General model establishment and optimization dispatch of integrated energy system with power-to-gas

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Abstract: It is an important way to solve the problem of energy environment to use the new energy to run the multi-type energy coupling integrated energy system. Firstly, the mathematical model of power-to-gas (P2G) and electric-to-gas (P2HSS) energy storage system is established in this paper, and then the comprehensive energy system model of power-to-gas is established by using the modeling method of general energy hub. With the goal of reducing costs, reducing emissions, increasing new energy output and increasing P2G and P2H conversion benefits, optimization dispatch analysis was conducted. The numerical example shows that the consumption of new energy in the system is good. At the same time, P2HSS system has a significant effect on peak cutting and valley filling to ensure the economic and stable operation of the system.

1. Introduction
The access of random and intermittent renewable energy brings new challenges to the study of integrated energy system. In recent years, the research on power-to-gas technology has become increasingly mature, which can effectively alleviate the consumption problems brought by renewable energy [1]. Power-to-gas is divided into two types: electricity to hydrogen (P2H) and electricity to natural gas (P2G). Electricity to hydrogen means to produce hydrogen and oxygen through electrolysis of water. The conversion of electricity to natural gas is based on the conversion of electricity to hydrogen. The hydrogen and carbon dioxide are catalyzed by Sabatier to form methane and water. The generated methane can be directly injected into the natural gas pipeline to supply the natural gas load. Literature [2] proposed the electric conversion energy storage system (P2HSS) of "electrolysis water - hydrogen storage - fuel cell" and studied its optimal configuration. Literature [3] connected the power-gas network through the coordination of power-to-gas and gas turbine, and verified that the power-to-gas and peak-filling model could effectively suppress net load fluctuation and improve the system's wind power absorption capacity. Although it is clear in the above literature that P2G equipment can improve the consumption of new energy, it is single for the equipment connecting multiple energy systems with low coupling, and the participation of multiple energy systems in coordination control and optimal dispatch is low.

For user-level integrated energy systems, the most important thing is the conversion of energy sources. The concept of Energy Hub (EH) first proposed by eth Zurich [4] is widely applied in the modeling of integrated Energy systems due to its good abstractness, versatility and scalability. The simple modeling, optimization planning, operation model and solution status of various models of
energy hub are classified and summarized in detail in literature [5]. On this basis, optimization dispatch [6], demand response [7], security assessment and other issues have also been studied, including some models containing P2G module. Literature [8] established an energy center containing P2G equipment, and studied the market equilibrium problem when various energy centers participate in multiple energy markets based on the framework of game theory. Literature [9] constructed a P2G multi-energy system optimization dispatch model, and analyzed the economic benefits generated by power-to-gas conversion to improve the power system’s absorption of wind power energy. At present, however, the model of multi-energy system based on energy hub with electric-to-hydrogen and electric-to-natural gas modules is incoherent. For energy hubs in different scenarios, the model needs to be rebuilt, which increases the modeling time and is not efficient.

For this reason, this paper firstly considered the simultaneous application of power-to-hydrogen and power-to-natural gas in the user-level integrated energy system, and fully considered the coupling characteristics of each equipment, combined with the series characteristics of the energy hub, established a universal multi-energy system model based on the energy hub. In the establishment of constraint conditions and scene analysis, the series characteristics of energy hubs are also made full use of. The purpose is to explore the coupling mechanism and optimal dispatch of energy hub more conveniently and effectively, so that it can play a cooperative role of multi-energy and achieve the optimal utilization of energy.

2. Mathematical model of power-to-gas equipment

2.1. Power to hydrogen energy storage (P2HSS) system

Hydrogen has the advantages of clean, pollution-free, high energy density. The surplus renewable energy is converted into hydrogen and stored in the gas storage device by electrolytic water hydrogen production technology. When the electricity is insufficient, the energy is stored and released by using the fuel cell to consume the hydrogen in the gas storage device to generate electricity. P2HSS system consists of electrolytic water, hydrogen tanks and fuel cells. In the process of water to hydrogen, the relation between the production of hydrogen and oxygen and the input of electric energy is:

\[
\eta_{P2H} = \frac{\eta_{P2H}}{P_{2H}} \frac{P_{2H}}{P_{2H}} \frac{P_{2H}}{HHV} \tag{1}
\]

In the formula: \(P_{2H}\) and \(P_{2H}\) are respectively the rate of hydrogen production by electrolysis of water and the power of electric energy consumption., HHV is the high calorific value of H2, \(\eta_{P2H}\) is the efficiency of H2 generated by P2H equipment.

The relationship between energy production and hydrogen consumption of fuel cells is:

\[
P_{e, FC} = \eta_{e, FC} \frac{P_{e, FC}}{P_{e, FC}} \tag{2}
\]

\[
P_{e, FC} = \eta_{h, FC} \frac{P_{e, FC}}{P_{e, FC}} \tag{3}
\]

In the formula: \(P_{e, FC}\) and \(P_{e, FC}\) are respectively the hydrogen consumption rate and electric energy output power of the fuel cell, \(\eta_{e, FC}\) and \(\eta_{e, FC}\) are the conversion efficiency of electricity and heat generated by the fuel cell.

For the hydrogen storage tank model, it is assumed that the gas storage and exhaust power are constant in time period t. The energy relationship between the equipment before and after charging and discharging[10]:

\[
W_{b, H2}(t) = W_{b, H2}(t-1) + P_{H2} \tag{4}
\]

\[
P_{H2} = \left[ P_{e, H2} \eta_{H2} - \frac{P_{H2}}{\eta_{H2}} (1 - \mu) \right] \times t \tag{5}
\]

In the formula: \(W_{b, H2}(t-1)\) and \(W_{b, H2}(t)\) are respectively the storage energy of the equipment before and after gas storage or gas release; \(P_{H2}\) and \(P_{H2}^{n}\) are respectively the energy stored or released by the
gas storage tank; $\eta_c$ and $\eta_{ch2}$ are the efficiency of gas storage and gas discharge respectively; $\mu$ is the 0-1 variable, 1 and 0 are respectively the inflated state and the deflated state.

2.2. Power to natural gas (P2G) system

P2G is a process that converts electric energy into natural gas, which has fast response and flexible scheduling characteristics. Therefore, the conversion time of this process is not considered, but only the relationship between electrolytic power and gas generation rate is considered:

$$P_{P2G}^e = \eta_{P2G} P_{P2G}^e / \text{HHV}_\text{CH4}$$

In the formula: $\text{HHV}_{\text{CH4}}$ is the high calorific value of CH4, which is 0.0155MWh/m3 in the standard state; $\eta_{P2G}$ represents the efficiency of P2G equipment in generating CH4.

3. Mathematical model of integrated energy system with power-to-gas

The multi-energy system is composed of input of various energy forms, coupling of different energy equipment and various energy requirements. Based on the concept of energy hub, a universal multi-energy system is established in this paper to describe the exchange and coupling relationship between energy, load and network in the system [12], as shown in figure 1. Among them, electric energy and natural gas are two main energy inputs. The coupling equipment includes P2G/P2HSS equipment, micro-gas turbine, boiler, refrigeration equipment and energy storage equipment, etc. Besides, the energy demand is abstracted into three categories: electricity, cold and heat.

![Figure 1. Universal energy hub](image)

The energy hub abstracts the multi-energy system into an input-output two-port network, and the coupling relationship between its internal related components can be described by the coupling matrix:

$$L = CP$$

Among them: $C$ is the coupling matrix; $L$ is the user load at the output end of the energy hub; $P$ is the energy power of the energy hub input.

In order to reflect the serial characteristics of energy supply, conversion, storage and consumption in the energy hub [11], this paper divides the energy hub into four modules: supply, conversion, storage and consumption, and gives a more detailed mathematical description of the energy hub. It can efficiently and quickly increase, decrease and replace the equipment in the energy hub.

4. Optimization dispatch model of integrated energy system with electricity to gas

4.1 The objective function

- Objective function 1: minimum energy cost

$$\min C_{\text{price}} = \sum_{t=1}^{24} C_e(t) P_e(t) + C_g(t) P_g(t)$$
In the formula, $C_e(t)$ and $C_g(t)$ are the electricity price and natural gas price at time $t$, where the electricity price includes the purchase price and the sale price. $P_{e}(t)$ and $P_{g}(t)$ are the grid exchange power and gas consumption volume at time $t$.

- **Objective function 2:** minimum emission of polluting gases
  \[ \min C_{en} = \sum_{t=1}^{24} (\alpha_{e} P_{e}^{i}(t) + \alpha_{g} P_{g}^{i}(t)) \]  

- **Objective function 3:** minimum output of abandoning renewable energy
  \[ \min C_{new} = \sum_{t=1}^{24} \alpha_{new} (P_{new}^{i}(t) - P_{new}^{max}(t)) \]  

- **Objective function 4:** P2G and P2H equipment conversion benefits are the highest
  \[ \min C_{P2G} = \sum_{t=1}^{24} \alpha_{P2G} (C_{e}(t) (P_{P2G}^{e}(t) + P_{P2G}^{g}(t)) - C_{g}(t)) \] 

$C_{en}$, $C_{new}$ and $C_{P2G}$ are respectively used as penalty items for gas emission, new energy abandonment and P2G conversion of profit and loss. They are calculated into the objective function as additional costs in a certain proportion, and $\alpha_{e} \sim \alpha_{t}$ represent penalty factors respectively. Therefore, the total objective function is:

\[ \min C_{price} + C_{en} + C_{new} + C_{P2G} \]  

4.2 **Constraints**

Because the load in the consumption module is abstracted, its constraint is not considered for the time being. For each device in the three modules of supply, transformation and storage as well as the coupling matrix of energy hub, there are the following constraints:

- **Distributed renewable energy component constraints**
  The output of distributed renewable resources is largely influenced by the natural environment.
  The output constraint of distributed renewable energy element $j$ in energy form $c$ is as follows:
  \[ 0 \leq P_{c,\text{out}}^{j}(t) \leq P_{c,\text{out}}^{\text{max}} \]  

  Among them, $P_{c,\text{max}}^{\text{out}}$ represents the maximum possible output of a renewable energy element with respect to energy form $c$ at time period $t$.

- **Energy conversion element constraints**
  Such constraints exist in all equipment participating in energy flow conversion in each module of the energy hub, including P2G, P2HSS system, micro-gas turbine, electric refrigerator, etc. Suppose the input and output energy forms of element $i$ are $a$ and $b$ respectively. The input and output relationship of the energy conversion element is:
  \[ P_{a,\text{out}}^{i}(t) = \eta_{i} P_{b,\text{in}}^{i}(t) \]  

  Where, $\eta_{i}$ is the performance coefficient of element $i$, and the coefficient of energy conversion element in this paper is constant maturity.

  The input and output of conversion elements both have upper and lower limits. Take the input as an example, its constraint is:

  \[ P_{a,\text{min}}^{\text{in}} \leq P_{a,\text{in}}^{i}(t) \leq P_{a,\text{max}}^{\text{in}} \]  

  Where, $P_{a,\text{min}}^{\text{in}}$ and $P_{a,\text{max}}^{\text{in}}$ respectively represent the upper and lower limits of input and output power of the conversion element $i$ regarding the energy form $a$.

- **Storage device constraint**
The storage equipment includes gas storage tank, hydrogen storage tank and heat storage tank. Take the gas storage tank as an example, the rated capacity of energy storage and the restriction of exchange power should be met at the same time.

Air storage tank filling and discharging constraints:
\[
0 \leq P_{ch} \leq P_{ch}^c \eta_{ch}^c
\]
\[
0 \leq P_{ch}^{dis} \leq P_{ch}^{dis} / \eta_{ch}^{dis}
\] (16)

Rated capacity constraints of air storage tank:
\[
W_{h\text{,min}} \leq W_h \leq W_{h\text{,max}}
\] (18)

The constraint that the daily net exchange power of gas storage tank is 0:
\[
\sum_{t=1}^{24} (P_{ch}(t) + P_{ch}^{dis}(t)) = 0
\] (19)

In the formula \(P_{ch}\) and \(P_{ch}^{dis}\) are respectively the energy stored or released by the heat storage tank; \(\eta_{ch}\) and \(\eta_{ch}^{dis}\) are respectively the efficiency of electricity storage and discharge. \(W_{h\text{,min}}\) and \(W_{h\text{,max}}\) are the largest and small energy storage tank.

5. Analysis of examples
This paper takes the integrated energy system shown in figure 1 as an example. Among them, the predicted maximum output of new energy and the typical daily load curve of the system are shown in appendix A, FIG. A1 and FIG. A2 respectively. Natural gas price is fixed at 3.3 元/m³; Electricity price adopts peak and valley electricity price, including purchase price and sale price, see appendix A, figure A3 for details; The conversion efficiency coefficients of each equipment are shown in table A1 of appendix A.

5.1 P2HSS module behavior analysis
P2HSS plays the role of energy storage in the integrated energy system in this paper. When the electricity price is low and the electric load is small, P2H works to convert electric energy into hydrogen and store it in the hydrogen storage tank. When the electricity price is high and the electricity demand is large, the hydrogen storage tank releases hydrogen to supply the fuel cell, and generates heat at the same time of discharge, as a supplement to the electric heating load. The optimized working status of P2HSS system is shown in figure 2:

![Figure 2. P2HSS system working status](image)

When P2H works, the hydrogen storage tank stores hydrogen (negative), while the fuel cell needs the hydrogen storage tank to release hydrogen (positive). It can be seen from figure 3 that the working state of P2HSS system is related to the price of electricity. P2H works at 3 hours and 7 hours of low electricity price, and 15-19 hours and 21-24 hours of flat electricity price, converting electric energy
into hydrogen and storing it in hydrogen storage tank. The stored hydrogen is used to supply fuel cells for power generation at peak electricity prices or during heavy electrical loads (11-12 hours, 14-16 hours, 19-22 hours). It can cut the peak and fill the valley, relieve the peak of electricity consumption and ensure the economy of the system.

5.2 Optimization dispatch results analysis

Figure 3-6 shows the balance of supply and demand of electricity, gas, heat and cold energy respectively. As shown in FIG. 3, the all-day micro-gas turbine is in a stable output state, and the output of the fan and the photovoltaic power supply are coordinated and fully utilized. At night, the wind resource is abundant and the fan output is relatively high. During the day, the sunlight resource is abundant and the photovoltaic output is obvious. The output of the above three kinds of equipment can basically meet the basic demand of electric load, and the fluctuation compensation and economic arbitrage of electric energy are responded by the power grid, P2G, P2H, fuel cell, electric boiler and electric refrigerator. In the valley electricity price (1am-8am), with abundant resources and favorable electricity price, the output of the fan and the micro-gas turbine can meet the electricity load demand, and P2G equipment is in working state, which can improve the conversion benefit of P2G. In peak and flat electricity price (9pm to 24pm), the demand for electric load increases, although microgas turbine and photovoltaic are fully utilized, there is still a large amount of shortage, which is satisfied by the power grid and supplemented by a small amount of fan output. In addition, the working status of P2HSS system has been analyzed in section 4.1. The existence of this system has improved the economy and stability of the system.

As shown in figure 4, the supply of natural gas is mainly natural gas network, P2G and gas storage tank playing a certain regulating role.

As shown in figure 5, the micro-gas turbine is used as the main output to meet the demand of thermal load, and a large amount of heat is used for the lithium bromide refrigerating machine to meet the demand of cooling load in summer. The micro-gas turbine is always in full steam. When the thermal load is high, the insufficient thermal energy will be made up by other equipment, and the selection of equipment is greatly affected by the electricity price. In the flat price, the use of electric boiler is more economical, but in the peak price, the system chooses to use gas boiler and heat storage tank to make up.

As shown in figure 6, the equipment that can meet the cooling load is relatively simple, mainly lithium bromide refrigerating machine. Only when the cooling load is high and the lithium bromide refrigerating machine cannot meet the cooling load, will it be supplemented by the electric refrigerating machine.

![Figure 3. Balance of power supply and demand](image-url)
Figure 4. Natural gas balance

Figure 5. Balance between supply and demand of thermal energy

Figure 6. Cold energy supply and demand balance

6. Conclusions
This paper analyzes the electrolytic hydrogen, hydrogen storage and fuel cell electric convert the applicability of the energy storage system (P2HSS), use of systemic energy hub modeling method to construct an integrated energy system model which includes four modules: supply, conversion, storage and consumption. The working status of P2HSS in this system is emphatically analyzed, and the optimized dispatch results of this integrated energy system are also analyzed. Examples show that
P2HSS system can effectively reduce peak-valley difference and improve the economic benefits of the system. The integrated energy system has the characteristics of economy, environmental protection, safety and stability.

This paper focuses on the modeling and analysis of a single energy hub. In the future, the multi-energy system of multiple regions will be further studied. Considering the complementarity of different regional loads, the energy utilization efficiency will be further improved to achieve the overall optimization.

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