sum_{u\in\Omega^{\text{GT}}}\lambda_{u,t}^{\text{GT}}\cdot S_{u,t}^{\text{GT}}+\sum_{v\in\Omega^{\text{TG}}}(a_v+b_v\cdot P_{v,t}^{\text{TG}}+c_v\cdot(P_{v,t}^{\text{TG}})^2)+R^{\text{P2G,FR}} \tag{24}$$

As shown in (22), the profit of the electricity system $R^{\text{E,PR}}$ consists of the income of selling electricity energy to P2GS and other users. The investment cost $C^{\text{E,IN}}$ is composed of the cost of constructing new electricity feeders to meet the load and to connect P2GS with the electricity system, which is shown in (23). The operation cost in (24) consists of cost paid to power generation, including the natural gas fuel cost for the gas turbines in NGFP and the generation costs of thermal generators, and the charge paid to P2GS for receiving the secondary reserve service.

3) The Payoff of Natural Gas System

Equation (25) states the definition of the natural gas system payoff. As shown in (26), the profit of the natural gas system is from selling gas to the gas turbines and other natural gas users. In (27), the investment of the gas system composes of investment of new gas pipelines to connect P2GS to the networks and new pipelines to satisfy other natural gas users' growing demands. The operation cost consists of expense of buying natural gas from gas sources and P2GSes and is stated in (28).

$$R^{\text{G}}=R^{\text{G,PR}}-(C^{\text{G,IN}}+C^{\text{G,OP}}) \tag{25}$$

$$R^{\text{G,PR}}=\sum_{y=1}^{Y}\frac{365}{(1+r)^{y-1}}\sum_{t=1}^{T}(\sum_{m\in\Omega^{\text{GB}}}\lambda_{m,t}^{\text{GAS}}\cdot S_{m,t}^{\text{GAS,SAL}}+\sum_{u\in\Omega^{\text{GT}}}\lambda_{u,t}^{\text{GT}}\cdot S_{u,t}^{\text{GT}}) \tag{26}$$

$$C^{\text{G,IN}}=\frac{1}{(1+r)^{Y-1}}(\sum_{mn\in\Omega^{\text{GCP}}}\eta_{mn}^{\text{PIPE}}\cdot\lambda_{mn}^{\text{PIPE}}\cdot l_{mn}^{\text{PIPE}}+\sum_{p\in\Omega^{\text{P2G}}}\eta_p^{\text{P2G}}\cdot\lambda_p^{\text{PIPE}}\cdot l_p^{\text{PIPE}}) \tag{27}$$

$$C^{\text{G,OP}}=\sum_{y=1}^{Y}\frac{365}{(1+r)^{y-1}}\sum_{t=1}^{T}(\sum_{i\in\Omega^{\text{GS}}}\lambda_{i,t}^{\text{GAS,INJ}}\cdot S_{i,t}^{\text{GAS,INJ}}+\sum_{p\in\Omega^{\text{P2G}}}\eta_p^{\text{PtG}}\cdot\lambda_{p,t}^{\text{P2G,SAL}}\cdot S_{p,t}^{\text{P2G,SAL}}) \tag{28}$$

C. The Centralized Planning Model and Sequential Planning Model for Comparison

By far, optimal planning strategies for IES have been studied by many scholars, but most of the studies are based on the *centralized planning model* [5, 10-15, 24], in which all the planning and operation tasks are conducted in a centralized manner by a single authorized entity. Another widespread practice for the planning of IES and P2GS is that the electricity system, natural gas system and the P2GS are separately deployed one after another, which is referred as the multi-step *sequential planning model* [9, 25, 26]. However, both models are quite contrary to the reality. Therefore, the centralized planning model and sequential planning model are briefly introduced here as the comparative cases to demonstrate the effectiveness of the proposed Nash bargaining based planning model.

1) Centralized Planning Model: In this model, it is assumed that the electricity system, the natural gas system and the P2GSes are unified managed and an authorized entity is in charge of all the planning tasks. The objective of the centralized planning model is to maximize the total payoff of the all parts while respects all the related constraints.

$$\max \quad R^{\mathrm{PtG}} + R^{\mathrm{E}} + R^{\mathrm{G}} \tag{29}$$

subject to (33) – (58)

2) Sequential planning model: In this planning strategy, P2GSes, electricity system and the natural gas system are planned independently and sequentially. The objective of every player is to maximize its own payoffs.

It is assumed the P2GSes are built firstly by the following P2GS planning model

$$\max \quad R^{\mathrm{PtG}} \tag{30}$$

subject to (33) – (41)

Then the electricity feeders are constructed to provide electricity energy to the P2GS as follows

$$\max \quad R^{\mathrm{E}} \tag{31}$$

subject to (42) – (49)

and the natural gas system is planned at last with the following objective and constraints

$$\max \quad R^{\mathrm{G}} \tag{32}$$

subject to (50) – (58)

IV. Numerical Results and Analysis

A. Description of Experiment Data

An IES consisting of a modified IEEE 24-bus electricity system and a modified 20-bus natural gas system are applied to evaluate the proposed model. As shown in Fig.3, the electricity system is composed of 10 generators (4 gas turbines and 6 thermal generators), 17 load buses and 31 transmission feeders. The natural gas system consists of 9 gas load buses, 6 gas source buses, 20 gas pipelines and 2 compressor stations. Parameters of the electricity system can be found in [45, 46]. Parameters of the natural gas system can be found in [47, 48]. The compressor parameters are given in Table I. For simplicity, we use the superscript ^{G} to denote the bus or pipeline number in the natural gas system, and the bus or feeder number without superscript ^{G} represents that this bus/feeder is in the electricity system.

Four gas turbines are located on bus 7, bus 15, bus 21 and bus 22 of the electricity system, and they are also gas load buses located on the natural gas system. Candidate P2GS is another kind of coupling bus which should be connected by both the electricity feeder and the natural gas pipeline to ensure its normal operation. Three P2GSes are assumed to be constructed in the IES in this case. The parameters of candidate P2GS and its supporting electricity feeders or gas pipelines are listed in Table II, and it can be observed from Table II and Fig.3 that the candidate P2GSes fall into three categories:

1) If a P2GS is built on the bus of the electricity system, new natural gas pipelines should be constructed to connect the P2GS with the natural gas system. (P2GS candidate No. 1 and 2)

2) If the P2GS is constructed on the bus of the natural gas system, new electricity feeders should be built to link the P2GS to the electricity system. (P2GS candidate No. 3 and 4)

3) If the P2GS is planned on an *isolated bus* which is neither in the electricity system nor in the natural gas system, both new electricity feeders and new natural gas pipeline should be constructed to ensure the connection with the two systems. (P2GS candidate No. 5)

In addition, to meet the increasing electricity and natural gas demands, another 10 new feeder candidates and 15 new pipeline candidates are considered to enhance the transmission capacity of the IES. The parameters of candidate electricity feeders are detailed in Table III. Table IV lists the parameters of candidate gas pipelines. The planning horizon is 10 years, and the yearly discount rate is set to be 5%. The prices in the electricity market and natural gas market are listed in Table V, which are obtained from the Nord Pool electricity market and European energy exchange (EEX) natural gas market. It can be observed from Table V that the prices for electricity and natural gas are uniform clearing prices, in which the nodal price mechanism is not considered.

B. Nash Bargaining Planning Results and Profitability Analysis Considering Ancillary Services

The planning results got by the Nash Bargaining are shown in Table VI to Table VII and the Fig.4. The highly efficient AMPL/BONMIN commercial solver is used to deal with the proposed complicated nonlinear model on a machine with 4 GB RAM and an Intel(R) Core(TM) i5 CPU clocked at 3.20 GHz. For the planning problems, the computation time is not critical but are still important [70]. The computational time for this optimization problem is 150 minutes, while the numbers of the variables and constraints of the optimization problem are 798 and 7590, respectively.

In the NBS, the payoffs of three players respectively are 59. 51M€ vs 216.36 M€ and 1189.1 M€, which are illustrated in Table IX. The detailed P2GSes planning results and their supporting electricity feeders or gas pipelines are illustrated as Table VI shows: P2GSes located on bus 20 and bus 23 (No. 1 and No. 2) in the electricity system are constructed; Gas pipelines from bus 20 to 11^G and from bus 23 to 10^G are respectively constructed to transport natural gas generated by No. 1 and No. 2 P2GSes to the natural gas system; The No. 5 P2GS located on the isolated bus is also chosen to be constructed while the electricity feeder from the No. 5 P2GS to bus 18, and the pipeline from the No. 5 P2GS to bus 1^G are planned to connect this P2GS to the electricity and natural gas systems. Besides, one more feeder (from bus 11 to 13) and one more pipeline (from 10^G to 11^G) are planned to meet the increasing system demands due to the operation of new P2GSes, and the details are given in Table VII and Table VIII.

Table X summarizes the details of the operation profits of P2GSes in the Nash bargaining model, which come from four sections: selling natural gas ($R^{\text{P2G,SA}}$), carbon reduction ($R^{\text{P2G,CAR}}$), providing secondary reserve capacity ($R^{\text{P2G,CA}}$) and providing secondary reserve energy ($R^{\text{P2G,EN}}$). It can be found that the operation profits are evenly split between the income from selling the generated natural gas and other incomes. Among other incomes, giving secondary reserve services contribute to the incomes of P2GSes, in which the secondary reserve capacity and energy services take up 15.2% and 13.1% of the total benefits respectively. Carbon reduction brings another part of P2GS incomes and results in 19.4% of the entire profits. It can be concluded that besides the income from selling natural gas $R^{\text{P2G,SA}}$, the revenue from providing secondary reserve service and carbon reduction service also play an important role in earnings. In an IES, holding higher penetration of fluctuating loads with higher requirements for clean energy generation, the prices for providing secondary reserve service and carbon reduction service will increase, and lead to an improvement of the operation profits of P2GSes. This profit improvement will facilitate widespread use of P2GSes in the near future.

Table IX gives a summary of the profits, construction costs and operation costs of all participants in the NBS. It can be seen that the operation costs of P2GSes are even higher than their construction costs (766.24 M€ vs 154.71 M€), which is mainly caused by the excessive cost of electrolysis process in the P2G technology. The high construction and operation cost hinder the popularization of P2GSes to a large extent. It can be foreseen that the application potentials of P2GSes are highly dependent on the construction and operation costs. If related technologies such as electrolysis and methanation processes continue to mature, the construction and operation costs will decrease, which makes the application of P2GSes more widely.

C. Nash Bargaining Model Versus Centralized and Sequential Models: A Comparative Study

The proposed Nash Bargaining model in this paper is compared with the commonly used centralized planning model and the sequential planning model. As the name implies, the electricity system, natural gas system, and P2GSes are planned simultaneously by a single entity in the centralized model. Meanwhile, the sequential planning strategy consists of 1)-3) step by step: 1) construct P2GSes; 2) deploy the electricity feeders after the P2GSes are planned; 3) construct the natural gas pipelines after the P2GSes and electricity feeders planning schemes are determined. The two comparative models are also solved by the AMPL/BONMIN efficiently. The computational times for solving the centralized model and sequential model are 18.72 minutes and 51.06 seconds, respectively.

1) The centralized planning model

The planning schemes of centralized planning and sequential planning are demonstrated in Table XI. It is clearly shown that different models result in apparently different choices of P2GS locations, electricity feeders and natural gas pipelines, thus inevitably leading to different profits and costs of P2GSes, electricity and natural gas systems. More specifically, the payoffs (net profits) of the three models, each of which consists of the payoffs of all participants (R^{P2G}, R^{E}, R^{G}), are illustrated in Table XII. For a more intuitive comparison among those payoffs in different models, Fig.5 is drawn corresponding to Table XII. It can be found from Fig.5 that the centralized model has the largest IES total profit. The value of the IES total profit in the NBS is between the centralized model and sequential model, while the sequential model has the minimum value of the IES total profit. Because the objective function of the centralized model aims to maximize the IES total payoffs, it is easy to understand that the centralized planning model obtains more total payoff than the other 2 models, which is 1568.18 M€.

For P2GSes, the total payoff of the P2GSes appears to be a deficit of 0.17 M€ in the centralized planning model. Meanwhile, both the electricity and natural gas systems earn the most payoffs (343.66 M€ and 1224.68 M€) in the centralized model than those in other two models. This indicates that to maximize the IES total payoff, the benefits of the P2GSes are sacrificed in the centralized planning model. In this situation, the P2GSes cannot be self-financed and fail to achieve a balance of payment, and potential investors' initiatives of planning P2GSes cannot be sustained in the liberalized market environment. Obviously, this capital loss caused by the centralized optimization will severely dampen the investor enthusiasm to build more P2GSes in the IES, especially in the initial stage of P2G technology development.

2) The sequential planning model

In comparison, P2GSes' total payoff reaches 68.47 M€ in the sequential planning model, which is the most among the three models. This is mainly because that the sequential model is basically a planning framework oriented by P2GSes, in which P2GSes are planned as a matter of priority. The electricity feeders and natural gas pipelines are constructed to supply energy to the P2GSes after the P2GSes planning scheme has been determined in the first step, and this planning sequence reduces the payoffs of electricity system and natural gas system significantly.

It can also be noticed in Fig.5 that the electricity system and natural gas system in this model have the least payoffs (157.7 M€ and 1182.52 M€) among the three planning solutions, while the sequential planning model results in 1408.69 M€ IES total payoffs, which are much smaller than that obtained by any of the other two models. Apparently, the sequential planning model effectively increases the motivation of planning more P2GSes by bringing in substantial revenue to the P2GS investors. However, the profitability of the natural gas and electricity systems are dramatically weakened, which will significantly reduce the initiatives of these two participants to construct enough electricity feeders and gas pipelines to support the safe and stable operation of P2GSes. Therefore, the plan for the IES may not be adopted by the electricity and natural gas systems, which consequently prevents the development of P2GSes.

3) The Nash bargaining planning Model

In the Nash bargaining planning model, it can be observed in Fig. 5 that the natural gas and the electricity systems gain more payoffs than that in the sequential model. The increased payoffs can be helpful for promoting the planners of the two systems to build enough feeders and pipelines to assist the popularization of P2GSes. Meanwhile, the payoffs of the P2GSes are just slightly decreased but are still considerable compared with the sequential model (59.51 M€ vs 68.47 M€). Moreover, the total payoff of the IES is 1464.98 M€, which is less than the payoff of the centralized model but more than the payoff of the sequential model. The major reason is that the Nash bargaining model always attempts to get the most fair and Pareto-efficient payoff allocation for the three independent participants compared with the centralized and sequential models, which maintains a good tradeoff between the fairness and the overall system performance. It can be concluded that the Nash bargaining solution is the most acceptable trade-off for all players in three models. A negotiated alliance can be established in this mechanism and each member of the alliance is willing to respect the obtained planning arrangement to cooperatively develop the IES in a compromising way.

4) Summary

The centralized planning model has the best performance in pursuing the overall system performance with a negative payoff allocated for P2GSes which does not consider the fairness among three participants. This model itself is unreasonable and illogical, Because it assumes three independent participants having conflicting interests are managed by one entity, which is quite contrary to the reality. Furthermore, the planning results demonstrate that P2GSes would not adopt this planning result because in this planning result its payoff is negative. In summary, this commonly used model in literatures cannot be applied for a practical situation.

In the planning solution of the sequential planning model, the payoffs of the electricity system and the natural gas system are the least among three models, while the payoff of P2GSes is the most. It is not fair for the electricity system and the natural gas system. Additionally, its least total payoff among three models means that the overall system performance obtained by the sequential planning model is also the worst. In the real world, if the electricity and the natural gas systems are not enforced to participate in the model, they would not agree with this planning result. Therefore, this model is also not suitable for the real applications.

Compared with the centralized planning model and the sequential planning model, the NBS obtained by the Nash bargaining planning model proposed in this paper results in the fair individual performance and the good overall system. In this model, three players are independent decision makers, which is in accordance with the reality. The NBS pursues the fair payoff allocation among them but does take the overall IES performance into consideration, which is easy to be accepted by participators. It can be concluded that the Nash bargaining model can be widely utilized for the real application.

V. Conclusions

An original negotiating planning framework based on the Nash bargaining theory for the P2GSes, electricity and natural gas systems in the IES is set up in this work. The proposed model considers the reality that the P2GSes, the electricity system and the natural gas system in the IES are independent decision makers and are responsible for their own profits. In addition, P2GSes' profitability potential of participating in ancillary markets is investigated systematically. The effectiveness of the proposed planning model is investigated in an IES system and compared with two commonly used planning models. The numerical results demonstrate that the utilized Nash bargaining theory is effective to result in a good tradeoff between the fair planning solutions for each participant and the overall IES system performance. The NBS aims to obtain the most fair payoff allocation for each decision maker, while maximizing the overall payoff of the IES if possible. Meanwhile, the simulation results also prove that the payoffs of P2GSes are improved significantly by providing carbon reduction and secondary reserve services in the ancillary markets. These additional revenues can cover high investment cost of P2GSes in the initial stage of P2G technology development and effectively promote its popularity. In summary, the proposed Nash bargaining planning model considering ancillary service of P2G can increase the motivation of P2GSes investment and contribute to the development of P2GSes in the future. Furthermore, the developed model has contributions such as 1) to popularize the P2G technology; 2) to promote the cooperation among the P2GSes, the electricity system and the natural gas system; 3) to enhance the comprehensive utilization of resources in electricity and natural gas systems; 4) to effectively help reduce energy waste, and to ensure reliable and efficient operation of the IES. Therefore, it is convinced that the proposed model has a high potential for the practical application in the IES planning.

References

[1] Quelhas A, Gil E, McCalley JD, Ryan SM. A multiperiod generalized network flow model of the US integrated energy system: Part I - Model description. IEEE Transactions on Power Systems. 2007;22:829-36.

[2] Shahidehpour M, Fu Y, Wiedman T. Impact of natural gas infrastructure on electric power systems. P IEEE. 2005;93:1042-56.

[3] Ozturk M, Yuksel YE, Ozek N. A Bridge between East and West: Turkey's natural gas policy. Renew Sust Energ Rev. 2011;15:4286-94.

[4] Uster H, Dilaveroglu S. Optimization for design and operation of natural gas transmission networks. Applied Energy. 2014;133:56-69.

[5] Chaudry M, Jenkins N, Qadrdan M, Wu J. Combined gas and electricity network expansion planning. Applied Energy. 2014;113:1171-87.

[6] Diagoupis TD, Andrianesis PE, Dialynas EN. A planning approach for reducing the impact of natural gas network on electricity markets. Applied Energy. 2016;175:189-98.

[7] Lo Cascio E, Borelli D, Devia F, Schenone C. Future distributed generation: An operational multi-objective optimization model for integrated small scale urban electrical, thermal and gas grids. Energy Conversion and Management. 2017;143:348-59.

[8] Shabanpour-Haghighi A, Seifi AR. Simultaneous integrated optimal energy flow of electricity, gas, and heat. Energy Conversion and Management. 2015;101:579-91.

[9] Qiu J, Zhao J, Yang H, Wang D, Dong ZY. Planning of solar photovoltaics, battery energy storage system and gas micro turbine for coupled micro energy grids. Applied Energy. 2018;219:361-9.

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

[11] Qiu J, Dong ZY, Zhao JH, Xu Y, Zheng Y, Li C, et al. Multi-Stage Flexible Expansion Co-Planning Under Uncertainties in a Combined Electricity and Gas Market. IEEE Transactions on Power Systems. 2015;30:2119-29.

[12] Qiu J, Dong ZY, Zhao JH, Meng K, Zheng Y, Hill DJ. Low Carbon Oriented Expansion Planning of Integrated Gas and Power Systems. IEEE Transactions on Power Systems. 2015;30:1035-46.

[13] Hu Y, Bie Z, Ding T, Lin Y. An NSGA-II based multi-objective optimization for combined gas and electricity network expansion planning. Applied Energy. 2016;167:280-93.

[14] Nunes JB, Mahmoudi N, Saha TK, Chattopadhyay D. A stochastic integrated planning of electricity and natural gas networks for Queensland, Australia considering high renewable penetration. Energy. 2018;153:539-53.

[15] Odetayo B, Kazemi M, MacCormack J, Rosehart W, Zareipour H, Seifi AR. A Chance Constrained Programming Approach to the Integrated Planning of Electric Power Generation, Natural Gas Network and Storage. IEEE Transactions on Power Systems. 2018:1-.

[16] Mazza A, Bompard E, Chicco G. Applications of power to gas technologies in emerging electrical systems. Renewable and Sustainable Energy Reviews. 2018;92:794-806.

[17] Bailera M, Lisbona P, Romeo LM, Espatolero S. Power to Gas projects review: Lab, pilot and demo plants for storing renewable energy and CO2. Renew Sust Energ Rev. 2017;69:292-312.

[18] Zoss T, Dace E, Blumberga D. Modeling a power-to-renewable methane system for an assessment of power grid balancing options in the Baltic States' region. Applied Energy. 2016;170:278-85.

[19] Kloess M, Zach K. Bulk electricity storage technologies for load-leveling operation - An economic assessment for the Austrian and German power market. Int J Elec Power. 2014;59:111-22.

[20] Zeng Q, Fang JK, Li JH, Chen Z. Steady-state analysis of the integrated natural gas and electric power system with bi-directional energy conversion. Applied Energy. 2016;184:1483-92.

[21] Hartel P, Doering M, Jentsch M, Pape C, Burges K, Kuwahata R. Cost assessment of storage options in a region with a high share of network congestions. J Energy Storage. 2016;8:358-67.

[22] Mukherjee U, Walker S, Maroufmashat A, Fowler M, Elkamel A. Development of a pricing mechanism for valuing ancillary, transportation and environmental services offered by a power to gas energy system. Energy. 2017;128:447-62.

[23] Grueger F, Möhrke F, Robinius M, Stolten D. Early power to gas applications: Reducing wind farm forecast errors and providing secondary control reserve. Applied Energy. 2017;192:551-62.

[24] Zeng Q, Zhang B, Fang J, Chen Z. A bi-level programming for multistage co-expansion planning of the integrated gas and electricity system. Applied Energy. 2017;200:192-203.

[25] Robinius M, Raje T, Nykamp S, Rott T, Müller M, Grube T, et al. Power-to-Gas: Electrolyzers as an alternative to network expansion – An example from a distribution system operator. Applied Energy. 2018;210:182-97.

[26] Guandalini G, Campanari S, Romano MC. Power-to-gas plants and gas turbines for improved wind energy dispatchability: Energy and economic assessment. Applied Energy. 2015;147:117-30.

[27] Andoni M, Robu V, Früh W-G, Flynn D. Game-theoretic modeling of curtailment rules and network investments with distributed generation. Applied Energy. 2017;201:174-87.

[28] Banez-Chicharro F, Olmos L, Ramos A, Latorre JM. Beneficiaries of transmission expansion projects of an expansion plan: An Aumann-Shapley approach. Applied Energy. 2017;195:382-401.

[29] Götz M, Lefebvre J, Mörs F, McDaniel Koch A, Graf F, Bajohr S, et al. Renewable Power-to-Gas: A technological and economic review. Renewable Energy. 2016;85:1371-90.

[30] Baumann C, Schuster R, Moser A. Economic potential of power-to-gas energy storages. 2013 10th International Conference on the European Energy Market (EEM)2013. p. 1-6.

[31] Irving, Malcolm, Song, Yonghua, Wang, Xifan. Modern Power Systems Analysis. Springer Berlin. 2013;29:399-413.

[32] Seungwon A, Qing L, Gedra TW. Natural gas and electricity optimal power flow. 2003 IEEE PES Transmission and Distribution Conference and Exposition (IEEE Cat No03CH37495)2003. p. 138-43 Vol.1.

[33] Li Y, Shahidehpour M, Liu W, Wen F, Wang K, Huang Y. Optimal Operation Strategy for Integrated Power-to-Gas and Natural Gas Generating Unit Facilities. IEEE Transactions on Sustainable Energy. 2018:1-.

[34] Lisbona P, Frate GF, Bailera M, Desideri U. Power-to-Gas: Analysis of potential decarbonization of Spanish electrical system in long-term prospective. Energy. 2018.

[35] Clegg S, Mancarella P. Storing renewables in the gas network: modelling of power-to-gas seasonal storage flexibility in low-carbon power systems. IET Generation, Transmission & Distribution. 2016;10:566-75.

[36] Yu N, Tesfatsion L, Liu C-C. Financial Bilateral Contract Negotiation in Wholesale Electricity Markets Using Nash Bargaining Theory. IEEE Transactions on Power Systems. 2012;27:251-67.

[37] Binmore K. Game Theory and the Social Contract. Journal De Economistes Et Des Etudes Humaines. 1994;5:429-36.

[38] Wang H, Huang J. Incentivizing Energy Trading for Interconnected Microgrids. IEEE Transactions on Smart Grid. 2018;9:2647-57.

[39] Roth AE, Rothblum UG. Risk Aversion and Nash's Solution for Bargaining Games with Risky Outcomes. Econometrica. 1982;50:639-47.

[40] Nash JF. The Bargaining Problem. Econometrica. 1950;18:155-62.

[41] Nash J. Two-Person Cooperative Games. Econometrica. 1953;21:128-40.

[42] Wang H, Huang J. Cooperative Planning of Renewable Generations for Interconnected Microgrids. IEEE Transactions on Smart Grid. 2016;7:2486-96.

[43] Nguyen HK, Khodaei A, Han Z. Incentive Mechanism Design for Integrated Microgrids in Peak Ramp Minimization Problem. IEEE Transactions on Smart Grid. 2017:1-.

[44] Nguyen HK, Mohsenian-Rad H, Khodaei A, Han Z. Decentralized Reactive Power Compensation Using Nash Bargaining Solution. IEEE Transactions on Smart Grid. 2017;8:1679-88.

[45] Bertoldi O, Salvaderi L, Scalcino S. Monte-Carlo Approach in Planning Studies - an Application to Ieee Rts. Ieee Transactions on Power Systems. 1988;3:1146-54.

[46] Subcommittee PM. Ieee Reliability Test System. Ieee T Power Ap Syst. 1979;98:2047-54.

[47] De Wolf D, Smeers Y. The gas transmission problem solved by an extension of the simplex algorithm. Management Science. 2000;46:1454-65.

[48] Unsihuay C, Lima JWM, Souza ACZd. Modeling the Integrated Natural Gas and Electricity Optimal Power Flow. 2007 IEEE Power Engineering Society General Meeting2007. p. 1-7.

[49] Lisbona P, Frate GF, Bailera M, Desideri U. Power-to-Gas: Analysis of potential decarbonization of Spanish electrical system in long-term prospective. Energy. 2018;159:656-68.

[50] Bailera M, Lisbona P. Energy storage in Spain: Forecasting electricity excess and assessment of power-to-gas potential up to 2050. Energy. 2018;143:900-10.

[51] Eveloy V, Gebreegziabher T. Excess electricity and power-to-gas storage potential in the future renewable-based power generation sector in the United Arab Emirates. Energy. 2019;166:426-50.

[52] de Boer HS, Grond L, Moll H, Benders R. The application of power-to-gas, pumped hydro storage and compressed air energy storage in an electricity system at different wind power penetration levels. Energy. 2014;72:360-70.

[53] Modiri-Delshad, Mostafa, et al. Backtracking search algorithm for solving economic dispatch problems with valve-point effects and multiple fuel options. Energy. 2016;116:637-649.

[54] Rafieerad, A. R., et al. Toward improved mechanical, tribological, corrosion and in-vitro bioactivity properties of mixed oxide nanotubes on Ti-6Al-7Nb implant using multi-objective PSO. Journal of the Mechanical Behavior of Biomedical Materials. 2017; 69:1-18.

[55] Kaboli, S. Hr Aghay, J. Selvaraj, and N. A. Rahim. Rain-fall optimization algorithm: a population based algorithm for solving constrained optimization problems. Journal of Computational Science. 2017.

[56] S. S. Sebtahmadi; H. Borhan Azad; S. H. Aghay Kaboli; M. D. Islam; S. Mekhilef, A PSO-DQ Current Control Scheme for Performance Enhancement of Z-source Matrix Converter to Drive IM Fed by Abnormal Voltage, in IEEE Transactions on Power Electronics, vol.PP, no.99, pp.1-1.

[57] Rafieerad, A. R., et al. GEP-based method to formulate adhesion strength and hardness of Nb PVD coated on Ti-6Al-7Nb aimed at developing mixed oxide nanotubular arrays. Journal of the mechanical behavior of biomedical materials 61 (2016): 182-196.

[58] Kaboli, S. Hr Aghay, et al. Long-term electrical energy consumption formulating and forecasting via optimized gene expression programming. Energy. 2017; 126: 144-164.

[59] Kaboli, S. Hr Aghay, J. Selvaraj, and N. A. Rahim. Long-term electric energy consumption forecasting via artificial cooperative search algorithm. Energy. 2016;115:857-871.

[60] Kaboli, S. Hr Aghay, et al. An expression-driven approach for long-term electric power consumption forecasting. American Journal of Data Mining and Knowledge Discovery 1.1 (2016): 16-28.

[61] Bonami, P., Lee, J.: ‘Bonmin users manual’, Retrieved[AQ4] November, 2007, 4, pp. 2008, https://projects.coin-or.org/Bonmin/browser/stable/0.1/Bonmin/doc/BONMIN_UsersManual.pdf?format=raw

[62] Ghaderi Darebaghi M , Amraee T . Dynamic multi-stage under frequency load shedding considering uncertainty of generation loss. IET Generation, Transmission & Distribution, 2017, 11(13):3202-3209.

[63] Sutradhar S , Choudhury N B D , Sinha N . MINLP for Hydro-Thermal Unit Commitment problem using BONMIN solver[C]// IEEE International Conference on Power Electronics. IEEE, 2017.

[64] D. Fudenberg and J. Tirole, Game Theory, MIT Press, Cambridge, MA. 1991.

[65] Zhang G , Yang K , Chen H H . Resource allocation for wireless cooperative networks: a unified cooperative bargaining game theoretic framework. IEEE Wireless Communications, 2012, 19(2):38-43.

[66] B. Niu and et al., “A cooperation stimulation strategy in wireless multicast networks,” IEEE Trans. Signal Process., vol. 8, no. 5, pp.667–678, 2011.

[67] Han Z , Ji Z , Liu K J R. Fair Multiuser Channel Allocation for OFDMA Networks Using Nash Bargaining Solutions and Coalitions. IEEE Transactions on Communications, 2005, 53(8):1366-1376.

[68] Zhang G , Yang K , Hu Q, et al. Bargaining Game Theoretic Framework for Stimulating Cooperation in Wireless Cooperative Multicast Networks. IEEE Communications Letters, 2012, 16(2):208-211.

[69] Z. Han, Z. Ji, and K. J. R. Liu, “Fair multiuser channel allocation for OFDMA networks using Nash bargaining solutions and coalitions,” IEEE Trans. Commun., vol. 53, no. 8, pp. 1366–1376, 2005.

[70] J. Iria and F. Soares, "A cluster-based optimization approach to support the participation of an aggregator of a larger number of prosumers in the day-ahead energy market," Electric Power Systems Research, vol. 168, pp. 324-335, Mar. 2019.

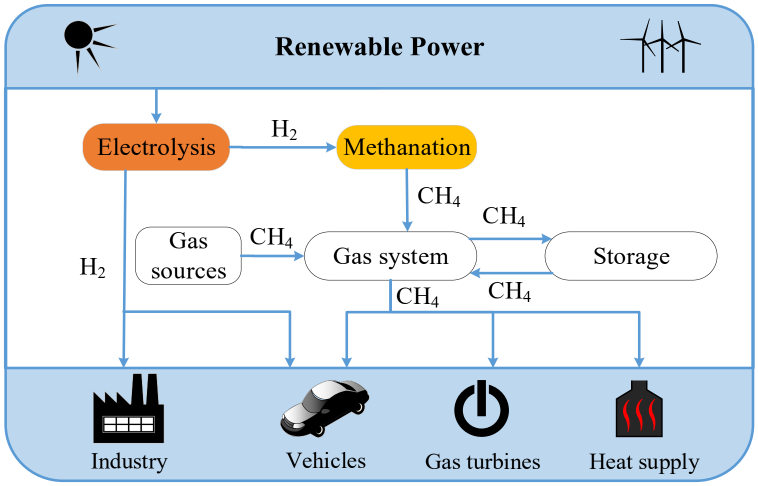

Fig. 1. The P2G process [30].

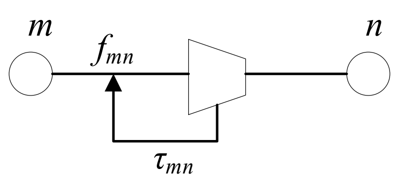

Fig. 2. The compressor model.

Table I Compressor Station Parameters

Station No.	Gas bus No.		B_k	Z_k	α_k	β_k	γ_k
	From	To					
1	4^G	14^G	228.74	0.2334	0	0.0002	0
2	17^G	18^G	228.74	0.2334	0	0.0002	0

Bus number with superscript ^{G} represents this bus is in the natural gas system. Bus number without superscript ^{G} represents this bus is in the electricity system.

Table II Candidate P2GS and Supporting Lines/ Pipelines Parameters

P2GS candidate No.	P2GS Location	P2GS candidate categories	Candidate feeders/pipelines to support P2GS				$P_p^{P2G,RAT}$ (MW)	μ_p^{EFF} (%)
			From	To	Length (km)	Type		
1	20	1)	20	11^G	10	pipeline	100	60
			20	13^G	15	pipeline		
			20	17^G	17	pipeline		
2	23	1)	23	9^G	22	pipeline	100	60
			23	10^G	15	pipeline		
			23	11^G	19	pipeline		
3	15^G	2)	11	15^G	10	feeder	100	60
			14	15^G	11	feeder		
			24	15^G	17	feeder		
4	18^G	2)	5	18^G	30	feeder	100	60
			11	18^G	23	feeder		
			12	18^G	19	feeder		
5	isolated	3)	isolated bus	1^G	9	pipeline	100	60
			isolated bus	2^G	10	pipeline		
			isolated bus	18	10	feeder		
			isolated bus	3^G	11	pipeline		

Bus number with superscript ^{G} represents this bus is in the natural gas system. Bus number without superscript ^{G} represents this bus is in the electricity system.

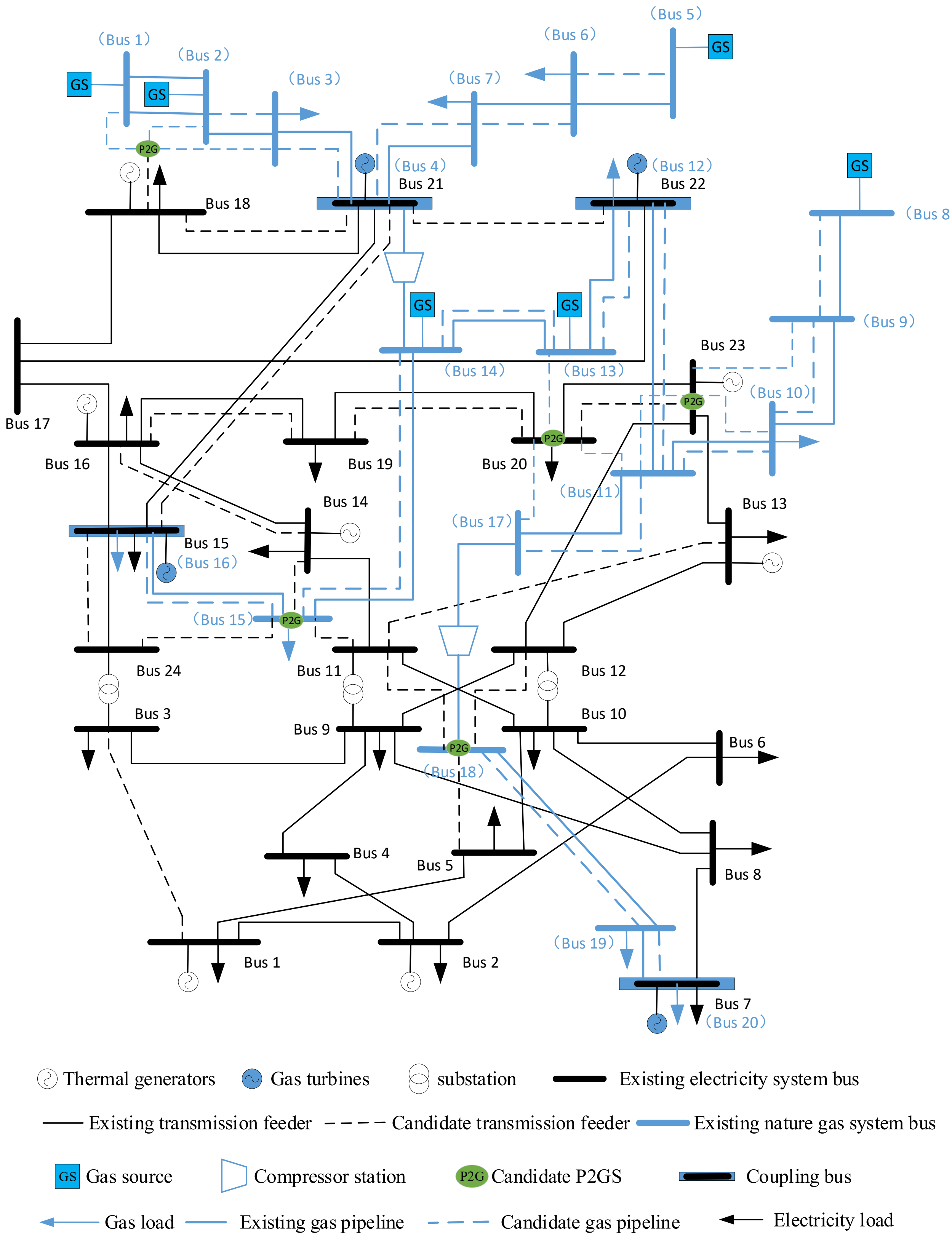

Fig. 3. The IES with candidate lines, pipelines and P2GSes.

TABLE III PARAMETERS OF CANDIDATE ELECTRICITY FEEDERS

Feeder No.	Electricity Bus No.		x_{ij} (p.u.)	$P_{ij}^{ECL,MAX}$ (MW)
	From	To		
32	21	22	0.0216	240
33	15	21	0.0678	400
34	18	21	0.049	400
35	19	20	0.0259	400
36	20	23	0.0396	400
37	11	13	0.0216	400
38	1	3	0.0476	400
39	14	16	0.2112	140
40	15	24	0.0389	400
41	16	19	0.0519	400

Bus/feeder number without superscript ^{G} represents this bus/feeder is in the electricity system.

TABLE IV PARAMETERS OF CANDIDATE PIPELINES

Pipeline No.	Natural Gas Bus No.		C_{mn}	f_{mn}^{MAX} (Mm^3/day)	l_{mn}^{PIPE} (km)
	From	To			
21^G	2^G	3^G	6.04685	102.13	6
22^G	3^G	4^G	1.39543	49.06	26
23^G	5^G	6^G	0.100256	13.15	43
24^G	6^G	7^G	0.1486551	16.01	29
25^G	7^G	4^G	0.226895	19.78	19
26^G	8^G	9^G	0.108033	13.65	5
27^G	9^G	10^G	0.0270084	6.83	20
28^G	10^G	11^G	1.45124	50.03	25
29^G	11^G	12^G	0.863836	38.6	42
30^G	12^G	13^G	0.907027	39.56	40
31^G	13^G	14^G	7.25622	111.88	5
32^G	14^G	15^G	3.62811	79.11	10
33^G	15^G	16^G	1.45124	50.03	25
34^G	18^G	19^G	0.0017032	3.33	98
35^G	19^G	20^G	0.027819	6.93	6

Bus/pipeline number with superscript ^{G} represents this bus/pipeline is in the natural gas system.

TABLE V PRICES IN THE ELECTRICITY MARKET AND NATURAL GAS MARKET

time interval	$\lambda_{m,t}^{GAS}$ (€/(MW·h))	$\lambda_{i,t}^{ELE}$ (€/(MW·h))	$\lambda_{p,t}^{P2G,SA}$ (M€/Mm^3)	$\lambda_{p,t}^{CA,UP}$ (€/MW)	$\lambda_{p,t}^{CA,DW}$ (€/MW)	$\lambda_{p,t}^{AC,UP}$ (€/(MW·h))	$\lambda_{p,t}^{AC,DW}$ (€/(MW·h))
1	30.435	20.29	0.3	10.615	10.615	27.306	14.916
2	29.85	19.9	0.3	14.08	14.08	40.761	9.614
3	29.685	19.79	0.3	16.753	16.753	36.783	10.538
4	29.85	19.9	0.3	17.941	17.941	27.135	14.443
5	36.06	24.04	0.3	17.941	17.941	40.626	14.08
6	47.535	31.69	0.3	19.525	19.525	45.9	21.648
7	92.61	66.15	0.3	7.447	7.447	102.501	42.251
8	95.746	68.39	0.3	13.2	13.2	108.225	42.779
9	79.842	57.03	0.32	11.968	11.968	69.021	46.64
10	62.748	44.82	0.32	10.142	10.142	55.773	35.651
11	62.762	44.83	0.32	8.91	8.91	46.233	43.021
12	54.67	39.05	0.32	12.243	12.243	38.016	39.699
13	61.628	44.02	0.32	12.408	12.408	44.325	43.274
14	57.022	40.73	0.32	11.11	11.11	43.209	37.994
15	49.395	32.93	0.32	8.624	8.624	31.041	34.573
16	48	32	0.32	8.69	8.69	32.886	30.811
17	49.245	32.83	0.31	11.22	11.22	36.234	29.436
18	58.575	39.05	0.31	13.2	13.2	39.402	38.313
19	85.515	57.01	0.31	21.208	21.208	58.914	54.604
20	47.49	31.66	0.31	13.2	13.2	30	34.199
21	34.59	23.06	0.31	13.2	13.2	20.46	25.146
22	39.165	26.11	0.31	13.2	13.2	24.3496	27.093
23	36.075	24.05	0.31	5.775	5.775	20	25.938
24	31.35	20.9	0.31	7.117	7.117	17	22.506

TABLE VI P2GSES PLANNING RESULTS OF THE NASH BARGAINING MODEL

P2GS No.	P2GS Location	P2GS categories	feeders/pipelines to support P2GS				$P_p^{P2G,RAT}$ (MW)	μ_p^{EFF} (%)
			From	To	Length (km)	Type		
1	20	1)	20	11^G	10	pipeline	100	60
2	23	1)	23	10^G	15	pipeline	100	60
5	isolated	3)	isolated bus	1^G	9	pipeline	100	60
			isolated bus	18	10	feeder		

Bus number with superscript ^{G} represents this bus is in the natural gas system. Bus number without superscript ^{G} represents this bus is in the electricity system.

TABLE VII ENHANCED ELECTRICITY SYSTEM FEEDER PLANNING RESULTS OF THE NASH BARGAINING MODEL

Feeder No.	From	To	x_{ij} (p.u.)	$P_{ij}^{ECL,MAX}$ (MW)
37	11	13	0.0216	400

Bus/feeder number without superscript ^{G} represents this bus/feeder is in the electricity system.

TABLE VIII ENHANCED NATURAL GAS SYSTEM PIPELINE PLANNING RESULTS OF THE NASH BARGAINING MODEL

Pipeline No.	From	To	C_{mn}	f_{mn}^{MAX} (m^3/day)	l_{mn}^{PIPE} (km)
28^G	10^G	11^G	1.45124	50.03	25

Bus/pipeline number with superscript ^{G} represents this bus/pipeline is in the natural gas system.

Table IX SUMMARY OF THE PROFITS AND COSTS OF THE NASH BARGAINING MODEL (M€)

	Profits R^{PR}	Construction costs C^{IN}	Operation costs C^{OP}	Payoffs
P2GSes	980.46	154.71	766.24	59.51
Electricity system	8519.5	4.81	8298.33	216.36
Natural gas system	44959.7	18.02	43753	1189.1

Table X P2GSES OPERATION INCOMES OF THE NASH BARGAINING MODEL

Income Type	Income Value (M€)	Percentages
$R^{P2G,SA}$	512.292	52.3%
$R^{P2G,EN}$	149.142	15.2%
$R^{P2G,CA}$	128.330	13.1%
$R^{P2G,CAR}$	190.698	19.4%
Total	980.462	100%

Table XI SUMMARY OF THE PLANNING RESULTS OF DIFFERENT MODELS

Planning models	P2GS locations	electricity feeders		gas pipelines	
		From	To	From	To
Nash bargaining	20, 23, isolated	isolated bus 11	18 13	20 23 isolated bus 10^G	11^G 10^G 1^G 11^G
Centralized	20, 15^G, isolated	14 isolated bus 11	15^G 18 13	20 isolated bus 10^G 19^G	11^G 1^G 11^G 20^G
Sequential	20, 15^G, isolated	isolated bus 24 11	18 15^G 13	isolated bus 20 10^G 18^G	3^G 17^G 11^G 19^G

Bus number with superscript ^{G} represents this bus is in the natural gas system. Bus number without superscript ^{G} represents this bus is in the electricity system.

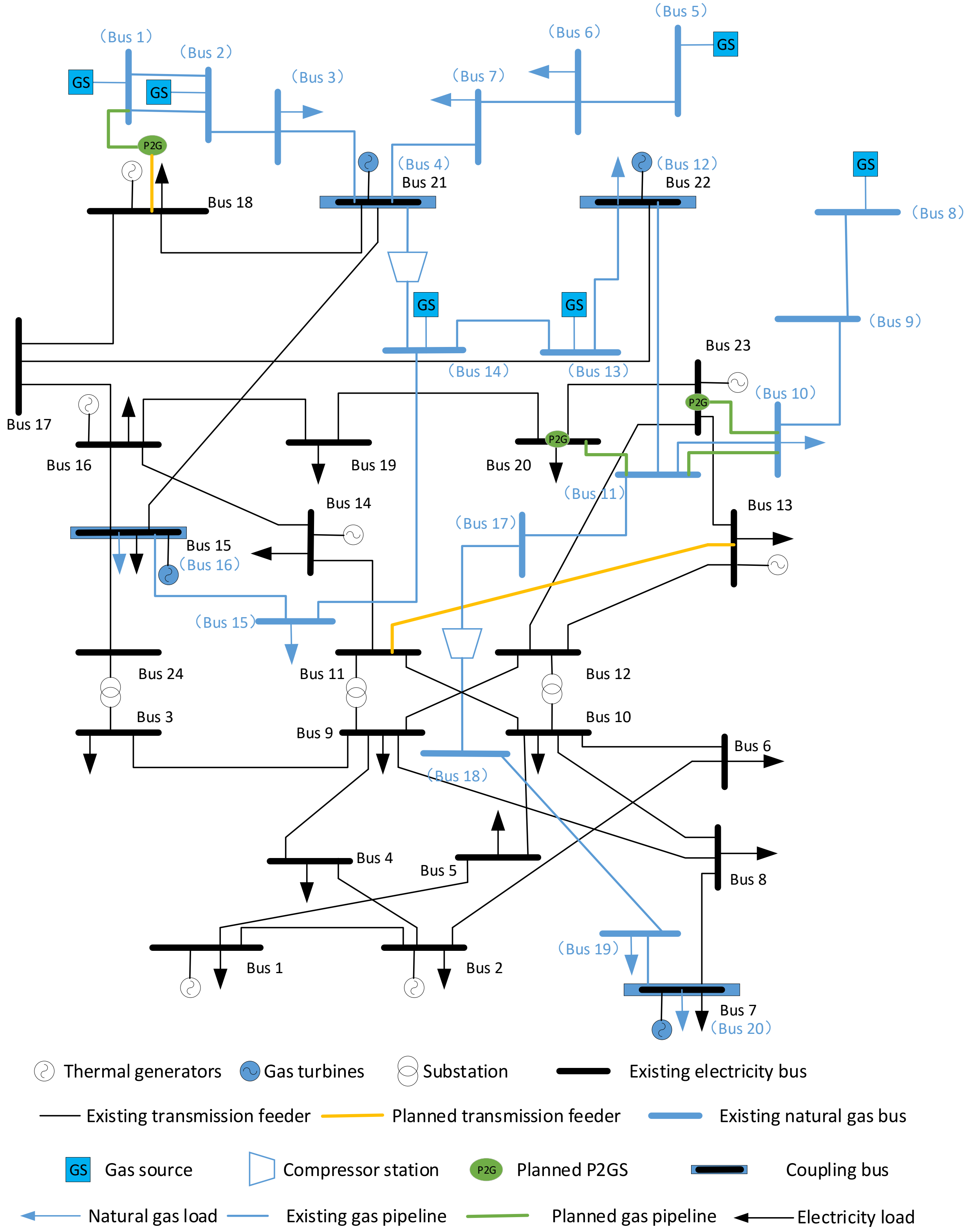

Fig. 4. The final planning scheme of the IES by Nash bargaining.

Table XII THE PAYOFFS OF DIFFERENT PLANNING MODELS (M€)

	Nash Bargaining	Centralized	Sequential
R^{P2G}	59.51	-0.17	68.47
R^{E}	216.36	343.66	157.7
R^{G}	1189.1	1224.68	1182.52
The IES total profit	1464.98	1568.18	1408.69

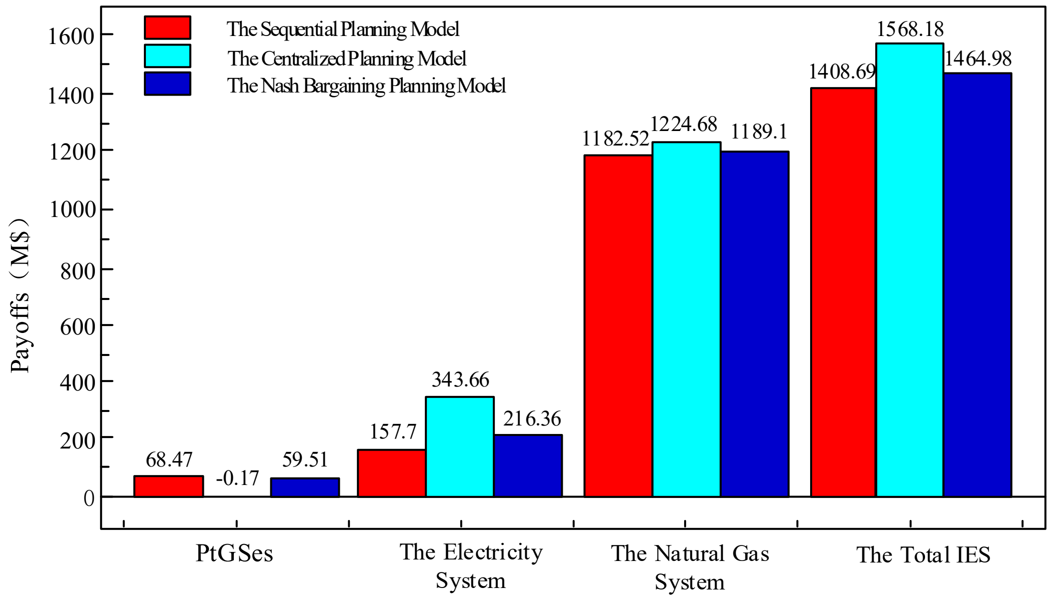

Fig. 5. The payoffs of participants in different planning models

APPENDIX

The constraints related to the P2GS as stated by (33) to (41)

$$P_p^{\mathrm{P2G,MIN}} \cdot \eta_p^{\mathrm{P2G}} \le P_{p,t}^{\mathrm{AC}} \quad \forall p \in \Omega^{\mathrm{P2G}}, t \in T \tag{33}$$

$$P_{p,t}^{\mathrm{AC}} \le P_p^{\mathrm{P2G,RAT}} \cdot \eta_p^{\mathrm{P2G}} \quad \forall p \in \Omega^{\mathrm{P2G}}, t \in T \tag{34}$$

$$0 \le P_{p,t}^{\mathrm{AC,UP}} \le P_p^{\mathrm{CAP,UP}} \cdot \eta_p^{\mathrm{P2G}} \quad \forall p \in \Omega^{\mathrm{P2G}}, t \in T \tag{35}$$

$$0 \le P_{p,t}^{\mathrm{AC,DW}} \le P_p^{\mathrm{CAP,DW}} \cdot \eta_p^{\mathrm{P2G}} \quad \forall p \in \Omega^{\mathrm{P2G}}, t \in T \tag{36}$$

$$\left| S_{\mathrm{p},t} \right| \le S_p^{\mathrm{MAX}} \cdot \eta_p^{\mathrm{P2G}} \quad \forall p \in \Omega^{\mathrm{P2G}}, t \in T \tag{37}$$

$$\left| P_{\mathrm{p},t} \right| \le P_p^{\mathrm{MAX}} \cdot \eta_p^{\mathrm{P2G}} \quad \forall p \in \Omega^{\mathrm{P2G}}, t \in T \tag{38}$$

$$S_{p,t}^{\mathrm{P2G,SAL}} = \mu_p^{\mathrm{EFF}} \cdot P_{p,t}^{\mathrm{AC}} \quad \forall p \in \Omega^{\mathrm{P2G}}, t \in T \tag{39}$$

$$P_{p,t}^{\mathrm{AC}} = P_{p,t}^{\mathrm{ETP}} - P_{p,t}^{\mathrm{AC,UP}} E_{ru,t} + P_{p,t}^{\mathrm{AC,DW}} E_{rd,t} \quad \forall p \in \Omega^{\mathrm{P2G}}, t \in T \tag{40}$$

$$\sum_{p \in \Omega^{\mathrm{P2G}}} \eta_p^{\mathrm{P2G}} = N \tag{41}$$

Constraint (33) ensures that the minimum operating power of P2GS is fulfilled. Inequality (34) is the maximum output power operating limit. (35) and (36) denote the upward and downward secondary reserve constraints. As shown in (37), the natural gas flow volume in the pipeline connecting P2GS p with the natural gas system should be less than the maximum capacity of the pipeline. According to (38), the power magnitude of the electricity feeder linking P2GS p with the electricity system should not be more than the capacity of the feeder. Equation (39) indicates the P2G converting process. (40) describes the actual consumed electricity by P2GS is composed of the day-ahead purchased energy and the deviations caused by providing the upward and downward secondary reserve service. The constraint of the number of planned P2GS is determined by (41).

The constraints of the electricity system are described by (42) to (49)

$$\sum_{i \in \Omega^{\mathrm{EBUS}}} P_{i,t}^{\mathrm{ELE,SAL}} + \sum_{p \in \Omega^{\mathrm{P2G}}} \eta_p^{\mathrm{P2G}} \cdot P_{p,t}^{\mathrm{ETP}} = \sum_{i \in \Omega^{\mathrm{GT}}} P_{i,t}^{\mathrm{GT}} + \sum_{i \in \Omega^{\mathrm{TG}}} P_{i,t}^{\mathrm{ELE,TG}} \quad \forall t \in T \tag{42}$$

$$P_{i,t}^{\mathrm{GT}} + P_{i,t}^{\mathrm{TG}} - P_{i,t}^{\mathrm{ELE,SAL}} - P_{i,t}^{\mathrm{ETP}} = \sum_{ij \in \Omega^{\mathrm{EL}}} P_{ij,t}^{\mathrm{EL}} + \sum_{ij \in \Omega^{\mathrm{ECL}}} P_{ij,t}^{\mathrm{ECL}} \ \forall i,j \in \Omega^{\mathrm{EB}}, t \in T \tag{43}$$

$$P_{ij,t}^{\mathrm{EL}} = \frac{\theta_{i,t} - \theta_{j,t}}{x_{ij}^{\mathrm{EL}}} \quad \forall ij \in \Omega^{\mathrm{EL}}, t \in T \tag{44}$$

$$P_{ij,t}^{\mathrm{ECL}} = \frac{\theta_{i,t} - \theta_{j,t}}{x_{ij}^{\mathrm{ECL}}} \cdot \eta_{ij}^{\mathrm{LINE}} \quad \forall ij \in \Omega^{\mathrm{ECL}}, t \in T \tag{45}$$

$$\left| P_{ij,t}^{\mathrm{EL}} \right| \le P_{ij}^{\mathrm{EL,MAX}} \quad \forall ij \in \Omega^{\mathrm{EL}}, t \in T \tag{46}$$

$$\left| P_{ij,t}^{\mathrm{ECL}} \right| \le P_{ij}^{\mathrm{ECL,MAX}} \cdot \eta_{ij}^{\mathrm{LINE}} \quad \forall ij \in \Omega^{\mathrm{ECL}}, t \in T \tag{47}$$

$$P_v^{\mathrm{TG,MIN}} \le P_{\mathrm{v},t}^{\mathrm{TG}} \le P_v^{\mathrm{TG,MAX}} \quad \forall v \in \Omega^{\mathrm{TG}}, t \in T \tag{48}$$

$$P_u^{\mathrm{GT.MIN}} \le P_{\mathrm{u},t}^{\mathrm{GT}} \le P_u^{\mathrm{GT,MAX}} \quad \forall u \in \Omega^{\mathrm{GT}}, t \in T \tag{49}$$

(42) and (43) are the typical direct current (DC) power flow equality constraints. (44) and (45) state the power flow calculation in the existing and candidate feeders. (46) and (47) give the power transmission limits of the existing and candidate feeders. The active output power limits of gas turbines and thermal generators ate stated as (48) and (49).

The constraints of the natural gas system are demonstrated as (50) to (58)

$$S_{m,t}^{\mathrm{GAS,INJ}} + S_{m,t}^{\mathrm{PTG,SAL}} - S_{m,t}^{\mathrm{GAS,SAL}} - S_{m,t}^{\mathrm{GT}} = \sum_{n \in \Omega^{\mathrm{GB}}} f_{mn,t} + \sum_{n \in \Omega^{\mathrm{C}}} \tau_{mn,t} \quad \forall m \in \Omega^{\mathrm{GB}}, t \in T \tag{50}$$

$$\left| f_{\mathrm{mn},t} \right| \le f_{mn}^{\mathrm{MAX}} \quad \forall mn \in \Omega^{\mathrm{GP}}, t \in T, \eta_{mn}^{\mathrm{PIPE}} = 0 \tag{51}$$

$$\left| f_{mn,t} \right| \le f_{mn}^{\mathrm{MAX}} \cdot \eta_{mn}^{\mathrm{PIPE}} \quad \forall mn \in \Omega^{\mathrm{GCP}}, t \in T, \eta_{mn}^{\mathrm{PIPE}} = 1 \tag{52}$$

$$S_m^{\mathrm{GAS,INJ,MIN}} \le S_{\mathrm{m},t}^{\mathrm{GAS,INJ}} \le S_m^{\mathrm{GAS,INJ,MAX}} \quad \forall m \in \Omega^{\mathrm{GB}}, t \in T \tag{53}$$

$$\pi_m^{\mathrm{MIN}} \le \pi_{m,t} \le \pi_m^{\mathrm{MAX}} \quad \forall m \in \Omega^{\mathrm{GB}}, t \in T \tag{54}$$

$$f_{mn,t} = \mathrm{sgn}(\pi_{m,t}, \pi_{n,t}) \cdot C_{mn} \cdot \sqrt{\left| {\pi_{m,t}}^2 - {\pi_{n,t}}^2 \right|} \quad \forall mn \in \Omega^{\mathrm{GP}}, t \in T, \eta_{mn}^{\mathrm{PIPE}} = 0 \tag{55}$$

$$f_{mn,t} = \mathrm{sgn}(\pi_{m,t}, \pi_{n,t}) \cdot C_{mn} \cdot \sqrt{\left| {\pi_{m,t}}^2 - {\pi_{n,t}}^2 \right|} \cdot \eta_{mn}^{\mathrm{PIPE}} \quad \forall mn \in \Omega^{\mathrm{GCP}}, t \in T, \eta_{mn}^{\mathrm{PIPE}} = 1 \tag{56}$$

$$\mathrm{sgn}(\pi_{m,t}, \pi_{n,t}) = \begin{cases} 1 & \pi_{m,t} \ge \pi_{n,t} \\ -1 & \pi_{m,t} < \pi_{n,t} \end{cases} \quad \forall m \in \Omega^{\mathrm{GBUS}}, t \in T \tag{57}$$

$$\begin{cases} H_{mn,t} = B_{mn} \cdot f_{mn,t} \cdot \left[\left(\dfrac{\pi_{m,t}}{\pi_{n,t}} \right)^{Z_{mn}} - 1 \right] \\ \tau_{mn,t} = \alpha_{mn} + \beta_{mn} \cdot H_{mn,t} + \gamma_{mn} \cdot \left(H_{mn,t} \right)^2 \end{cases} \quad t \in T \tag{58}$$

(50) is gas flow generation and consumption balance constraint in the natural gas system, which is in fact a detailed formulation resulted from the mass-flow balance equation (7). (51) and (52) give the gas flow capacity limits of the existing and candidate gas pipelines. The injection amount of natural gas is restricted by (53) due to the equipment and technical limitations. Constraint (54) gives the feasible ranges of the nodal natural gas air pressure. (55)-(58) are based on (3)-(6), which give the mathematical expressions of the steady state natural gas flow model.