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# A New Commerce Operation Model for Integrated Energy System Containing the Utilization of Bio-Natural Gas

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**Abstract:** To promote the collaborative development of the bio-natural gas (BNG) industry and the integrated energy system (IES), this paper proposes a new commerce operation model considering the gas price adjustment mechanism for the IES with the utilization of bio-natural gas. The bi-level optimization model is used to simulate the clearing process within the open energy market framework, and the uncertainties of variable renewable energy output are modeled with a set of scenarios through the stochastic programming approach. In the upper-level model, the energy management center adjusts the bio-natural gas price rationally to minimize the expected total operating cost and release the price signal to the lower-level model; the lower-level model simulates the sub-markets clearing process to formulate detailed operation schemes. The bi-level model is transformed into a mathematical programming problem with equilibrium constraints (MPEC) through the Karush–Kuhn–Tucker (KKT) condition of the lower-level model, and the nonlinear model is converted into a mixed-integer linear programming problem and solved. The numerical results verified the effectiveness of the proposed model.

**Keywords:** integrated energy system; distributed renewable energy sources; bio-natural gas; open energy markets; bi-level optimization model

## 1. Introduction

Combining the distributed renewable energy sources (DRES) with other distributed controllable energy supply equipment to form an integrated energy system (IES) is becoming an ideal choice to achieve the smooth transition from the traditional power supply structure to a sustainable energy system [1,2]. An IES can match up energy demand profile with local natural resources well and enhance the coupling and complementarity among different energy flow through various energy conversion equipment to ensure the efficient and safe operation of the energy system [3,4]. Micro gas turbine and gas boiler have been widely applied in an IES for its flexible and efficient characteristics and good compatibility with bio-natural gas [5]. BNG, as the purified product of biogas, is one of the primary forms of clean and efficient biomass energy utilization, which inherited the advantages of both traditional fossil fuels and sustainable energy. It can provide a green and dispatchable resource to overcome the inherent defect of other variable renewable energy [6–8].

With the continuous marketization of the energy and electricity industry in China, the electricity market has been constantly reconstructed, and the market players have also shown the trend of

diversification [9,10]. In this context, the increasingly intense market competition and advanced energy supply methods give birth to the new energy consumption and service models [11,12]. The integrated energy system gathering various local natural resources (wind and solar), integrating power, heating (cold), and other energy supplies based on distributed gas utilization to provide users with overall energy solutions, will become a typical scenario for BNG utilization in the future. Furthermore, the review article [6,8] revealed the huge resource potential and broad market demand for BNG in China's energy sector. Therefore, it is vital to study the suitable method and commerce operation model for the integrated energy system utilizing bio-natural gas.

Several studies about utilizing biomass energy in integrated energy systems and multi-energy markets have been published in recent years, mainly from European and Chinese researchers.

Wang et al. [13] proposed an optimal operation strategy for a hybrid solar and biomass power plant that the intricate energy flow combination of biomass fuels, uncertain solar energy, and thermal energy storage system is represented using a linear model. Chen et al. [14] designed a solar-aided biomass-fired cogeneration system by integrating solar heat into the steam cycle and assessed its thermodynamic and economic performance. In references [15], a bi-level programming approach has been applied to seek an optimal biomass-coal co-firing method under the carbon emissions allowance allocation scheme. References [13–15] carried out research about the joint usage of biomass energy and solar energy in hybrid energy systems. However, these researches did not tell the difference between solid biomass fuel and BNG utilization. Moreover, they are limited to discussing the solid biomass fuel direct combustion utilization pattern by modeling it as a cost function similar to traditional thermal power generation.

Reference [16–21] have explored utilizing biomass energy in the form of fuel gas within the IES. Reference [16] has established a biomass-based poly-generation system of generating power, heating, cooling, and methanol, where the solid biomass converts into fuel gas through a gasification block. This integrated energy system's optimization strategy has also been developed in the paper and treated as a deterministic MINLP model. Reference [17] presented a minimum cost unit commitment model for a biogas-fed solid oxide fuel cell combined heat and power system retrofitted from wastewater treatment plants and carried out the technical and economic feasibility study for this system based on a real plant operating near Turin. Reference [18] proved that a comprehensive energy system could be powered totally with RES by integrating biogas and thermal energy storage. It exhibited the excellent energy and exergy performance of this tri-source RE powered integrated energy system. In reference [19], a 100% renewable energy hub framework also has been formed to study the biogas-solar-wind energy complementarities in stand-alone Microgrids. This work's case studies demonstrated that the coupling interaction of batteries, biogas, and other RESs could enhance renewable penetration and biogas yield with a significant reduction in operation costs. Reference [20] has constructed a wind, biogas, and vanadium redox flow battery storage integrated hybrid microgrid to achieve uninterrupted access to electric power for the rural areas with weak or no grid scenario. Reference [21] proposed an optimal planning model of an islanded solar-biogas IES, which can supply thermal, electrical, and gas loads in remote locations by considering the complementarity of solar energy and biogas.

Although, the above five references have made a positive exploration of this field. However, there are still some limitations. Most of these models in the above works have considered the energy storage equipment, displaying biogas' flexibility and dispatchability indistinctly. In addition, these studies only focus on technical detail optimization, not give any new insights for the utilization pattern of biogas under the market liberation environment.

Reference [22–24] discussed the roles of biogas plants in the energy system from the market perspective. Reference [22] conducted an economic assessment of the different extension paths and modes of operation of the biogas plants in Germany's future electricity system. It verified that adding biogas plants in Germany's future electricity system should be accompanied by further benefits in other energy sectors and areas to ensure an economically feasible operation. References [23] investigate the operation of biogas plants in advanced energy markets after energy crops become limited in their use

and biogas plants exit subsidy schemes for electricity production, and the results showed that biogas power plant participating in the electricity balancing market and the biomethane market jointly could be a profitable operation strategy in the post-feed-in-tariff era. References [24] estimated the revenue potential of biogas plants in the power sector, considering its flexible power output characteristic.

The above works illustrate the importance of biogas in electricity markets as flexible and dispatchable sources. Besides, all of these works mentioned that upgrading the biogas to bio-natural gas and then coupling it with other energy sectors could be a more efficient and economical way for biogas utilization. Therefore, this paper aimed to construct a new commerce operation model for an IES, which suits BNG and variable renewable energy simultaneously, considering all the previous works. The multi-energy markets are considered in this model to conform to China's energy industry marketization trend.

The major contributions of this paper are summarized as follows:

1. Proposed a new commerce operation model for an IES, and an open energy market framework which contains multi-type energy transaction has been established.
2. Multiple power output scenarios represent the forecast error of DRES, and the day-ahead energy markets and real-time markets are jointly cleared to alleviate the power imbalance phenomenon.
3. The gas price adjustment mechanism has been applied in this model to minimize the total operation cost, which can stimulate the market players by price signals, thus optimizing the operation scheme of an IES.

## 2. The New Commerce Operation Model for an IES

### 2.1. The Composition of Integrated Energy System

An IES's structure is very flexible, which means it can be customized according to the regional resource conditions and energy demands. This paper takes the typical IES with electric and heat load as the research object. An IES's composition can be divided into three parts: Energy input, energy conversion, and energy consumption. For the IES considered in this work, as illustrated in Figure 1, the energy input includes the bio-natural gas supply station, distributed renewable energy units (photovoltaic and wind power), and coal-fired combined heat and power (CHP) units; the energy conversion includes a micro-gas turbine, electric boiler, and gas boiler; the energy consumption contains the electric and heat load. However, differing from the centrally organized type of IES at the present regulatory market, the IES interested in this work is assumed to operate under an ideal open energy market environment. Multiple stakeholders exist in this IES, and the energy equipment within this IES belongs to different stakeholders. The energy management operator (EMO) only serves as the IES operation center to formulate the safe and economical operation plan for this energy system based on the bidding information provided by all market participants. Bio-natural gas stations (BNGS) only sell BNG within the IES as a gas supplier and do not own energy conversion equipment.

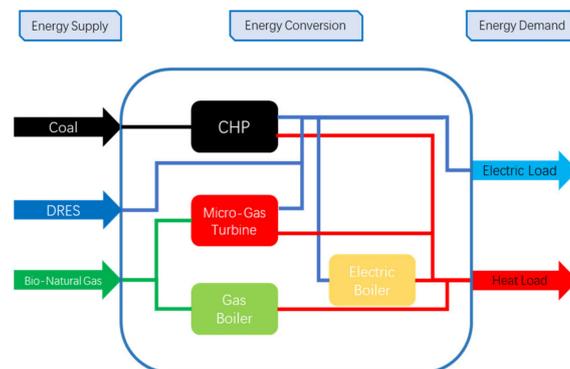
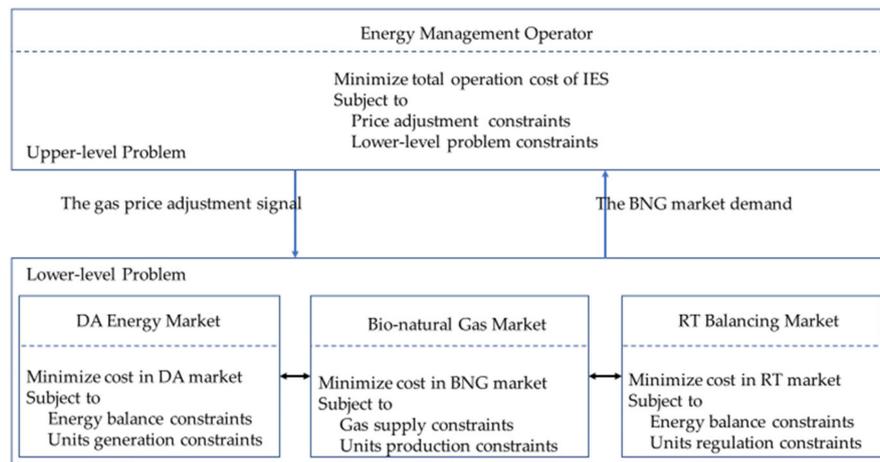


Figure 1. The composition of the integrated energy system.

## 2.2. The Framework of Open Energy Market

In this work, we assume that the IES operates under an ideal open energy market environment, where the market framework consists of a day-ahead energy market, a real-time balancing market, and BNG market. The main framework is illustrated in Figure 2. The market operation model can be described as follows.



**Figure 2.** The framework of the open energy market. IES, integrated energy system.

In the day-ahead energy market, EMO make the unit operation plan according to the bidding information from each power unit (including DRES forecasting output, the generation cost of each unit) and the load curve.

During the real-time operation stage, the deviation between the forecast value and the actual output of DRES leads to the imbalance between the supply and demand of energy within the IES. In the real-time balancing market, EMO adjusts the unit's power output based on each unit's flexible resources to ensure the energy balance between supply and demand, which is vital to the stability and safe operation of the IES.

In the BNG market, BNGS schedules the bio-natural gas production plan based on market demand, ensuring a stable gas supply and sells it at the market marginal price. Therefore, the operating cost of the energy conversion equipment fueled by bio-natural gas within the IES is directly related to the market BNG price.

## 2.3. The Gas-Price Adjustment Mechanism

The aim of applying the gas-price adjustment mechanism in this work is to emphasize the value of BNG as the internal dispatchable renewable energy resources in the IES. The price of BNG is adjusted appropriately by EMO to accurately reflect the real-time value of dispatchable renewable resources to optimize the overall energy supply scheme within the IES by releasing price signals to different energy markets.

The commerce operation model considering the gas-price adjustment mechanism can be modeled as a bi-level optimization problem. The objective of the upper-level model is to minimize the total operation cost of the IES by reasonably adjusting the price of BNG, with the consideration of the uncertainty of DRES output and the operating costs of each market; the lower level model simulates the three markets clearing process, respectively, based on the price signal from the upper-level model, the BNG market marginal price, the operating cost of each unit and the system load level. Once the clearing process at all markets is finished, a detailed operation plan for the IES is formulated.

To simplify this complex market problem, there is an assumption that all market participants bid according to their actual cost that means the generation cost of coal or gas-fired units are directly linked to the market price of fuel. The marginal generation cost of DRES is 0, so their offer is 0. To ensure

the priority utilization of renewable energy, the penalty cost of renewable energy power curtailment is introduced. The IES internal demand-side only offers quantity without price, so there is no price elasticity on the load side. The risk of the loss of load, due to insufficient flexibility resources within the system, is quantified through the penalty cost for loss of load.

### 3. Mathematical Description of the Model

#### 3.1. Upper-Level Problem

##### 3.1.1. Upper-Level Model Objective Function

Under the open energy market environment, EMO aims to minimize the total operating cost within the system, which takes the total energy supply cost and other related expenses into account simultaneously. The objective function can be described as:

$$\begin{aligned} \text{Min. } & \sum_{t \in T} [\sum_{i \in I_c} c_i \cdot p_{i,t} + \sum_{b \in B} c_b \cdot g_{b,t} \\ & + \sum_{s \in S} \pi_s ((c_b^{up} \cdot g_b^{up} - c_b^{down} \cdot g_{s,b,t}^{down}) + \sum_{i \in I_c} (c_i^{up} \cdot p_{s,i,t}^{up} - c_i^{down} \cdot p_{s,i,t}^{down}) + c^{sh,E} \cdot I_{s,t}^{sh,E} + c^{sh,H} \cdot I_{s,t}^{sh,H} + c^{sp,DER} \cdot p_{s,r,t}^{sp,DER})] \end{aligned} \quad (1)$$

where  $I_c$  is the set of the coal fired CHP units;  $c_i$  is the cost coefficient of the coal fired CHP unit  $i_c$ ;  $p_{i,t}$  is the power output of the unit  $i_c$  in period  $t$ ;  $B$  is the set of the bio-natural gas stations;  $c_b$  is the cost coefficient of the bio-natural gas station  $b$ ;  $g_{b,t}$  is the gas production power of gas station  $b$  in period  $t$ ;  $S$  is the set of real-time DRES actual power output scenarios;  $\pi_s$  is probability of scenario  $s$ ;  $c_b^{up}$  and  $c_b^{down}$  are the cost of increasing and reducing gas production power of gas station  $b$ ;  $g_{s,b,t}^{up}$  and  $g_{s,b,t}^{down}$  are the upregulation or downregulation of gas production power of the gas station  $b$  in period  $t$  under scenario  $s$ ;  $c_b^{up}$  and  $c_b^{down}$  are the cost of increasing and reducing gas production power of gas station  $b$ ;  $p_{s,i,t}^{up}$  and  $p_{s,i,t}^{down}$  are the upregulation or downregulation of power production of the unit  $i_c$  in period  $t$  under scenario  $s$ ;  $c^{sh,E}$ ,  $c^{sh,H}$  and  $c^{sh,E}$  correspond to the penalty cost of electric load loss, heat load loss and renewable energy power curtailment, respectively.

It is to note that, for the energy conversion equipment fueled by bio-natural gas, their energy supply cost can be directly transferred to the cost of bio-natural gas production. Thus, the upper-level model only considers the energy supply cost of coal-fired CHP units, BNG production cost, and the cost of load loss and renewable energy power curtailment within the IES.

##### 3.1.2. Upper-Level Model Constrains

There are two premises for EMO to adjust the BNG price to release the price signal: First, the acceptability of market users for price fluctuations should be considered; second, the benefits of BNGS and other stakeholders must be guaranteed. Therefore, adjusting the BNG price should meet the following constraints:

$$|x_t| \leq X, \forall t \quad (2)$$

$$\sum_{t \in T} \sum_{i_g, i_h \in I_{gt}, I_{gb}} x_t = 0 \quad (3)$$

Equation (2) is the maximum and minimum adjusting limitations for BNG price, where  $x_t$  is the adjustment amount of gas price in period  $t$ ;  $X$  is the price adjustment limit of bio-natural gas within the IES.

Equation (3) indicates that, during one operation cycle, the gas price adjustment mechanism brings no revenue deviation for BNGS, which also guarantees the interests of other market players in this market.

### 3.2. Lower-Level Problem

The lower-level model simulates the market clearing process to make the IES's detailed operation plan in the day-ahead energy market and real-time balancing market. It will also determine the total gas demand in the BNG market. In the lower-level model, the three markets are closely coupled and influenced by the price signal from the upper-level model.

#### 3.2.1. Day-Ahead Energy Market

In the day-ahead energy market, EMO formulates the day-ahead operation plan based on each market participant's declared information to minimize the total energy supply cost. The objective function and constraints are as follows:

$$\text{Min.} \sum_{t \in T} \sum_{i \in I_c, I_{gt}, I_{gb}, eb} c_i \cdot p_{i,t} \quad (4)$$

$$s.t. \\ c_{i_{gt,gb},t} = (\lambda_t^{G\_DA} + x_t) \varphi_{i_{gt,gb}}, \forall t \quad (5)$$

$$\sum_{i \in I_c, I_{gt}} \eta_{i,pe} \cdot p_{i,t} + \sum_{r \in R} p_{r,t} - p_{eb,t} = D_t^E, \forall t \quad (6)$$

$$\sum_{i \in I_c, I_{gt}, I_{gb}} \eta_{i,ph} \cdot p_{i,t} + \eta_{eb} \cdot p_{eb,t} = D_t^H, \forall t \quad (7)$$

Equation (4) is the objective function in the day-ahead energy market, aiming to meet the end user's energy demand with minimum cost. Where  $I_c$ ,  $I_{gt}$ ,  $I_{gb}$  and  $eb$ , respectively, represent the set of coal-fired CHP units, micro gas turbines, gas-fired boilers, and electric boilers;  $c_{i,t}$  is the power supply cost declared to EMO by each power unit.

Equation (5) represents the operation cost of gas-feed energy conversion devices. Where  $\lambda_t^{G\_DA}$  is the marginal market price of BNG in the day-ahead market in period  $t$ . According to duality theory, it is the dual variable of day-ahead gas supply equilibrium constraint;  $\varphi_{i_{gt,gb}}$  is the gas consumption coefficient of the micro gas turbine and the gas boiler, which is the reciprocal of the product of equipment efficiency and the calorific value of bio-natural gas.

Equations (6) and (7) represent power supply balance constraint and heat supply balance constraint, respectively.  $R$  represents the distributed renewable energy sources units;  $P_{r,t}$  is the power output of DRES unit  $r$  in period  $t$ ;  $D_t^E$  and  $D_t^H$  are the electrical and heat load within the system in period  $t$ ;  $\eta_{i,pe}$  and  $\eta_{i,ph}$  are the electricity generation and heat generation coefficients of unit  $i$ .

#### 3.2.2. Real-Time Balancing Market

In the real-time balancing market, EMO adjusts unit power output based on the system's real-time operation status and the declared dispatchable capacity and cost of each unit to suppress energy supply and demand fluctuations. The model aims at minimizing the weighted sum of the expected balancing costs of all scenarios. The objective function and constraints are as follows:

$$\text{Min.} \sum_{s \in S} \pi_s \left[ \sum_{t \in T} \sum_{i \in I_c, I_{gt}, I_{gb}} (c_i^{up} \cdot p_{s,i,t}^{up} - c_{s,i}^{down} \cdot p_{s,i,t}^{down}) + c^{sh,E} \cdot f_{s,t}^{sh,E} + c^{sh,H} \cdot f_{s,t}^{sh,H} + c^{sp,DER} \cdot p_{s,r,t}^{sp,DER} \right] \quad (8)$$

$$s.t. \\ c_{s,i_{gt,gb},t}^{up,down} = (\lambda_{s,t}^{G\_RT} + x_t) \varphi_{i_{gt,gb}} \quad \forall s, i, t. \quad (9)$$

$$\sum_{i \in I_c, I_{gt}, I_{gb}} \eta_{i,pe} \cdot \Delta p_{s,i,t} + \Delta p_{s,eb,t} + l_{s,w,t}^{sh,E} + (P_{s,r,t} - p_{s,r,t}^{sp,DER} - p_{r,t}^{DA}) = 0 \quad \forall s, i, t \quad (10)$$

$$\sum_{i \in I_c, I_{gt}, I_{gb}} \eta_{i,ph} \cdot \Delta p_{s,i,t} + \eta_{eb} \cdot \Delta p_{s,eb,t} + l_{s,w,t}^{sh,H} = 0, \quad \forall s, i, t \quad (11)$$

Equation (8) is the objective function in the real-time balancing market, aiming to minimize the expected balancing cost. Where  $c_{s,i,t}^{up,down}$  is the operation cost increased or saved of per unit power regulation of unit  $i$  in period  $t$  under scenario  $s$ ;  $P_{s,i,t}^{up,down}$  is the up or down-regulation amount of power output of unit  $i$  in period  $t$  under scenario  $s$ .

$\lambda_{s,t}^{G-RT}$  in Equation (9) is the marginal market price of BNG in the real-time market in period  $t$  under scenario  $s$ , according to duality theory, it is the dual variable of real-time gas supply equilibrium constraint.

Equations (10) and (11) represent the constraints of real-time power balance;  $\Delta p_{s,i,t}$  is equivalent to  $P_{s,i,t}^{up,down}$ ;  $P_{s,r,t}$  is the actual power output of DRES unit  $r$  in period  $t$  under scenario  $s$ ;  $p_{s,r,t}^{sp}$  represents the amount of renewable energy curtailment in period  $t$  under scenario  $s$ ;  $p_{i,t}^{DA}$  is the scheduled power output of unit  $i$ .

### 3.2.3. Bio-Natural Gas Market

In the bio-natural gas market, the seller is the BNGS, and the buyer is the micro gas turbine and gas boiler owner. EMO releases price signals to the markets through reasonable gas price adjusting, thus affecting the system's energy supply mix. The BNGS is formulating the gas production plan to minimize the total daily gas production cost and meet the constraints of maximum gas production power, gas supply balance, and maximum daily production at the same time. The objective function and constraints are as follows:

$$Min. \sum_{t \in T} \sum_{b \in B} [c_b \cdot g_{b,t} + \sum_{s \in S} \pi_s (c_b^{up} \cdot g_{s,b,t}^{up} - c_b^{down} \cdot g_{s,b,t}^{down})] \quad (12)$$

$$s.t. \\ 0 \leq g_{b,t} \leq G_b^{\max}, \forall b, t \quad (13)$$

$$\sum_{b \in B} g_{b,t} - \sum_{i \in I_{gt}, I_{gb}} \varphi_i \cdot p_{i,t} = 0, \forall t \quad (14)$$

$$\sum_{t \in T} \sum_{b \in B} g_{b,t} \leq \sum_{b \in B} V_b^{daily} \quad (15)$$

$$\sum_{b \in B} \Delta g_{s,b,t} - \sum_{i \in I_{gt}, I_{gb}} \varphi_i \cdot \Delta p_{s,i,t} = 0, \forall s, t \quad (16)$$

$$\sum_{t \in T} \sum_{b \in B} (g_{b,t} + \Delta g_{s,b,t}) \leq \sum_{b \in B} V_b^{daily}, \forall s \quad (17)$$

Equation (12) is the objective function in the gas market, aiming to minimize the total gas supply and operation cost of BNGS. Where  $c_{s,i,t}^{up,down}$  is the operation cost increased or saved of per unit power regulation of unit  $i$  in period  $t$  under scenario  $s$ ;  $P_{s,i,t}^{up,down}$  is the up or down-regulation amount of power output of unit  $i$  in period  $t$  under scenario  $s$ .

Equation (13) represents the gas production power constraints. Where  $G_b^{\max}$  is the maximum gas production power of gas station  $b$ . Equation (14) is the gas supply balance for the day-ahead market. Equation (15) represents the maximum daily gas production constraint. Where  $V_b^{daily}$  is the maximum daily bio-natural gas production amount of gas station  $b$ . Equation (16) is the gas supply balance for

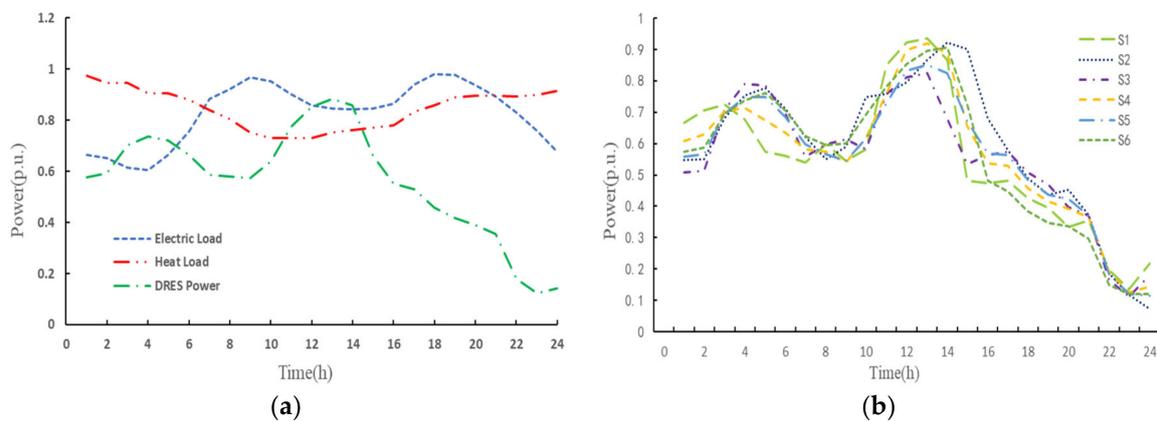
the real-time operation stage. Where  $\Delta g_{s,b,t}$  indicates the gas production regulation amount in the real-time market of gas station  $b$  in period  $t$  under scenario  $s$ . Equation (17) represents the maximum daily gas production constraint, with the considerations of intraday adjustment.

Note that other constraints, such as equipment operation constraints, also have been considered in the lower-level model, and they are not listed here due to the space limits.

## 4. Case Study

### 4.1. Basic Data

A simulation study for a specified integrated energy system was carried out, which consists of two coal-fired CHP units with 8 MW and 11 MW installed capacity, three micro-gas turbines fueled by bio-natural gas with an installed capacity of 9 MW, 8 MW, and 7 MW, respectively, one bio-natural gas-fired boiler and one electric boiler. The total installed capacity of DRES in this system (including distributed wind power and distributed photovoltaic) is 17.8 MW; four industrial-grade bio-natural gas stations in this region can be served as BNGS, and the cost of BNG production varies with the size of BNG station and the purification technology applied in them. The maximum electric load and heat load inside the system are 35.5 MW and 38.6 MW, respectively. The day-ahead forecast curves of load and DRES power output are shown in Figure 3a. To simulate the volatility of DRES output during the actual operation period, the clustering algorithm is adopted in this work to generate a set of equal probability DRES output scenarios to represent the randomness of the real-time output of DRES, which is shown in Figure 3b.

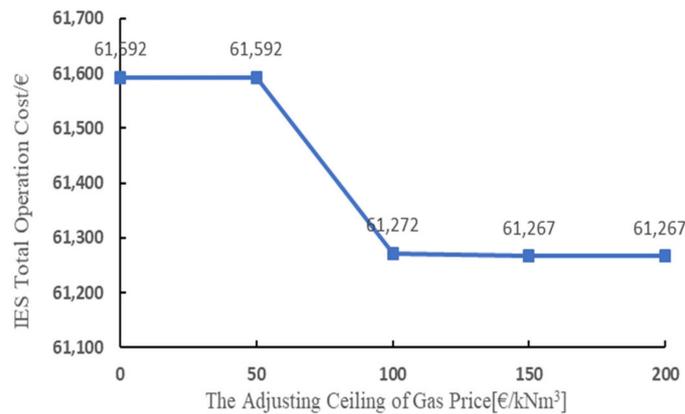


**Figure 3.** (a) DRES joint output and power/heat demand day-ahead forecast curve; (b) actual output of DRES under different scenarios.

### 4.2. The Analysis of Gas-Price Adjustment Limits

To display the impact of the gas price adjustment mechanism on the IES total operation cost and choose the optimal gas price adjustment limit, different adjusting limits of gas price were set as the boundary conditions for system simulation.

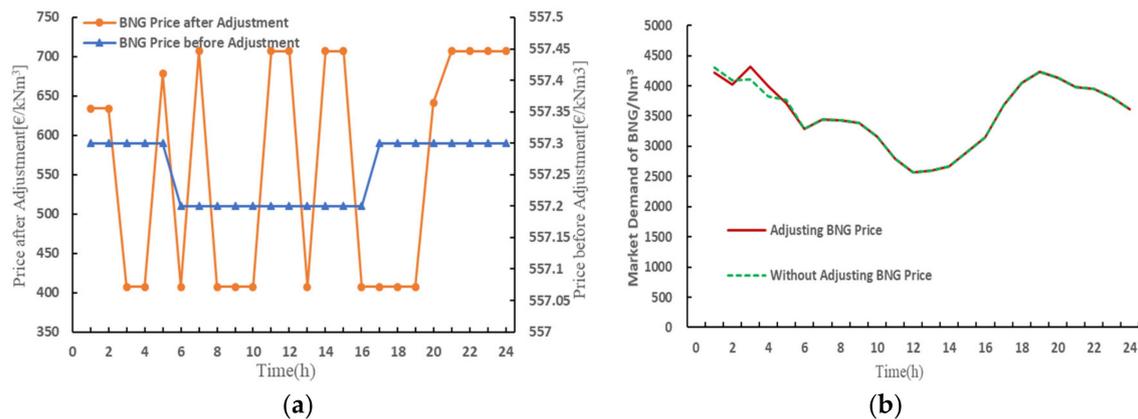
The simulation results in Figure 4 show that applying the gas price adjustment mechanism can effectively reduce the total operating cost of the IES. Besides, from the variation tendency in Figure 4, the effective adjustment interval of the gas price that can affect the total operating cost of the system is 50 €/kNm<sup>3</sup> to 150 €/kNm<sup>3</sup>. This means when the price adjustment is lower than the minimum threshold, it cannot release effective price signals to the market, and when the price adjustment is higher than the maximum threshold, the total operating cost of the IES cannot be further reduced, due to the actual energy demand of the system. Given an overall consideration of the total benefits and the acceptance of market users for price fluctuation, the 150 €/kNm<sup>3</sup> is selected as the optimal adjustment ceiling of gas price in this work.



**Figure 4.** The total operating cost of the IES under different gas price adjustment limits.

#### 4.3. The Analysis of Simulation Results with and without the Gas Price Adjustment Mechanism

The simulation results with and without the gas price adjustment mechanism at the conditions of DRES installed capacity of 17.8 MW and gas price adjustment limit of 150 €/kNm<sup>3</sup> are shown in Figures 5 and 6.

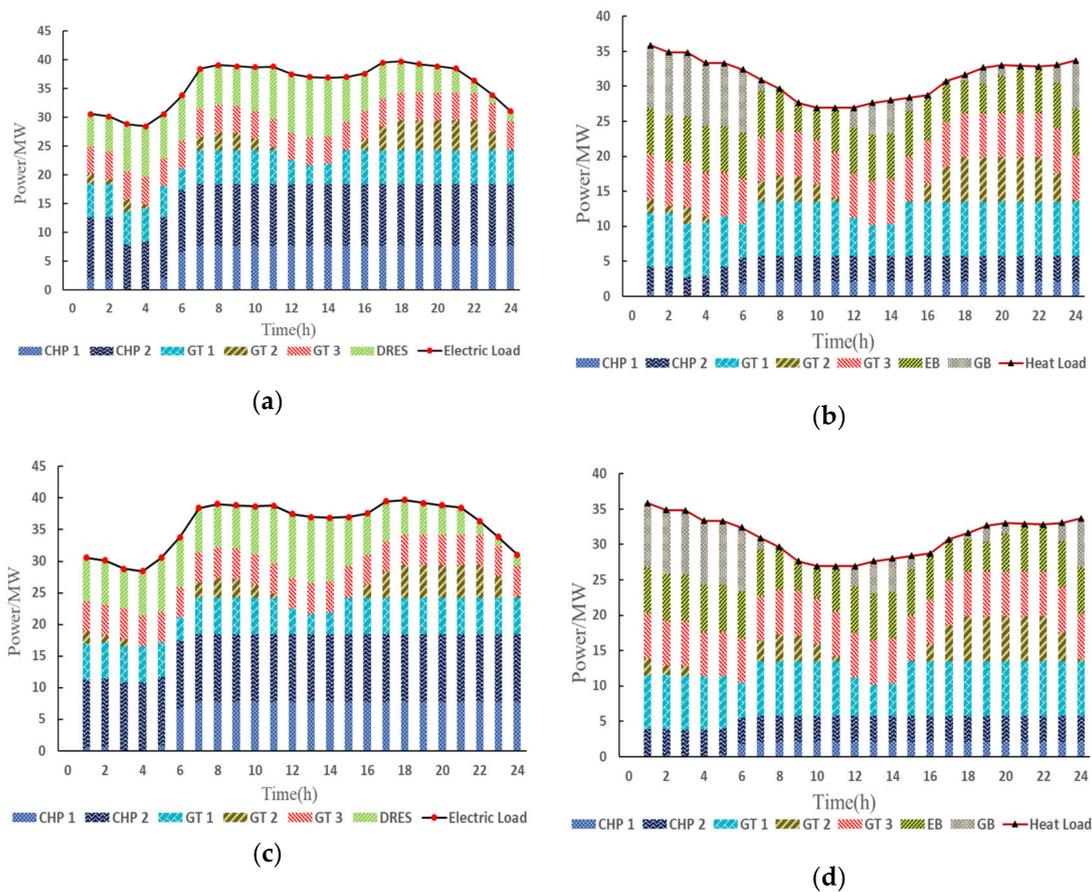


**Figure 5.** (a) A comparison chart of gas price in the day-ahead market; (b) a comparison chart of gas consumption before and after gas price adjustment in the day-ahead market.

Figure 5a reflects the fluctuation trend of BNG price in the market before and after the gas price adjustment. It can be found that the BNG market price fluctuates between 557.2 €/kNm<sup>3</sup> and 557.3 €/kNm<sup>3</sup> before the adjustment, which is relatively stable, and the fluctuation trend is proportional to the heat load level inside the system. After adjusting, both the fluctuation range and the frequency of BNG price significantly increased, and the price fluctuates among 407.2 €/kNm<sup>3</sup> and 707.3 €/kNm<sup>3</sup> frequently. When combining Figure 5a with Figure 5b, we can see that the market demand for BNG is slightly reduced by increasing the gas price from 01:00 to 02:00; however, the demand for BNG was increased by lowering the gas price from 02:00 to 05:00.

As shown in Figure 6, during the system heat load level is significantly higher than the electric load level, and the power output of DRES is relatively high, the energy supply mix in the IES is improved markedly through the gas price adjustment mechanism. At this period, the output of micro gas turbines and gas boilers have been increased, in contrast, the output of coal-fired CHP unit have been reduced, due to the high thermal efficiency of micro gas turbine and gas boiler, and the low thermoelectric ratio coal-fired CHP units. This explained that the BNG market demand increased during this period. At the same time, more heat loads are supplied by electric boilers, which further increases the consumption amount of renewable energy. Furthermore, frequent adjustment of the

BNG price can release more price signals in the real-time balancing market, which will provide more flexibility resources in the IES for alleviating the energy supply and demand imbalance caused by the deviation between the actual output of DRES and the day-ahead forecast value.



**Figure 6.** A comparison chart of the day ahead market operation scheme before and after gas price adjustment: (a) Electricity supply mix considering price adjustment; (b) heat supply mix considering price adjustment; (c) electricity supply mix without considering price adjustment; (d) heat supply mix without considering price adjustment.

#### 4.4. Sensitivity Analysis of DRES Capacity

To analyze the influence of the DRES penetration rate on the IES operation cost, this section gives a comparative analysis for the simulation results with and without the gas price adjustment mechanism under different DRES penetration rates, which are shown in Table 1. Note that in Table 1, case 1 represents adjusting the BNG price, and the case2 represents without adjusting the BNG price.

**Table 1.** The IES operation cost under different DRES penetration rates.

DRES Penetration Rate/%	40%		50%		60%	
Operation Model	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
Total Operation Cost/€	62,595.8	62,609.1	61,266.9	61,592.3	60,122.3	61,546
The Cost in DA market/€	62,639	62,612.5	61,291.9	61,245.3	60,103.7	60,026.2
The Cost in RT market/€	-43.3	-3.4	-24.9	34.6	8.5	63.3
DRES curtailment penalty cost/€	0	0	0	312.4	10.1	1456.5
BNG supply cost/€	48,454.2	48,452.6	47,530	47,476.3	46,794.4	46,532.4

Table 1 reveals that during the process of DRES penetration rate within the IES increases from 40% to 60%, the total operation cost of the system, the cost of energy supply in the day-ahead market, and the actual gas supply cost of BNGS all showed a significant downward trend. However, the real-time market balancing cost, DRES curtailment penalty cost, and the cost difference caused by whether or not to consider the gas price adjustment mechanism have shown a clear upward trend. With the increase of renewable energy penetration rate within the IES, more energy demand can be supplied by DRES with an extremely low marginal cost; thus, a considerable amount of fuel cost can be saved. However, as the penetration rate of DRES increases, the imbalance of energy supply and demand within the system caused by DRES forecast errors has become more serious, which will lead to the high cost of real-time balancing. In addition, the system without considering gas price adjustment mechanisms is hard to consume the high proportion of renewable energy, due to the lack of flexibility. Therefore, the DRES curtailment penalty cost increases dramatically with renewable energy penetration increases.

The results in Table 1 also shows that with the penetration rate of renewable energy continues to rise, compared to the traditional model, the new commerce model that considers the gas price adjustment mechanism can effectively increase the market demand for bio-natural gas, which is beneficial to promote the commercial development of the bio-natural gas industry, to accelerate the realization of the goal of a 100% renewable energy system in the future.

## 5. Conclusions and Discussions

A suitable commerce operation model for the IES with the utilization of bio-natural gas has been proposed in this paper. The price adjustment mechanism applied in this work realizes the economical and efficient operation of the system. Through the implementation of case studies based on a customized test system, the following conclusions can be drawn:

The optimal operation model considering the gas price adjustment mechanism can effectively reduce the system's total operating cost by improving the energy supply mix when the system heat/electric load level is relatively high. Frequent adjustment of the price of biogas can release effective price signals in the real-time balancing market to increase the system's flexibility and improve the system's ability to solve the real-time energy supply and demand imbalance caused by the forecast error of renewable energy output. At the primary development stage BNG industry, BNG price is relatively high; the gas price adjustment mechanism can effectively increase the market demand for BNG under the high penetration rate of renewable energy conditions.

It should be pointed out that this work ignores the constraints of the energy transmission system.

The integrated energy system considered in this work is assumed to be a short-distance transmission community-integrated energy system. Therefore, without considering the energy network constraints, which have little effect on the hourly-based operation strategies applied in this paper, are reasonable and acceptable. In the next research step, the transmission capacity constraints of power lines and bio-natural gas pipelines will be considered to ensure that the proposed model is more in line with the practical application in the large regional integrated energy system. This paper was mainly focused on the optimal operation of the IES with electric and heat load. In the future, more in-depth research will be conducted on the IES with more types of energy demand and energy conversion equipment.

**Author Contributions:** Y.W. (Yaowu Wu) proposed the core idea; G.Z. developed the models, performed the simulations, and exported the results; S.L. and Y.W. (Yang Wu) helped analyze the data and edited the figures and tables; X.W. provided some important reference material. All authors have read and agreed to the published version of the manuscript.

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