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# Optimization Decomposition of Monthly Contracts for Integrated Energy Service Provider Considering Spot Market Bidding Equilibria

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**Abstract:** Under the current power trading model, especially in the context of the large-scale penetration of renewable energy and the rapid integration of renewable energy into the power system, reasonable medium- and long-term decomposition can reduce the fluctuation in the energy price when the integrated energy service provider (IESP) participates in the spot market. It helps to avoid the price risk of the spot market. Additionally, it promotes the optimization of the operation of the regional energy day-ahead scheduling. At the present stage, most of the medium- and long-term contract decomposition methods focus on the decomposition of a single power and take less consideration of the bidding space in the spot market. This limitation makes it challenging to achieve efficient interaction and interconnection among multi-energy resources and smooth integration between the medium- and long-term market and the spot market. To address these issues, this paper proposes an optimal monthly contract decomposition method for IESPs that takes into account the equilibrium of spot bidding. First, the linking process and rolling framework of multi-energy transactions between the medium- and long-term market and the spot market are designed. Second, an optimal decomposition model for monthly contracts is constructed, and a daily decomposition method for monthly medium- and long-term contracts that accounts for the spot bidding equilibrium is proposed. Then, the daily preliminary decomposition result of medium- and long-term multi-energy contracts is used as the boundary condition of the day-ahead scheduling model, and the coupling characteristics of the multi-energy networks of electricity, gas, and heat are taken into account, as well as the operational characteristics. Then, considering the coupling characteristics and operating characteristics of electricity, gas, and heat networks, the optimal scheduling model of a multi-energy network is constructed to minimize the sum of cumulative daily operating costs, and the monthly final contract decomposition value and daily spot bidding space are derived. Finally, examples are calculated to verify the validity of the decomposition model, and the examples show that the proposed method can reduce the variance in spot energy purchase by about 4.64%, and, at the same time, reduce the cost of contract decomposition by about USD 0.33 million.

**Keywords:** spot bidding equilibrium; monthly homogeneous decomposition; medium- and long-term markets

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## 1. Introduction

In recent years, the global energy sector has been undergoing profound changes with the large-scale penetration of renewable energy sources and the growing emphasis on the operation of a low-carbon economy. The rapid development of renewable energies has given new impetus to the power system; however, the challenges that come with it are becoming increasingly apparent. Power grids are faced with higher demand for renewable energy integration, increased uncertainty in energy supply, and the complexity of energy trading markets.

In this context, effective trading strategies and optimization methods are essential to achieving a balance between efficient operation, low carbon emissions, and economic viability in the new power system. It is necessary to steadily increase the scale of medium- and long-term power trading, solidly promote the trial operation of spot pilot settlements, actively and steadily push forward the construction of the power spot market, and strengthen the organic connection between the medium- and long-term, spot, and auxiliary service markets for power [1–4]. However, the complexity and variety of energy types in the integrated energy system (IES) and its participation in the spot market transactions are susceptible to the impact of the energy decomposition results of the medium- and long-term market; therefore, it is necessary to take into full account the demand for spot market bidding and the coupling and complementary study of multi-energy resources compatible with the medium- and long-term market and the contract decomposition of the spot market to alleviate the fluctuations in the spot market volume and price and to ensure that the market has a stable and economic operation [5–7].

Compared with the spot market, most of the power transactions conducted in the medium- and long-term markets are longer time scales such as annual or monthly markets [8,9]. To realize the effective connection between the medium- and long-term market and the spot market, its minimum time scale should be consistent with that of the spot market; therefore, the medium- and long-term contract decomposition methods at the present stage are all power decomposition with curves [10,11]. The current research on the decomposition of medium- and long-term contracts mainly focuses on the research of medium- and long-term curve decomposition methods and the research of the method of connecting the medium- and long-term market with the spot market.

In terms of medium- and long-term market curve decomposition methods, current studies mainly focus on the decomposition of power [12–14]. The decomposition of power refers to a method used in the context of energy markets, specifically for breaking down medium- and long-term power contracts into smaller, more manageable timeframes, typically for operational or trading purposes. This method is primarily concerned with decomposing the energy from a single type of power source, such as electricity, without considering the interplay or conversion between different types of energy resources. Literature [15] delves into the medium- and long-term trading mechanism within the electricity spot market. Market players customize bilateral and listed transactions to shape trading curves. Centralized competitive transactions are decomposed based on typical curves like the average curve and the peak curve. Literature [16] designs the bilateral spot market mechanism and proposes that the medium- and long-term contracted electricity on both the generation side and the user side should be curve-decomposed to form medium- and long-term transaction settlement curves. Literature [17], for the new type of power market and scheduling characteristics, constructs a two-stage wind power consumption model considering the connection of medium- and long-term transactions and short-term scheduling to realize the effective connection between the market and schedule. Literature [18] constructs a decomposition model for thermal electricity in the context of the Turkish electricity market by integrating the derivatives market, the bilateral contract market, and the spot market under the curve decomposition for single electricity. In literature [19], the Nordic region performs a curve decomposition of the contracted power to continue to organize the coupled clearing of the Nordic market, which results in the clearing of the coupled market as a basis for the settlement and execution of the coupled market. The above study proposes the decomposition method of medium- and long-term contracts considering both supply and demand and short-term scheduling, which is more flexible and diversified, but the above decomposition method is power decomposition, and it fails to consider the conversion of energy between electricity, gas, heat, and other energy sources and is unable to realize the synergistic supply of multiple energies in the day-to-day situation.

In terms of the convergence of the medium- and long-term market and spot market transactions, the traditional decomposition method is mostly for the average decomposition of the medium- and long-term contract volume, and the decomposition result of the medium- and long-term market is used as the clearing boundary of the spot market to obtain the final actual operating curve [20–22]. Literature [23] proposes a quadratic planning method for the decomposition of the medium- and long-term contracted power volume and takes the decomposed daily power volume as the constraint to ensure the fairness of the bidding unit scheduling. Literature [24] addresses the problem of the autonomous decomposition of medium- and long-term contracted power for power producers and investigates the medium- and long-term contracted power decomposition method based on distributional robust optimization for power producers in the environment of serious uncertainty in spot market price. Literature [25] adopts the method of monthly bidding space equalization to decompose the annual winning contract into months, and the unfinished monthly decomposition of the total annual winning power in actual operation is corrected to the subsequent part on a rolling basis while maintaining the monthly bidding space equalization in the remaining months. Literature [26], concerning the Nordic region, performs a curve decomposition of the contracted power to continue to organize the coupled clearing of the Nordic market, which results in the clearing of the coupled market as a basis for the settlement and execution of the coupled market. In literature [27], the marginal node tariff mechanism is commonly used in the US electricity market to differentially reflect the value of electrical energy in time and space by selecting a series of nodes that are less affected by blockages and awarding them with a fixed weight, and then calculating a representative weighted average price to realize the transaction convergence. The above studies are mostly on the monthly or weekly decomposition of the medium- and long-term contracted electricity, without considering the bidding space and bidding fluctuations in the spot market, which makes it difficult to realize the smooth connection from the medium- and long-term market to the spot market.

Aiming to address the aforementioned issues, this paper proposes an optimal decomposition method for monthly contracts of IESPs. This method takes into account the equilibrium of spot bidding and considers the coupling and complementarity of multiple types of energy sources within the IES, as well as the effective connection between the medium- and long-term market and the spot market. First, a daily decomposition model of monthly medium- and long-term contracts is constructed, with weekly equilibrium decomposition of the centralized bidding volume and the remaining multi-energy demand supplemented by the contracted volume, and the objective of minimizing the variance in the residual load after the decomposition of the medium- and long-term contracts and minimizing the cost of decomposition is to perform the daily decomposition of the medium- and long-term contracted volume. Secondly, based on the results of the daily decomposition of the medium- and long-term contracts, the day-ahead scheduling model of the IES is constructed by considering the coupling and complementarity of the multi-energy streams to minimize the sum of the cumulative daily operating costs of the network. A reasonable medium- and long-term energy decomposition method can reduce the volatility and uncertainty of the IESP's participation in the spot market transactions and ensure the effective execution of the medium- and long-term contracted energy at the day-ahead level.

To distinguish this paper from other studies, its main contributions can be summarized in the following three areas:

(1) Given the difficulties in the connection between the medium- and long-term market and the spot market and the volatility and uncertainty of the price and quantity of the spot market transactions, this paper designs a medium- and long-term monthly contract optimization decomposition strategy that can stabilize the bidding space in the spot market and reduce the fluctuation in the demand of spot bidding by considering the equilibrium of the bidding space in the spot market to ensure the smooth connection between the medium- and long-term market and the spot market;
(2) To ensure the effective execution of the mid-and long-term contract decomposition results daily and reduce the contract decomposition deviation, this paper constructs a day-ahead scheduling model of the IES that accounts for the coupling of multiple energy flows, takes into account the substitution and cross-complementary character-

istics of electricity, gas, and heat of multi-energy resources, and carries out the optimal scheduling of various types of resources based on the daily decomposition results of the mid-and long-term contracts;

(3) To effectively alleviate the pressure of energy supply at the energy supply point and realize the efficient interconnection and interaction of electricity, gas, and heat networks in the IES, this paper considers the dynamic pipe storage characteristics of the gas network and realizes the low storage and high generation of the gas network. The results show that the method can effectively reduce the dispatch operation cost.

## 2. The Connection Process of Multi-Energy Transactions between the Medium- and Long-Term Market and the Spot Market

Given the high flexibility of the spot market, the IESP, acting as a third-party entity, engages in supplemental multi-energy trading in the spot market after procuring the bulk of energy in the medium- and long-term market. A rational approach to decomposing medium- and long-term energy can mitigate the volatility and unpredictability of the IESP's involvement in spot market transactions, thereby fostering a seamless transition between the medium- and long-term market and the spot market. The challenge lies in effectively optimizing the daily decomposition of IESP's medium- and long-term traded energy while ensuring the stability of the bidding space in the spot market. On one hand, it is crucial to ensure that the decomposed medium- and long-term energy can be effectively implemented on the spot time scale. On the other hand, it is equally important to minimize the fluctuation in spot bidding demand to ensure a smooth bidding space for IESPs in the spot market. Moreover, the IESP must also thoroughly consider fairness among units when decomposing the capacity of units and gas source points. The interface between the medium- and long-term and the spot market is illustrated in Figure 1.

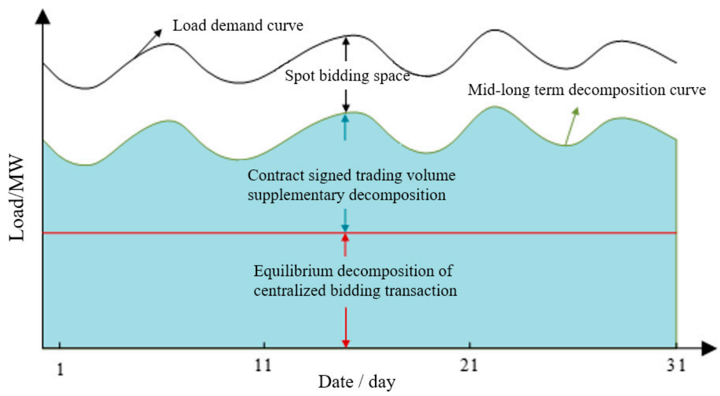


**Figure 1.** The decomposition and connection relationship between long-term contracts and spot markets of IESPs.

As illustrated in Figure 1, the IESP's decomposition of medium- and long-term contract volumes encompasses the equilibrium decomposition of centralized bidding transactions and supplementary decomposition of the contracted volume. The centralized bidding transactions are primarily decomposed through weekly equilibrium decomposition, ensuring a stable level of daily transaction decomposition. The contracted volume, on the other hand, serves as a supplementary decomposition to meet the remaining multi-energy demand, thereby mitigating the fluctuating amplitude of the medium- and long-term bidding transactions' tariffs. When conducting the monthly and weekly decomposition of multi-energy trading volumes, the decomposition schematic is demonstrated in Figure 2.

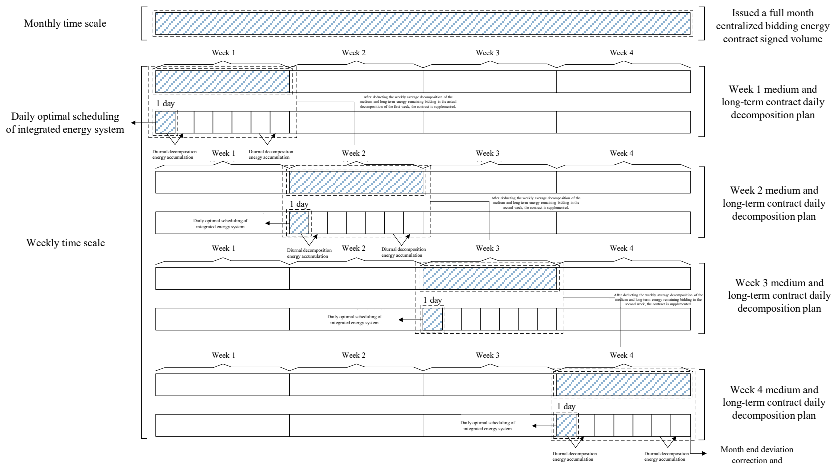


**Figure 2.** Optimal decomposition of long-term time scale contract considering spot bidding equilibrium of IESP.

When the IESP executes the optimized decomposition of the medium- and long-term contract equilibrium, it initiates a weekly decomposition of the total monthly contracted energy sourced from the transactions. Throughout the decomposition process, the centralized bidding trading volume is consistently maintained at a weekly equilibrium. The contracted volume serves as a supplement to the remaining medium- and long-term demand portion, and the weekly balance energy is computed into the contracted energy for the ensuing week, continuing in this manner until the final week of the month. Specifically, for the daily contract volume decomposition within a week, the IESP takes into account the daily IES dispatch optimization. The daily contract decomposition volume is accumulated to the medium- and long-term contracted trading volume allocated in the corresponding week, and the balance volume accumulated by the end of the week is counted as the allocable energy for the remaining week.

## 3. Daily Decomposition of Monthly Medium- and Long-Term Contracts Considering Spot Bid Equalization

### *3.1. Monthly Contract Optimization Decomposition Model*

#### 3.1.1. Objective Function

Drawing from the daily optimal scheduling model, this paper introduces an optimal decomposition method for the energy of medium- and long-term contracts. This method uses a week as the time window, decomposes the medium- and long-term energy from month to day, conducts rolling decomposition from week to week, and performs deviation assessment every month. The method takes into account the deviation in contract execution, load demand, network security checks, and the balance of spot bidding space, thus ensuring that the decomposition of medium- and long-term contracts is as efficient and balanced as possible. The objective is to minimize the variance in the residual load following the decomposition of the medium- and long-term contract and to minimize the cost of decomposition, as represented in Equations (1) and (2):

$$minR = \frac{1}{M_{mth}}[\sum_{w=1}^{W}\sum_{d=1}^{D}(P_{buye,d,w}-\overline{P}_{buye,d,w})^2+(f_{buyg,d,w}-\overline{f}_{buyg,d,w})^2] \tag{1}$$

$$\begin{aligned} minOF &= \sum_{d=1}^{D}[\sum_{i=1}^{N_{gene}}(E_{e,i,d}^{bid}q_{e,i,d}^{bid}+E_{e,i,d}^{cone}q_{e,i,d}^{cone}+E_{e,i,d}^{buye}q_{e,i,d}^{buye}) \\ &+\sum_{m=1}^{N_{gas}}(E_{g,m,d}^{bid}q_{g,m,d}^{bid}+E_{g,m,d}^{cone}q_{g,m,d}^{cone}+E_{g,m,d}^{buye}q_{g,m,d}^{buye})] \end{aligned} \tag{2}$$

where $R$ represents the sum of the variances of the monthly residual load; $OF$ stands for the cost of contract decomposition; $M_{mth}$ is the number of days in the month; $P_{buye,d,w}$ is the total spot electricity purchase volume on day d of week $w$; $\overline{P}_{buye,d,w}$ is the average monthly spot electricity purchase volume on day $d$ of week $w$; $f_{buyg,d,w}$ is the total spot gas purchase volume on day $d$ of week $w$; $\overline{f}_{buyg,d,w}$ is the average monthly spot gas purchase volume on day $d$ of week $w$.

### 3.1.2. Restrictive Condition

This section discusses the constraints of the monthly contract optimisation decomposition model, which are essential to ensure that the model is practical and meets the actual operational requirements. The specific constraints are listed below:

$$P_{buye,d,w} = \sum_{t=1}^{T} [\sum_{n=1}^{N_{EL}} (P_{e,n,t} - P_{WT,n,t} - P_{EH,n,t})] - \sum_{i=1}^{N_{gene}} E_{e,i,d,w} \tag{3}$$

$$P_{re,d,w} = \sum_{t=1}^{T} \sum_{n=1}^{N_{EL}} (P_{e,n,t} - P_{WT,n,t} - P_{EH,n,t}) \tag{4}$$

$$\overline{P}_{buye,d,w} = \frac{1}{M_{mth}} \sum_{w=1}^{W} \sum_{d=1}^{D} P_{buye,d,w} \tag{5}$$

$$E_{e,i,d,min} \leq E_{e,i,d,w} \leq E_{e,i,d,max}, \forall i \in N_{gene} \tag{6}$$

$$f_{buyg,d,w} = \sum_{t=1}^{T} [\sum_{k=1}^{N_{GL}} (f_{g,k,t} + f_{EH,k,t})] - \sum_{m=1}^{N_{gas}} E_{g,m,d,w} \tag{7}$$

$$f_{rg,d,w} = \sum_{t=1}^{T} \sum_{k=1}^{N_{GL}} (f_{g,k,t} + f_{EH,k,t}) \tag{8}$$

$$\overline{f}_{buyg,d,w} = \frac{1}{M_{mth}} \sum_{w=1}^{W} \sum_{d=1}^{D} f_{buyg,d,w} \tag{9}$$

$$E_{g,m,d,min} \leq E_{g,m,d,w} \leq E_{g,m,d,max}, \forall m \in N_{gas} \tag{10}$$

where $E_{e,i,w}^{bid}$ is the upper and lower bounds of the monthly contract decomposition to the daily contract energy; $P_{re,d,w}, f_{rg,d,w}$ is the simulated electricity/gas load demand on day $d$ of week $w$.

Building upon the decomposition of the monthly contract, it is also essential for the IESP to consider the fulfilment of said contract. This paper contemplates the weekly decomposition of the monthly contract to ensure its effective decomposition and execution. Notably, the weekly decomposition energy comprises both the decomposition of centralized bidding energy and contract signing energy.

$$\sum_{d=1}^{D} E_{e,i,d,w} = E_{e,i,w}^{bid} + E_{e,i,w}^{con}, \ \forall i \in N_{gene} \tag{11}$$

$$\sum_{d=1}^{D} E_{g,m,d,w} = E_{g,m,w}^{bid} + E_{g,m,w}^{con}, \forall m \in N_{gas} \tag{12}$$

where $E_{e,i,w}^{bid}$ represents the centralized bidding electricity volume of generator set $I$ in week $w$; $E_{e,i,w}^{con}$ is the monthly contract signing electricity volume of generator set $I$ in week $w$; $E_{g,j,w}^{bid}$ is the centralized bidding gas volume of gas source point $j$ in week $w$; $E_{g,m,w}^{con}$ is the contract signing gas volume of gas source point $m$ in week $w$.

Based on the literature [25,28], in this paper, in the weekly optimal decomposition of the monthly energy, the bidding energy balanced decomposition is used to decompose the centralized bidding energy in a balanced way, and the remaining part is supplemented by using the contracted volume. The calculations are as follows:

$$E_{e,i,w}^{bid} = \frac{1}{W} E_{me,i}^{bid}, \forall i \in N_{gene} \tag{13}$$

$$E_{g,m,w}^{bid} = \frac{1}{W} E_{mg,m}^{bid}, \forall m \in N_{gas} \tag{14}$$

where $E_{g,m,w}^{bid}$ is the monthly bidding power of generating unit $I$; $E_{g,m,w}^{bid}$ is the monthly bidding gas volume of gas source point $m$.

For the remaining weeks, the centralized bidding energy decomposition and the contract signing volume decomposition are as follows:

$$E_{e,i,w}^{bid} = \frac{1}{4-j}[\sum_{w=j+1}^{W} \sum_{d=1}^{D} P_{re,d,w} - (E_{me,i}^{con} - \sum_{w=1}^{j} E_{e,i,w}^{con,real})], \forall i \in N_{gene} \tag{15}$$

$$E_{e,i,w}^{con} = \sum_{d=1}^{D} P_{re,d,w} - [\frac{1}{4-j}(E_{me,i}^{bid} - \sum_{w=1}^{j} E_{e,i,w}^{bid,real})], \forall i \in N_{gene} \tag{16}$$

$$E_{g,m,w}^{bid} = \frac{1}{4-j}[\sum_{w=j+1}^{W} \sum_{d=1}^{D} f_{rg,d,w} - (E_{mg,m}^{con} - \sum_{w=1}^{j} E_{g,m,w}^{con,real})], \forall m \in N_{gas} \tag{17}$$

$$E_{g,m,w}^{con} = \sum_{d=1}^{D} f_{rg,d,w} - [\frac{1}{4-j}(E_{mg,m}^{bid} - \sum_{w=1}^{j} E_{g,m,w}^{bid,real})], \forall m \in N_{gas} \tag{18}$$

where $j$ is the week number;$E_{e,i,w}^{con,real}$ is the actual disaggregated bid and contracted power obtained in week $w$ of generating unit $I$; $E_{g,m,w}^{con,real}$ is the actual decomposition of bidding gas and contracted gas obtained in week $w$ at the gas source point $m$.

In addition to this, to ensure the stable operation of the system, the unit's mandatory energy constraints, network security constraints, and end-of-month deviation energy assessment constraints need to be taken into account, as shown in the following equation:

$$\begin{cases} 0 \le |\sum_{w=1}^{W} (E_{e,i,w}^{bid} - E_{e,i,w}^{bid,real})| \le 0.3 \times \sum_{w=1}^{W} E_{e,i,w}^{bid} \\ 0 \le |\sum_{w=1}^{W} (E_{e,i,w}^{con} - E_{e,i,w}^{con,real})| \le 0.3 \times \sum_{w=1}^{W} E_{e,i,w}^{con} \end{cases} \tag{19}$$

$$\begin{cases} 0 \le \sum_{w=1}^{W} (E_{g,i,w}^{bid} - E_{g,i,w}^{bid,real}) \le 0.1 \times \sum_{w=1}^{W} E_{g,i,w}^{bid} \\ 0 \le \sum_{w=1}^{W} (E_{g,i,w}^{con} - E_{g,i,w}^{con,real}) \le 0.1 \times \sum_{w=1}^{W} E_{g,i,w}^{con} \end{cases} \tag{20}$$

## 4. A Day-Ahead Scheduling Model for IESs Accounting for Multiple Energy Flow Coupling

### *4.1. Objective Function*

After completing the medium- and long-term contract transactions, the IESP needs to perform a daily decomposition of the traded monthly electricity to facilitate the optimal operation of the electrical and thermal multi-energy network under its jurisdiction as well as to improve the interface relationship between the spot market and the medium- and long-term market. The optimal dispatch model of the multi-energy network is based on the objective of minimizing the sum of cumulative daily operating costs of the network, as shown in the following equation:

$$minC = \sum_{w=1}^{W} \sum_{d=1}^{D} (C_{gen,d,w} + C_{\text{grid},d,w} + C_{\text{buy},d,w}) \tag{21}$$

$$C_{gen,d,w} = \sum_{t=1}^{T} \sum_{i=1}^{N_{gene}} c_{start,i} P_{gene,i,t} \mu_{gene,i,t} \tag{22}$$

$$C_{\text{grid},d,w} = \sum_{t=1}^{T} [ \sum_{i=1}^{N_{gene}} (a_{e,i} P_{gene,i,t}^2 + b_{e,i} P_{gene,i,t} + c_{e,i}) + \sum_{i=1}^{N_{EH}} c_{EH,i} P_{EH,i,t} + \sum_{i=1}^{N_{gas}} c_{gas,i} f_{gas,i,t}] \tag{23}$$

$$C_{\text{buy},d,w} = \sum_{t=1}^{T} (P_{buye,t} \rho_{spot,e,t} + f_{buyg,t} \rho_{spot,g,t}) \tag{24}$$

where $C$ is the total monthly cost of the IESP's operating region; $W$, $D$, and $T$ are the number of weeks, days, and moment numbers; $C_{gen,d,w}$ is the unit startup cost on day $d$ of week $w$; $C_{grid,d,w}$ is the network operating cost on day $d$ of week $w$; $C_{buy,d,w}$ is the cost of purchasing power in the spot market on day $d$ of week $w$; $C_{dr,d,w}$ is the cost of the demand response to load on day $d$ of week $w$; $N_{gene}$, $N_{EH}$, $N_{gas}$, $N_{EL}$, $N_{GL}$, $N_{HL}$ are the number of generating units, the number of energy hubs, the number of gas points, the number of electrical load nodes, the number of gas load nodes, and the number of heat load nodes, respectively; $c_{start,I}$ is the unit startup cost of the $i$th unit; $\mu_{gene,i,t}$ is a 0–1 variable indicating the unit's operating status; $P_{gene,i,t}$ is the output of the $i$th unit in time period $t$; $a_{e,I}$,$b_{e,I}$,$c_{e,i}$ are the output cost coefficients for generating unit $i$, respectively; $c_{EH,i}$ is the unit cost of output for the energy hub; $P_{EH,i,t}$ is the injected power for the energy hub; $c_{gas,i}$ is the unit cost of gas purchased at the point of origin; $f_{i,t}$ is the output flow rate at time period $t$ at the gas source point; $P_{buye,t}$, $\rho_{buye,t}$ are the spot market purchased power and purchased price in time period $t$; $f_{buyg,t}$, $\rho_{buyg,t}$ are the volume and price of gas purchased in the spot market at time $t$.

### *4.2. Restrictive Condition*

In the context of an integrated energy network, gas pipelines exhibit certain storage characteristics during day-ahead optimized scheduling due to the relatively slow gas flow [29,30]. Such characteristics will have a large impact on the daily energy decomposition of the IESP in the region. This impact is likely to cause uneven energy decomposition and may lead to the failure of some energy decomposition plans. Therefore, it is necessary to consider the daily network-related constraints, including grid operation constraints, gas network operation constraints, heat network operation constraints, energy hub constraints, etc., in the energy decomposition.

#### 4.2.1. Grid Operation Constraints

Based on the references [30], the current constraints of the power network are as follows:

$$P_{mn,t} = \frac{\theta_{m,t} - \theta_{n,t}}{X_{mn}} \tag{25}$$

$$P_{e,n,t} + \sum_{n \in m} P_{mn,t} = P_{EH,n,t} + \sum_{i=1}^{N_{gene}} (P_{buye,i,t} + P_{gene,i,n,t}) + P_{WT,n,t} \tag{26}$$

$$\mu_{gene,i,t} P_{gene,i,min} \leq P_{gene,i,t} \leq P_{gene,i,max} \mu_{gene,i,t} \tag{27}$$

$$RD_{gene,i} \leq P_{gene,i,t} - P_{gene,i,t-1} \leq RU_{gene,i} \tag{28}$$

$$\sum_{t=1}^{T} P_{gene,i,t} \leq E_{gene,i,d}^{real} \tag{29}$$

$$(\mu_{gene,i,t-1} - \mu_{gene,i,t})(T_{\text{on},i,t-1} - T_{\text{on},i,min}) \geq 0 \tag{30}$$

$$(\mu_{gene,i,t} - \mu_{gene,i,t-1})(T_{\text{off},i,t-1} - T_{\text{off},i,min}) \geq 0 \tag{31}$$

where $P_{mn,t}$ is the line transmission power of the branch $mn$; $\theta_{mn,t}$ is the phase angle difference between node $m$ and node $n$ at time $t$; $X_{mn}$ is the reactance of the branch $mn$; $r_{mn}$ is the resistance of the branch $mn$; $P_{\text{e},n,t}$ is the electrical load power of node $n$ in time period $t$; $P_{gene,i,n,t}$ is the sum of the outputs of the generating units decomposed to node $n$ in time period $t$; $P_{PV,n,t}$ is the outgoing power of the PV at node $n$ for time period $t$; $P_{WT,n,t}$ is the output of wind power at node $n$ in time period $t$; $P_{gene,i,min}$, $P_{gene,i,max}$ are the upper and lower output limits of generator set $i$, respectively; $RU_{gene,i}$, $RD_{gene,i}$ are the upward and downward climbing power of genset $i$; $E^{real}_{gene,i,d}$ is the actual total daily electricity for the medium- and long-term power breakdown to day $d$; $T_{on,i,t}$,$t$, $T_{off,i,t}$ are the number of hours the generating unit $i$ has been out of service and the number of hours it has been shut down, respectively; $T_{on,i,min}$, $T_{off,i,max}$ are the minimum output duration and minimum downtime, respectively.

#### 4.2.2. Gas Network Operational Constraints

Based on the reference [31], the dynamic properties of the gas network model are mainly reflected in the pipeline inventory. Therefore, the tidal flow constraints of the gas network are as follows:

$$f_{kl,t} = \tau_{kl,t} \times 5.72 \times 10^{-4} \sqrt{\frac{(p^2_{k,t} - p^2_{l,t})D^5}{FSL_{kl}}} \tag{32}$$

$$F = 0.0044(1 + \frac{12}{0.276D}) \tag{33}$$

$$\sum_{l \in k} f_{kl,t} = \sum_{k \in l} f_{kl,t} f_{lk,t} + f_{gas,k,t} + f_{buyg,k,t} - f_{EH,k,t} - (f_{g,k,t} - f_{drg,k,t}) \tag{34}$$

$$f_{kl,min} \leq f_{kl,t} \leq f_{kl,max} \tag{35}$$

$$-f_{gas,k,max} \leq f_{gas,k,t} \leq f_{gas,k,max} \tag{36}$$

$$M_{kl,t} = M_{kl,t-1} + f_{kl,t} + f_{lk,t} \tag{37}$$

$$\frac{C_{kl,con}}{L_{kl}} M_{kl,t} = p_{kl,t} \tag{38}$$

$$p_{k,min} \leq p_{k,t} \leq p_{k,max} \tag{39}$$

$$M_{kl,0} = M_{kl,T} \tag{40}$$

$$\sum_{t=1}^{T} f_{gas,k,t} \leq E^{real}_{gas,i,d} \tag{41}$$

where $f_{kl,t\ t}$ is the gas flow rate through pipe $kl$ at time $t$; $\tau_{kl,t}$ is the flow of natural gas in pipeline $kl$ from $k$ to $l$. Then, flowing from $l$ to $k$, $p_{k,t}$, $p_{l,t}$ are the pressures at nodes $k$ and $l$; $D$ is the pipe diameter; $F$ is the pipe friction coefficient; *Sis* is the specific gravity of the gas; $L_{kl}$ is the length of pipe $kl$; $f_{gas,k,t}$ is the output gas flow rate of the gas source at node $k$ in period $t$; $f_{EH,k,t}$ is the gas flow rate output/consumed by the energy hub at node $k$ in period $t$; $f_{g,k,t}$ is the gas load flow at node $k$ in period $t$; $f_{kl,\,max}$, $f_{kl,\,min}$ are the upper and lower limits of the pipe flow, respectively; $f_{gas,k,\,max}$, $f_{gas,k,\,min}$ are the upper and lower limits of the output gas flow at the gas source point, respectively; $M_{kl,t}$ is the pipe inventory of pipe $kl$ at period $t$; $C_{kl,\,the\ con}$ is a constant related to the length, diameter, etc., of the pipe; $p_{k,\,max}$, $p_{k,\,min}$ are the upper and lower limits of the air pressure at the pipe node; $E^{real}_{gas,i,d}$ is the actual gas production broken down to day $d$ of the medium- and long-term contract signed by the IESP.

#### 4.2.3. Thermal Network Operational Constraints

The thermal network model is divided into a hydraulic model and a thermal model, and the hydraulic model is as follows:

$$Am = m_q \tag{42}$$

$$Bh_f = 0 \tag{43}$$

$$h_f = Km|m| \tag{44}$$

where $A$ is the network correlation matrix; $m$ is the flow rate of water flow in the heat network pipe; $m_q$ is the flow rate of water flow into the load node or out of the heat source node; $B$ is the loop correlation matrix; $h_f$ is the pressure drop in the pipe caused by friction loss; and $K$ is the pipe resistance coefficient.

The thermal modeling is as follows:

$$H - H_{drh} = C_p m_q (T_s - T_o) \tag{45}$$

$$T_{out,ij,t} = (T_{s,t} - T_{a,t})e^{-\lambda L_{ij}/C_p m_{ij,t}} + T_{a,t} \tag{46}$$

$$\left(\sum m_{out} T_{out}\right) = \sum (m_{in} T_{in}) \tag{47}$$

$$T_{s,min} \le T_s \le T_{s,max} \tag{48}$$

$$T_{o,min} \le T_o \le T_{o,max} \tag{49}$$

where $H$ is the heat load matrix; $H_{drh}$ is the load power matrix consisting of the tangential heat load; $T_s$ is the nodal water supply temperature; $T_{s,min}$, $T_{s,max}$ are the upper and lower bounds of the nodal water supply temperature; $T_o$ is the nodal return temperature; $T_{o,min}$, $T_{o,max}$ are the upper and lower bounds of the nodal return temperature; $T_{out,ij,t}$ is the exit temperature of the pipeline end; $\lambda$ is the heat transfer coefficient; $C_p$ is the specific heat capacity of water; $m_{in}$ is the flow rate of the pipeline into the node; $m_{out}$ is the flow rate of the pipeline out of the node; $T_{\mathrm{in}}$ is the temperature of the input pipeline end; $T_{out}$ is the nodal mixing temperature.

#### 4.2.4. Source Hub Constraint

The energy hub, as a key support for connecting the multi-energy network, internally involves cogeneration equipment to realize the conversion of natural gas to electricity and heat, and the external input–output model is shown below:

$$P_{EH,i,t} = f_{EH,i,t} H_{vg} \lambda_e \tag{50}$$

$$h_{EH,i,t} = f_{EH,i,t} H_{vg} \lambda_h \tag{51}$$

where $H_{vg}$ is the calorific value of natural gas, taken as 7.8 kW·h/m$^3$; $\lambda_e$, $\lambda_h$ are the natural gas to electricity and heat transfer efficiencies, respectively.

### *4.3. Model Solving Steps*

The solution flow of the IESP monthly contract daily optimization decomposition method, constructed in this paper to account for the dynamic characteristics of the network, is illustrated in Figure 3. First, input the monthly total bidding volume and total contract signing volume, make $w$ = 1, calculate the total bidding volume of the first week as the boundary of the contract supply energy within the week, make $d$ = 1, input the daily load forecast value, spot market clearing price, and integrated energy network parameters, use the CPLEX solver to optimize and solve the IES scheduling model, and derive the daily output of each unit and gas source point. Make $d$ = $d$ + 1, solve the optimization model for $D$ times of daily scheduling in a loop, superimpose the power of units and gas source points derived from $D$ times, and determine whether the variance in the spot bidding volume reaches the minimum; if it meets the convergence condition, then make $w = w + 1$. Determine whether it meets the convergence condition corresponding to whether the monthly integrated energy optimization scheduling result reaches the minimum and whether the variance in the spot trading volume reaches the minimum of the weekly; if it meets the condition, output the day-to-day energy decomposition value of the medium- and long-term contract and the corresponding daily spot bidding space.

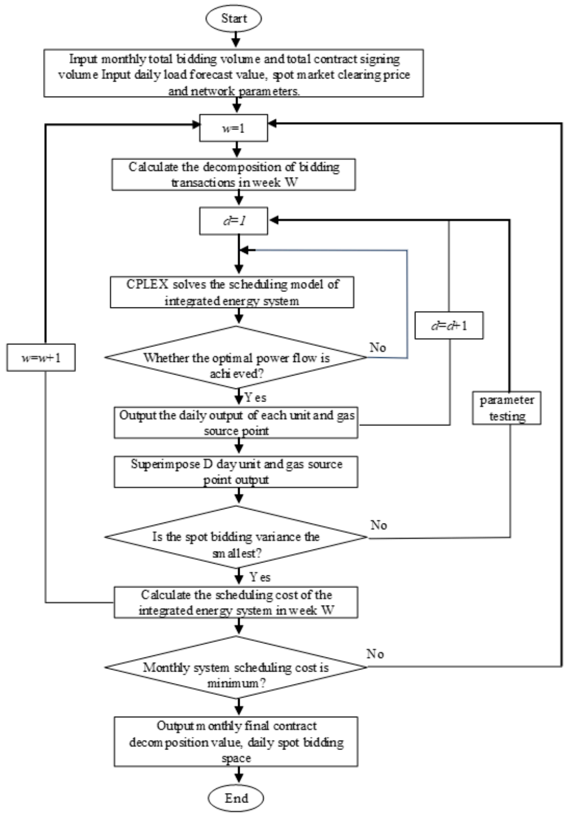


**Figure 3.** Solving process.

## 5. Calculus Analysis

### *5.1. Basic Data*

To validate the effectiveness of the contract optimization decomposition method proposed in this chapter, the model is solved using the EMP + MINLP algorithm package in GAMS 43 with the YALMIP + CPLEX solver in MATLAB 2020a. In this chapter, an IES consisting of an IEEE 39-node electric system, a 20-node natural gas system, and a 6-node thermal system is used, as shown in Figure 4, with the specific parameters described in reference [31]. The system is connected with two EHs and the grid's 36 nodes are connected to the gas grid's 20 nodes with gas turbines. The power system consists of seven generating units, the gas system consists of four gas source points, and the heat system is supplied by the EHs. The EHs adopt the heat-determined power method, in which the electric efficiency of the EHs is 0.375 and the thermal efficiency is 0.5. The monthly contracted price is set at 13.3 USD/MWh, the centralized bidding price is set as a step offer, the power interval is [20,000, 60,000], the interval band is [20,000, 600], the initial band offer is set at 12.5 USD/MWh, the gas interval is set at [15, 500], and the gas interval is set at [15, 500]. Based on the data of a typical month, the initial electricity/gas/heat load curve is shown in Figure 5. The monthly spot electricity and gas prices and the 24 h electricity and gas prices for a particular day of the month are shown in Figure 6.

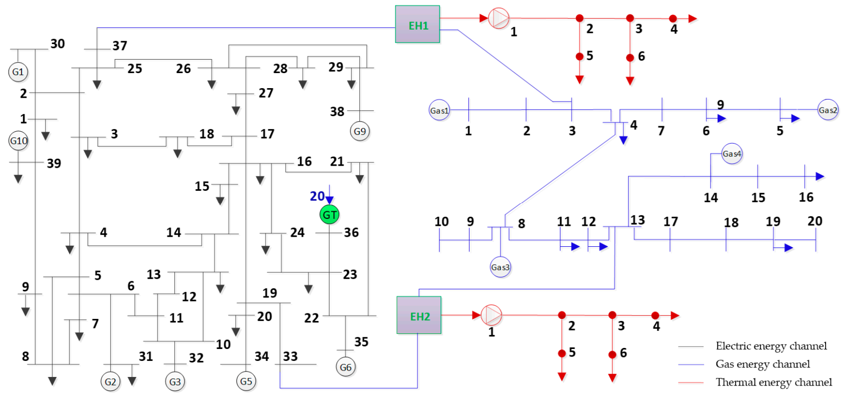


**Figure 4.** Integrated energy example system diagram.

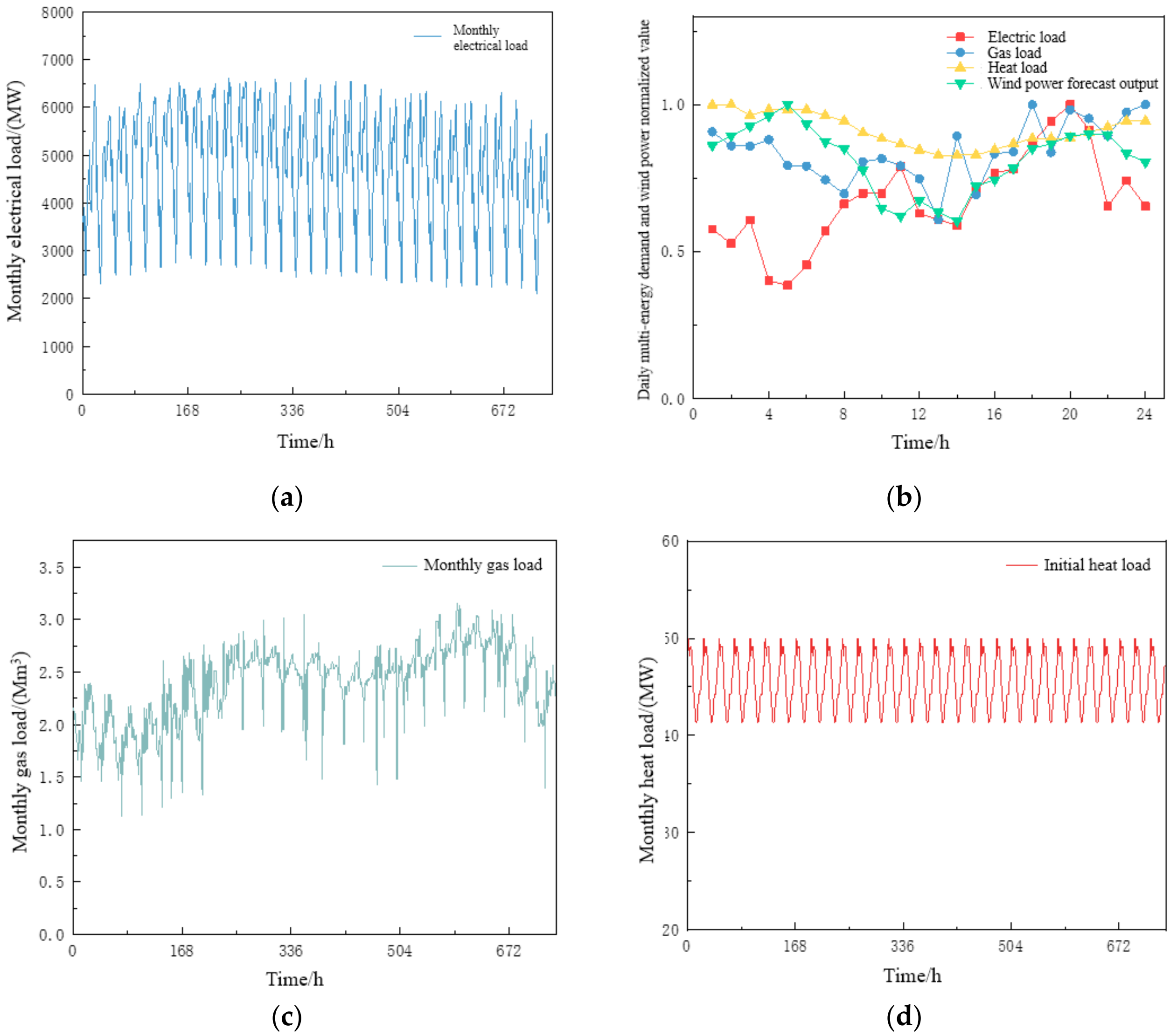


**Figure 5.** Initial load curve (**a**); (**b**) daily wind power and demand; (**c**) monthly gas demand; (**d**) monthly calorie requirements.

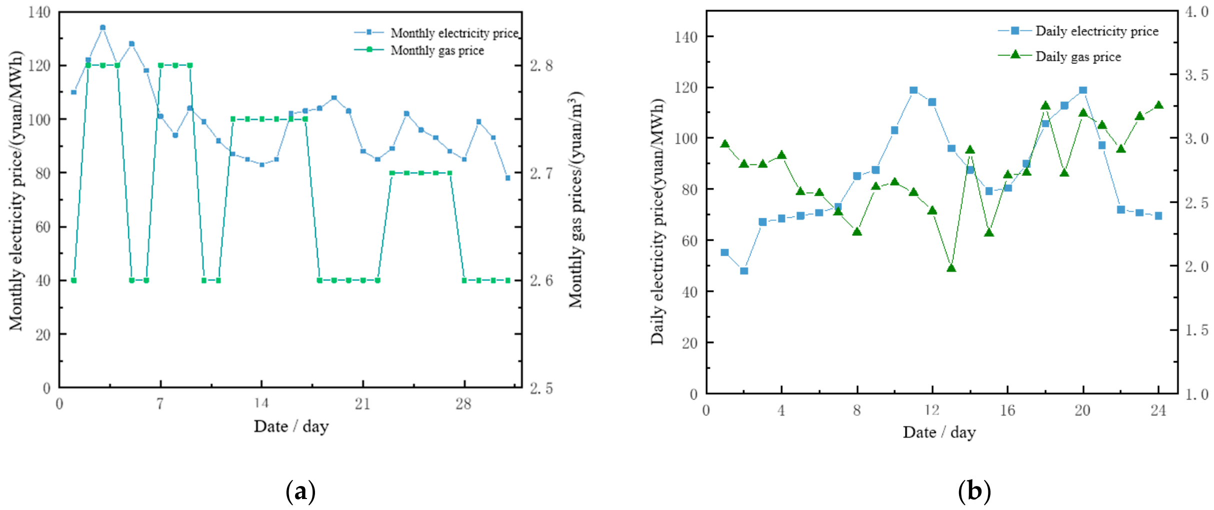


**Figure 6.** Electricity price and gas price diagram. (**a**) Monthly spot energy price curve; (**b**) daily spot energy price curve.

### *5.2. Analysis of the Effectiveness of the Monthly Contract Equalization Decomposition Method*

To verify the rationality and effectiveness of the spot bidding equilibrium decomposition method proposed in this paper, three scenarios are set up for comparative analysis, respectively:

S1: Contract decomposition using the traditional decomposition method, i.e., average contract volume decomposition;

S2: A contractual decomposition using the proposed centralized bidding volume equilibrium decomposition, but not considering the spot bidding equilibrium;

S3: A contractual decomposition using the proposed centralized bidding volume equalization decomposition and taking into account the spot bidding equalization.

Considering that the heat load demand of the IESP is all converted to energy via an EH and decomposed to electricity demand and gas demand, the heat load demand is converted to electricity/gas demand every month to arrive at the electricity demand and gas demand and the initial decomposition is carried out by using the methodology proposed in this chapter, as shown in Figure 7.

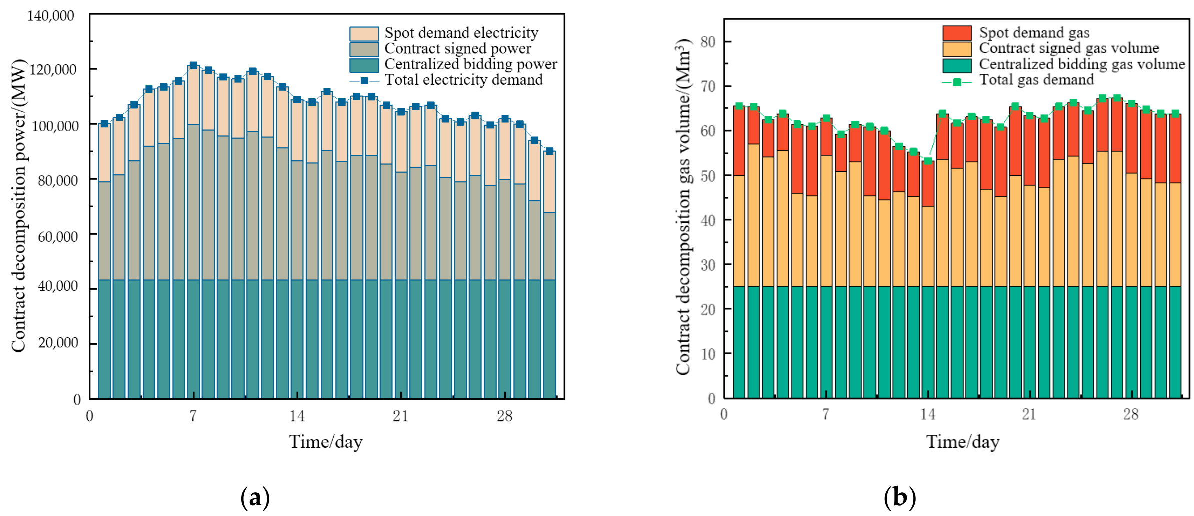


**Figure 7.** Contract decomposition results in S3 scenario. (**a**) Preliminary breakdown of monthly electricity contracts; (**b**) preliminary breakdown of monthly gas contracts.

As can be seen from Figure 7, the trend of contracted electricity and gas volume is consistent with the monthly electricity/gas demand while the centralized bidding electricity and gas volume is in a constant state, and the daily decomposition of the spot purchasing energy obtained is basically in an equilibrium state due to the consideration of the equilibrium of the space of the spot bidding, but it also shows a certain tendency to increase or decrease with the fluctuation in the price.

The contract disaggregation costs for the three scenarios are shown in Table 1, and the fluctuations in spot purchase energy for each scenario are shown in Figure 8.

**Table 1.** Contract decomposition cost comparison under different scenarios.

| Scene | Contract Decomposition Cost/(USD) | Spot Purchase Energy Variance |
|---|---|---|
| S1 | 45,871,627 | 24.5681 |
| S2 | 44,302,449 | 87,193.68 |
| S3 | 45,534,180 | 23.4273 |

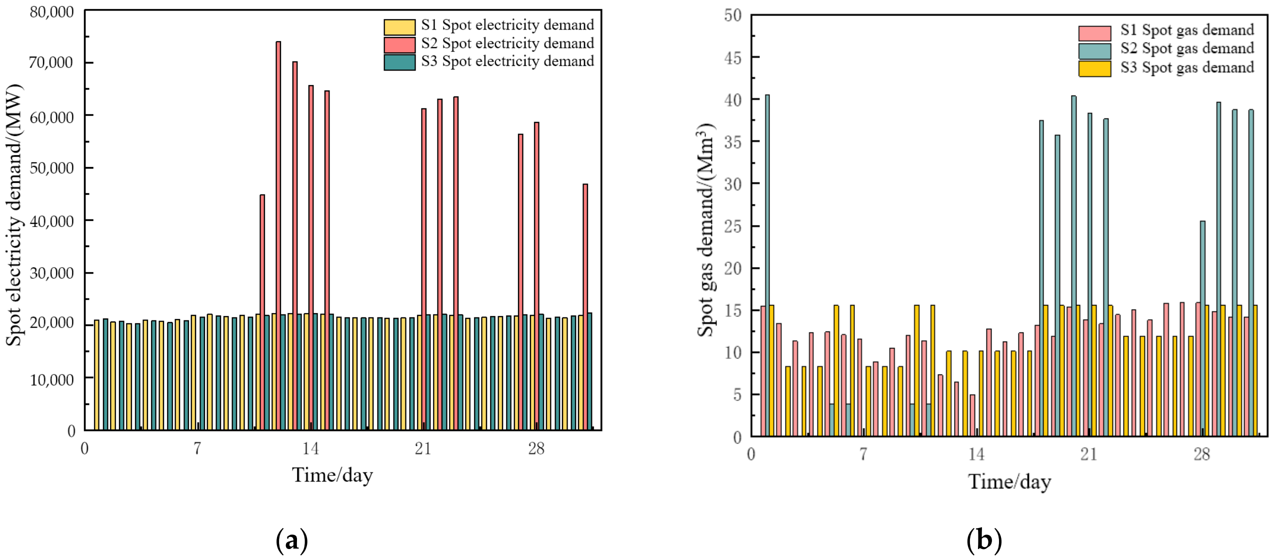


**Figure 8.** Spot purchase energy in different scenarios. (**a**) Spot power contract breakdown results; (**b**) spot gas contract breakdown results.

As can be seen from Table 1, after S3 takes into account the bidding equilibrium decomposition, the cost of contract decomposition is reduced by about USD 0.33 million compared with S1, and the variance in spot energy purchase also decreases by about 4.64%; this leads to the conclusion that the equilibrium decomposition is less costly compared with the average decomposition method of the monthly contract, and the smaller variance in the spot energy purchase indicates the smaller fluctuation in the daily spot price, which is conducive to the stabilization of the intra-month spot market trading. As shown in Figure 8, S2 does not take into account the equilibrium of the spot space and is combined with the monthly energy price curve in Figure 6a. The IESP prefers to participate in the spot market to purchase energy at the time when the price is cheaper, and thus the contract decomposition cost of S3 is improved by about 2.7% relative to that of S2. Yet, the impact of S2 on the variance in spot energy purchased surpasses that of S3. This is evident in Figure 8, illustrating the daily differences in spot energy purchases. Consequently, daily spot bidding transactions throughout the month experience significant price–volume fluctuations. This instability hampers the smooth functioning of the spot market and adversely affects the profitability of participating market players' bids.

*5.3. Analysis of the Actual Daily Performance of Monthly Contracts*

After arriving at the preliminary decomposition results of the monthly contract, considering the execution effect of the actual decomposed quantity daily, the execution of the decomposed quantity is verified by utilizing the day-ahead contract decomposition model proposed in this paper, which results in the output of the generating units, the gas source points, and the EHs in the IES under the management of the IESP with the actual execution of the contract as shown in Figures 9 and 10.

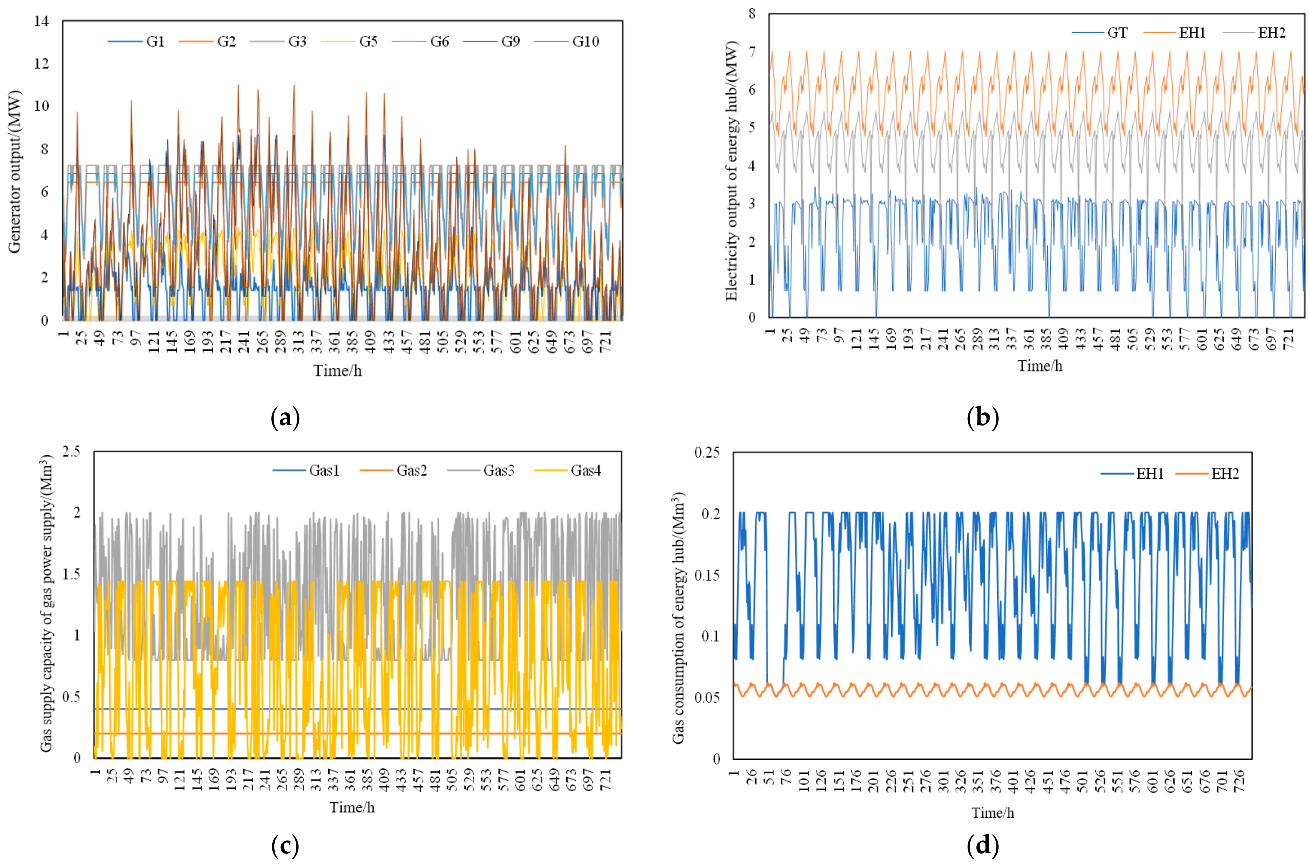


**Figure 9.** Daily actual power/gas output of IES in typical months. (**a**) Actual power output of generating units; (**b**) actual power output of energy conversion hub; (**c**) actual gas supply of the gas source point; (**d**) actual gas consumption of the energy conversion hub.

As can be seen from Figure 9a,b, the daily trend of the generating unit and gas point output is more consistent, which is mainly due to the overall load trend of each node of the system being similar, and the difference is mainly reflected in the difference in the amount of load, so the output curve of each unit is in a roughly consistent state. At the same time, due to the large difference in the operating cost of each unit, such as generators G1 and G5 with higher operating costs, the output of G1 and G5 is in a lower state in most cases while the remaining part of the unit's output cost is relatively low, such as G3 and G6, and therefore it has been in a full output state after startup. When the daily load is in high demand, the original unit output cannot meet the load demand, and then G9 and G10 units enhance their output to help the system reach the trend balance. From Figure 9c,d, it can be seen that the gas supply at the gas source point is basically in the full state, and the gas supply of Gas3 and Gas4 is in the complementary state. This is mainly because, on the one hand, the capacity of these two gas source points is larger, and the cost of the gas supply of Gas3 and Gas4 is comparatively smaller and its regulation ability is more flexible; on the other hand, due to the existence of the EH, the heat load demand of the two heat networks need to be supplied indirectly by the gas network, which makes the gas supply at the gas source point larger than that at the gas supply point. On the other hand, due to the existence of the EH, the heat load demand of both heat networks has to be indirectly supplied by the gas network, which makes the gas supply capacity of the gas source points larger, and, combined with the pipe storage characteristics of the gas network, the load demand of the heat network and the power grid can be effectively satisfied.

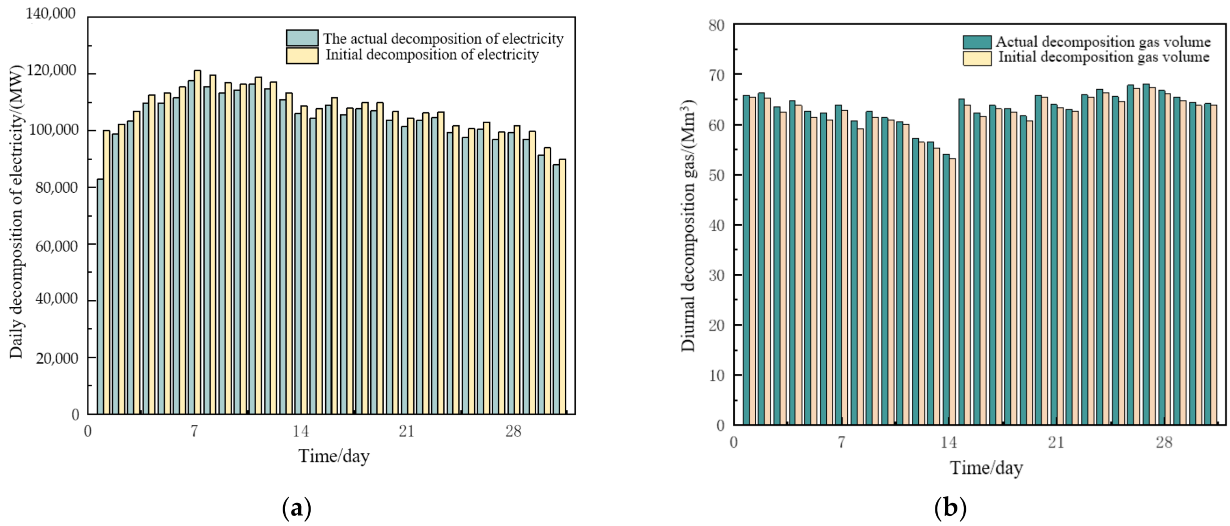


**Figure 10.** Contract decomposition daily total execution. (**a**) Actual execution and preliminary decomposition of electric quantity; (**b**) actual execution and preliminary decomposition of gas quantity.

From Figure 10, it can be found that, after adopting the decomposition method proposed in this chapter, the gap between the actual daily execution and the initial contractual decomposition amount is small, and the actual electric/gas output execution deviations are all within 3% by constraints (49) and (50). And, comparing Figure 10a,b, it can be found that the actual gas supply exceeds the projected gas supply from the gas source point while the actual electricity output is smaller than the projected electricity output, which is mainly due to the heat-to-electricity method in the EH and the presence of a gas turbine in the grid. In this setup, the gas grid needs to provide a part of the additional gas to meet the natural gas demand of the GT and the EH, and the cost of the energy conversion equipment's output is smaller than the generating unit's operating costs, hence the positive and negative deviations described above.

The day of the month was selected for the attribution determination of the specific breakout contract volumes, and the breakout contract volumes attributed to each generating unit, gas source point, and EH are shown in Figure 11.

As depicted in Figure 11, the contract decomposition attribution for a day of the month reveals a distinct distribution trend. In Figure 11a, the three units on the left tend to derive revenue from centralized bidding contracts, driven by higher marginal costs. Consequently, there is an increase in the volume of centralized bidding in decomposition to enhance revenue from centralized bidding offers. Concurrently, in the period of higher spot power prices as illustrated in Figure 6b spot power sales contracts are pursued for profit maximization, aiming to capitalize on revenue opportunities. According to Figures 3–11a, since the marginal cost of G9, G10, and other units is small, they can choose the stable medium- and long-term physical contract accordingly and tend to sell electricity in the period of higher spot prices to improve their income from electricity sales and further reduce their operating costs. For the decomposition of the power output of the energy hub in Figure 11c, as the energy hub adopts the heat-determined power mode, its power output trend is approximately the same as the trend of the heat network load, and the trend is opposite to the price of electricity, which makes the decomposition of the power output of the energy hub not able to participate in the spot transaction effectively and obtain large profits from it. Therefore, in the relatively high price period, such as 4:00~8:00, the spot contract will be chosen, while, for the rest of the period, the centralized bidding and physical contract will be chosen to ensure their interests.

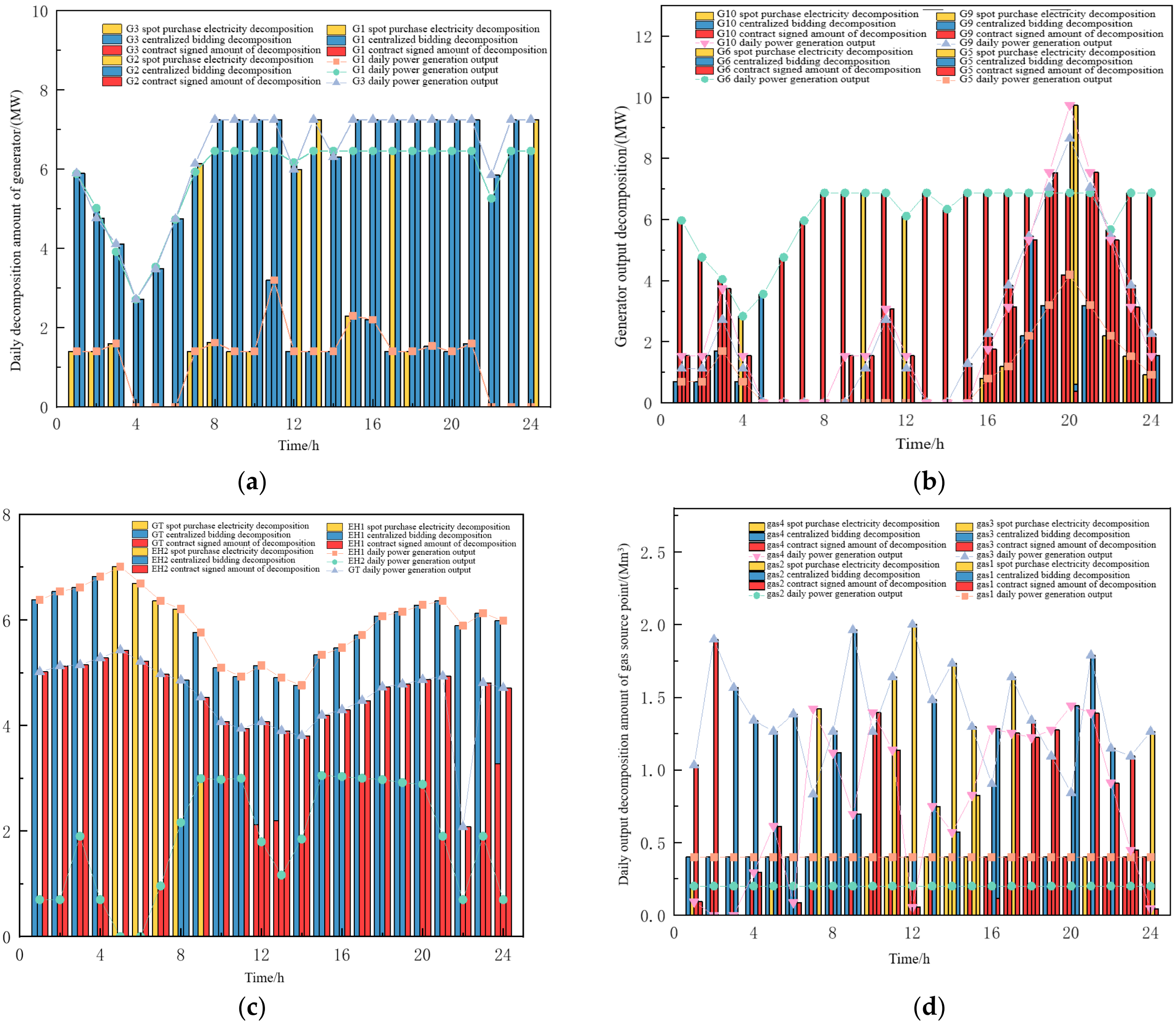


**Figure 11.** Daily output decomposition of generator set and gas source point. (**a**) Daily output decomposition of generator set; (**b**) daily output decomposition of generator set; (**c**) daily power decomposition of energy conversion hub; (d) daily output decomposition amount of gas source point.

Figure 11d shows the decomposition of gas supply at the gas source points, combining the high and low cost of gas supply at each gas source point: Gas1 and Gas2 are higher, Gas3 and Gas4 are lower, and, from the figure, it can be seen that Gas1 and Gas2 are more inclined to select spot bidding contracts to obtain more revenue from the sale of gas during the time of high gas prices, whereas Gas3 and Gas4 are more inclined to select centralized bidding contracts versus physical contracts. Gas3 and Gas4 prefer centralized bidding contracts and physical contract contracts, and spot contracts are only identified during a few peak gas price periods. The attribution of generating units and gas source points can effectively improve their operating income through the decomposition of their output and ensure the effective execution of medium- and long-term trading contracts and balanced trading in the spot market.

The dynamic pipe storage characteristics of the gas network are considered in the IES constructed in this paper, and, to verify the influence of the pipe storage characteristics on the optimal operation of the system, the changes in the gas supply volume at the gas source point and the changes in the network operation cost are analyzed with and without considering the pipe storage. The IES incurs an operating cost of USD 0.54 million without factoring in the pipe storage characteristic. With this, the gas network's operating cost amounts to USD 123.14 million. Conversely, considering that the pipe storage characteristic lowers the IES's operating cost to USD 0.525 million, with the gas network's operating cost reduced to USD 115.14 million, the network's operating cost decreases by approximately 2.01% when incorporating the pipe storage characteristic, while the gas network's cost drops by about 6.4%. Therefore, the operating cost of the system can be effectively reduced after considering the pipe storage characteristics of the gas network to promote the economic and stable operation of the IES. Specifically, the changes in the gas supply volume of each gas source point in the gas network are shown in Figure 12, and the changes in the gas supply volume of Gas3 and Gas4 are given in Figure. Since the maximum capacity of Gas1 and Gas2 in the gas network is small and is at full output in both scenarios, it is not discussed here.

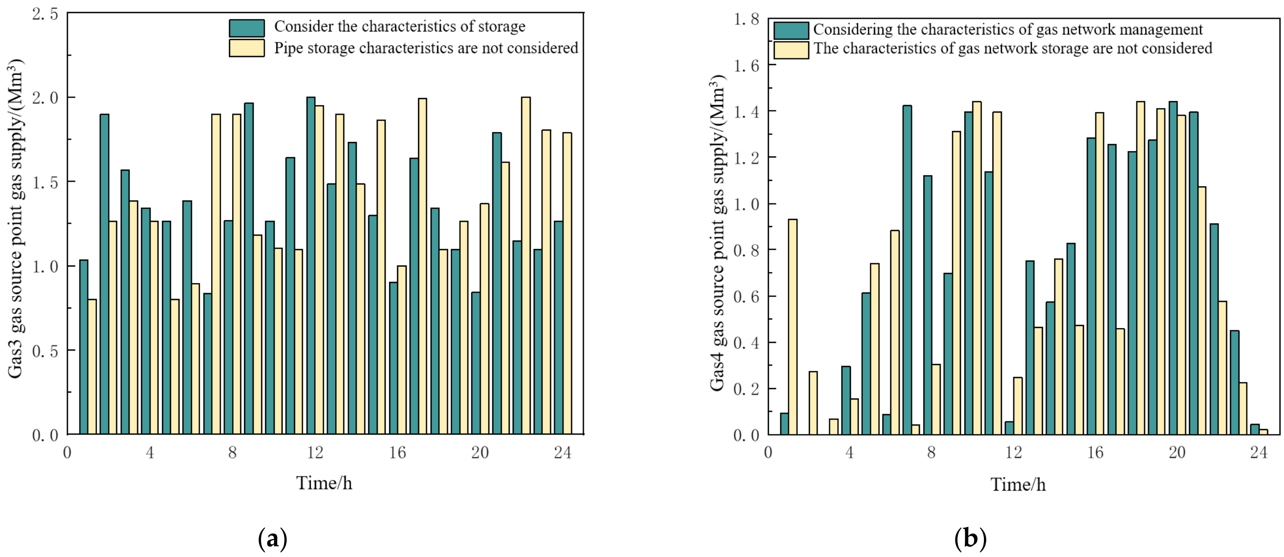


**Figure 12.** Change trend of gas supply at gas source point considering pipe storage characteristics. (**a**) Gas3 gas supply change; (**b**) Gas4 gas supply change.

As can be seen in Figure 12, after considering the dynamic pipe storage characteristics of the gas network, the gas supply at Gas3 is significantly lower during peak demand hours, such as 8:00~12:00 and 20:00~24:00, compared with the gas supply at Gas3 without considering the pipe storage, and the gas output at Gas3 is relatively higher during the trough hours of the gas load, when the pipeline gas storage is used to release gas in the peak hours to alleviate the pressure of gas supply at Gas3. The gas supply at Gas3 and Gas4 is the same during 0:00~4:00 and 8:00~12:00, and Gas3 and Gas4 are also the same during 0:00~4:00 and 8:00~12:00. The pressure of gas supply at the gas source point is also the same for gas supply at Gas4 during the hours of 0:00 to 4:00 and 8:00 to 12:00, and Gas3 and Gas4, due to the small difference in cost, will have a relatively lower output of the other gas source point when the output of one of the gas source points is higher on the basis of satisfying the balance of the trend of the gas network. Specifically, the total gas network inventory changes are shown in Figure 13.

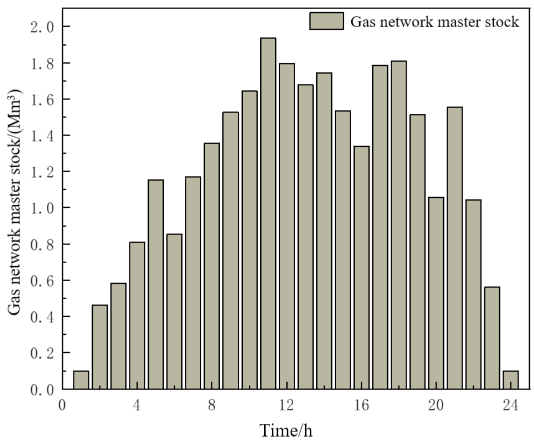


**Figure 13.** Change in the trend of gas network master stock.

As can be seen from Figure 13, natural gas pipelines store gas during the gas load trough time and supply gas during the gas load demand peak time, forming a complementary trend with the output of the gas source point, effectively alleviating the gas supply pressure at the gas source point and stabilizing the pipeline air pressure of the gas network to a certain extent, preventing the risk of overrun of the pipeline air pressure. In summary, the pipe storage characteristics of the gas network can help the IES to alleviate the energy supply pressure at the energy supply point.

## 6. Conclusions

Aiming at the problem that there are fewer medium- and long-term decomposition methods for electricity/gas multi-energy contracts under multi-energy coupling and that the connection between integrated energy medium- and long-term and spot markets is unclear, this chapter proposes an optimal decomposition method for IESPs' monthly contracts that takes into account the equilibrium of spot bidding, and the specific conclusions are as follows:

(1) The proposed method in this chapter considers the equilibrium decomposition of the centralized bidding volume as well as the equalization of the spot bidding space, which reduces the contract decomposition cost by about USD 0.33 million compared to the contract decomposition cost without considering the equilibrium decomposition, and the spot energy purchase variance also decreases by about 4.64%; at the same time, the consideration of the spot bidding variance can also effectively alleviate the fluctuation in the spot market and achieve smooth convergence of the spot market with the medium- and long-term market;

(2) In this chapter, the daily operation plan of the IES is formulated based on the preliminary decomposition of the contract, which ensures that the deviation in daily energy supply and output does not exceed 3% in response to the assessment index at the end of the month, and then the optimized decomposition of the attributed amount of the medium- and long-term contract and the spot purchase plan is carried out so that the daily decomposition of the contract can maximize the operating income of each supplier;

(3) Considering that the dynamic pipe storage characteristics of the gas network trim the overall daily operating cost of IES by 2.01% compared to the scenario without this consideration, the noteworthy cost reduction is predominantly in the gas network, lowered by approximately 6.4%. Simultaneously, the gas source point's output exhibits a smoother trend. This substantiates the effectiveness of gas network pipe storage characteristics in easing energy supply pressure at the energy supply point and achieving efficient interconnection of the electricity, gas, and heat networks in the IES.

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