Electricity-heat-hydrogen Modelling of Hydrogen Storage System considering Off-design Characteristics

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ABSTRACT With the advantages of zero carbon emission and multi-energy comprehensive utilization, hydrogen storage is the pivotal technology to help realize the goal of net-zero carbon and establish a new energy system. Combining the simple linear model and the complex mechanism model, this paper proposes an electricity-heat-hydrogen model of the hydrogen storage system considering off-design characteristics. In the proposed off-design hydrogen storage system (OD-HSS) model, critical operating variables like input power and electrolyte temperature are included to achieve a compromise between practicability and accuracy. Furthermore, the proposed OD-HSS model is applied to practical scheduling to verify its advantages in accuracy and practicality through the case studies. The results indicate that the proposed OD-HSS model managed to depict the efficiency changes under different circumstances, promote flexibility in heat storage, and lead to a more economical energy supply.

INDEX TERMS electricity-heat-hydrogen modeling, hydrogen storage system, multi-energy comprehensive utilization, off-design characteristics, optimal scheduling

I. INTRODUCTION

UNDER the development goal of net-zero carbon, clean and low-carbon energy supply is becoming the primary development trend for the energy system [1]. As a type of new clean energy featured with no pollution, no carbon emission, and high calorific value, hydrogen is considered as a significant energy type to realize “carbon neutral” [2], [3]. Hydrogen storage system (HSS), consisting of the electrolytic cell (EL), the fuel cell (FC), and the hydrogen storage tank (HT), is hopeful to become the multi-energy conversion hub in the future multi-energy systems, owing to the advantages of multi-energy utilization and low carbon emission. The modeling and scheduling of the HSS are increasingly becoming the current research hotspot [4], [5].

As for research on the scheduling of the HSS, the simple linear model is widely used, using a linear efficiency constant to describe the relationship between the input power and output power. The simple linear model is used to solve the scheduling strategy for the HSS in the market in [6]. In [7], the simple linear model is also applied to solve the optimal integrated scheduling for the HSS, wind turbines, and nuclear power plants. In [8], using the simple linear model of electrolytic cell and fuel cell, the method of planning and operation for HSS in the regional multi-energy system is studied. The simple linear model of the electrolytic cell is used in [9] to solve the optimal scheduling strategy of the HSS considering demand response. Such a model is also applied to analyze abandoned wind power consumption benefits of the HSS in [10]. In [11], a linear multi-energy model for HSS is proposed and further used to solve optimal operation strategy for the electro-thermal hybrid system. Based on the simple linear model of electrolytic cell and fuel cell respectively, optimal real-time operation strategy and energy sharing policy is proposed in [12] and [13]. Some researchers tentatively
consider the off-design characteristics for part of the HSS, paying attention to a certain device or a certain energy type instead of the whole system. In [14] and [15], approximately linear correlation between output power and the electrolyte temperature for the electrolytic cell is proposed for hydrogen-battery integrated scheduling and seasonal hydrogen storage scheduling, respectively. Despite the advantages of simple form and fast solution, there exist two disadvantages for the simple linear model. One is poor accuracy, unable to reflect the efficiency change under different operating conditions, and thus causing significant deviation in practical scheduling. The other is lack of consideration for multi-energy coupling characteristics, following the mode of fixing heat based on power and neglecting the independent, flexible, and economical scheduling for heat supply and storage.

In order to overcome the disadvantages above, some researchers consider the complex mechanism model for the HSS, containing a multitude of parameters and complex nonlinear relations. The nonlinear volt-ampere characteristic equation of fuel cell is used in [16], to solve optimal operation strategy for grid-connection HSS, where particle swarm optimization and genetic algorithm are used for optimization solution. Combined with the complex mechanism model of electrolytic cell and fuel cell, optimal control theory is applied in the optimization solution of optimal scheduling strategy for a multi-energy system in [17], Coyote optimization algorithm and teacher learning algorithm are respectively used to optimal scheduling polity solution for HSS considering nonlinear mechanism model in [18] and [19]. Based on the complex mechanism model considering multi-energy coupling characteristics, piecewise linearization is adopted in [20] and [21], to approximately solve optimal scheduling strategy for the electrolytic cell and inter-module scheduling strategy for electrolytic cell modules, respectively. Nonetheless, many parameters in the complex mechanism model are hard to collect in practical engineering and complex nonlinear relation is inconvenient and restricted owing to its solution difficulty.

To sum up, the current simple linear model neglected the efficiency change under different operating conditions and flexible scheduling for heat supply and storage, while the complex mechanism model, featured with difficult form and restricted application, is incompetent to deal with the disadvantages above in practical scheduling. To settle these problems, this paper pays attention to critical operating condition variables such as the input power and the electrolyte temperature and proposes the multi-energy model of the HSS considering the off-design characteristics. The main contributions are as follows.

1) The off-design characteristics of the electrolytic cell and the fuel cell are analyzed by simulation data based on the complex mechanism model. The influence of the electrolyte temperature and the input power on the energy conversion efficiency is evaluated.

2) Based on the analysis of the off-design characteristics, the multi-energy off-design hydrogen storage system (OD-HSS) model is proposed considering critical operating variables of the electrolyte temperature and the input power. The OD-HSS model is formulated through simplification fitting based on simulation data, to achieve a compromise between accuracy and simple form.

3) The advantages of the OD-HSS model are quantitatively evaluated in practical scheduling. The accuracy, flexibility, and economy of the OD-HSS model in practical scheduling are verified through case studies.

The rest of the paper is arranged as follows: Section 2 introduces the structure and operation mode of a multi-energy system containing the HSS. Section 3 analyzes the off-design characteristics of the HSS, based on which the OD-HSS model is proposed in section 4. The case studies are discussed and analyzed in section 5 following by the conclusions in section 6.

II. STRUCTURE AND OPERATION MODE OF A MULTI-ENERGY SYSTEM WITH HSS

The structure of a multi-energy system containing the HSS is shown in Fig.1. A multi-energy system consists of local clean energy generation and diverse types of load, including electrical load, heat load, and hydrogen load. The HSS (i.e. the part in the dotted box in Fig.1) is a subsystem acting as the multi-energy conversion hub in the multi-energy system, comprehensively supplying diverse types of load. In addition, the multi-energy system is connected to the power grid and the heat network, able to purchase electricity and heat from outside to fill the gap of load.

The three parts of the HSS, i.e. electrolytic cell, hydrogen storage tank, and hydrogen fuel cell, are used for hydrogen production, storage, and consumption. Based on the principles of electrolysis of water, the electrolytic cell is used to transform electricity into hydrogen energy. Meanwhile, hot water acts as the heat-conducting medium to participate in heat network circulation via the heat exchanger. The hydrogen storage tank is used to compress produced hydrogen and store it in the form of compressed gas. The hydrogen fuel cell realizes the inverse process of the electrolytic cell, by electrical-chemical reaction between Hydrogen and air (oxygen) in its electrolyte. Similarly, in the meantime, part of the energy can be also utilized to supply heat via the heat exchanger in the type of hot water.

The operation mode of the hydrogen storage subsystem is flexible, mainly four types as below. (i) Electrolytic cell transforms electricity into hydrogen. (ii) Fuel cell transforms hydrogen into electricity. (iii) Electrolytic cell or fuel cell stores heat by raising the electrolyte temperature. (iv) Electrolytic cell or fuel cell supplies heat by lowering the electrolyte temperature. As should be noticed, type (iii) and type (iv) are based on the fact that storing or supplying thermal power and electrolyte temperature can be controlled by certain means [15]. The type (iii) or (iv) can be flexibly combined with the type (i) and (ii). However, the traditional linear model neglects the flexible mode of supplying or

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storing heat, usually following the mode of fixing heat based on power.

In the multi-energy system, the HSS acts as the energy conversion hub, for the mutual transformation and joint storage/supply of electricity heat and hydrogen. Accordingly, local clean energy like wind and solar power can be fully consumed to optimized energy purchase and system operation. Furthermore, electricity, heat, and hydrogen can be efficiently and comprehensively utilized in the energy system.

III. ANALYSIS ON THE OFF-DISIGN CHARACTERISTICS OF HSS

A. ELECTROLYTIC CELL CHARACTERISTICS ANALYSIS

In the complex mechanism model of the electrolytic cell, equations of electrochemical characteristics and hydrogen production rate are as follows:

\[
U = n_c(U_{rev}^0 - k_{re}v(T - T_{ref}) + r_1 + r_2T/S + k_{elec}\ln\left(\frac{k_1 + k_2 + k_3I}{S}\right) + 1))
\]

\[
q_{H2} = \frac{(\frac{1}{2})^2}{(\frac{1}{2})^2 + k_{f2}^2}k_{f2}n_cI/2F
\]

where \(U\), \(I\), \(T\), \(S\) are input voltage, input current, electrolyte temperature, and exchange membrane area, respectively. \(U_{rev}^0\) is the reversible voltage for water electrolysis, whose value is about 1.23V. \(k_{re}v\) is the temperature characteristics parameter, while \(r_1\), \(r_2\) are resistance characteristic parameters. \(k_{elec}\), \(k_1\), \(k_2\), \(k_3\) are parameters related to both temperature and current. \(q_{H2}\) (mol/h) are rate for hydrogen production. \(F\) is Faraday constant, whose value is 96486C/mol. \(k_{f1}\), \(k_{f2}\) are parameters related to hydrogen production characteristics.

The mechanism model contains many detailed parameters and variables, most of which are not critical and hard to achieve. In practical engineering, the input power or output power is more noteworthy. Based on (1)–(2), as well as parameters in [22], the relations between input power and output power of the electrolyte cell under different electrolyte temperatures are simulated, shown in Fig.2. Input-output relation is approximately linear in a large interval, as shown in Fig.2(a). Besides, illustrated in Fig.2(b), the electrolyte temperature has a certain influence on the output power, causing an overall offset of the input-output curve.

B. FUEL CELL CHARACTERISTICS ANALYSIS

The basic electrochemical characteristic equation of proton exchange membrane fuel cell is shown as follows.

\[
U_{fc} = U_{nstat} - U_{act} - U_{ohm} - U_{con}
\]

\[
U_{nstat} = \frac{\Delta G}{2F} + \frac{\Delta S(T - T_{ref})}{2F} + R_aT\ln(P_{H2}/P_{O2})^{1/2}
\]

\[
U_{act} = k_1 + k_2T + k_3T\ln(C_{O2}) + k_4T\ln i
\]

\[
U_{ohm} = l((\frac{Im}{d}) + R_c)
\]

\[
U_{con} = me^{\frac{R_a}{d}}
\]

As for thermodynamic characteristics, the energy conservation equation of the electrolytic cell is shown in (3).

\[
C_{el}\frac{dT_{el}(t)}{dt} = P_{el}(t) - M_{el}(t) - \frac{T_{el}(t) - T_a}{R_{el}} - H_{el}^{cool}(t)
\]

where \(C_{el}\), \(R_{el}\) are thermal capacity and thermal resistance, respectively. \(C_{el}\frac{dT_{el}(t)}{dt}\) and \(T_{el}(t) - T_a\) are respectively the heat-absorbing power of the electrolyte and heat power loss. \(H_{el}^{cool}(t)\) is the heat absorption power of circulating water in the electrolytic cell, which can be used for both-way heat exchange with heat network via the heat exchanger. However, in the simple linear model, the temperature change is usually ignored so that the thermal power is in proportion to electrical power, which reduces the flexibility of the scheduling.

The temperature change of the electrolyte cell will cause the overall offset of the electrochemical characteristics curve and can be regulated to realized both-way heat exchange, which is neglected by the simple linear model.
activation overpotential. \( r_M \) and \( R_C \) are empirical constants for resistivity and resistance. \( m \) and \( n \) are empirical constants related to concentration overpotential.

Similar to the electrolytic cell, the mechanism model of the fuel cell pays attention to the detailed electrochemical process, which is not as critical in practical engineering as the input or output power. Similarly, the relations between input power and output power of fuel cell under different electrolytic temperatures are simulated and illustrated in Fig.3, based on (4) and parameters in [19]. Output power increases with the increase of input power, with the rate decreasing. In Fig.3 (b), the electrolyte temperature has a certain influence on the output power, and different from the electrolytic cell, the influence increases with the increase of input power.

As for thermodynamic characteristics, the energy conservation equation of the fuel cell is shown in (5).

\[
C_{fc} \frac{dT_{fc}(t)}{dt} = M_{fc}(t) - P_{fc}(t) - \frac{T_{fc}(t) - T_a(t)}{R_{fc}} - H_{cool}(t)
\]

where \( C_{fc} \) and \( R_{fc} \) are thermal capacity and thermal resistance, respectively. \( C_{fc} \frac{dT_{fc}(t)}{dt} \) and \( R_{fc} \) are respectively the heat absorbing power of the electrolyte and heat power loss. \( H_{cool} \) is heat absorption power of circulating water in the electrolytic cell. Equation (5) is similar to (3), with temperature neglected in the simple linear model.

The temperature change of the fuel cell will influence the electrochemical characteristics curve and can be regulated to realized both-way heat exchange, similar to the electrolytic model. Besides this neglect in the simple linear model, the nonlinear relationship between input power, output power, and electrolytic temperature is also significant, which should also be considered for accurate modeling.

IV. MULTI-ENERGY MODELING OF HSS CONSIDERING OFF-DESIGN CHARACTERISTICS

A. OFF-DESIGN MODELING OF THE HSS

Based on the conclusions from the characteristics analysis of the electrolytic cell and the fuel cell, the influence of the temperature change should be considered in the OD-HSS model. Besides, to fit the practical engineering, the OD-HSS model should pay attention to the input and output power instead of detailed variables. Nonlinear relations should also be taken into account.

As for the electrolytic cell, owing to the approximately linear relationship between the input power and output power, as well as the overall offset caused by the temperature change, linear items of the input power and the electrolytic temperature are considered. Without loss of generality, each item should be given in the per-unit form, and thus the electrochemical characteristics of the electrolytic cell can be formulated into:

\[
\frac{M_{fc}(t)}{P_{fc}^{ref}} = \eta_{fc} + \varepsilon_{fc} - \frac{T_{fc}(t) - T_{ref}^{ref}}{T_{ref}^{ref}}
\]

where \( M_{fc}(t) \), \( P_{fc}(t) \) are real-time hydrogen output power and electrical input power of the electrolytic cell. \( \eta_{fc} \) and \( \varepsilon_{fc} \) are fitting coefficients for power item and temperature item. \( T_{fc}(t) \) is the electrolyte temperature. \( P_{fc}^{ref} \) and \( T_{ref}^{ref} \) are basic values for power and temperature.

It should be noted that as for the fitting problem, the input power and the electrolyte temperature are taken as the independent variables, and the output power is taken as the dependent variables. The results of the fitting coefficients are achieved by minimizing the mean relative error between the real output power and the calculated output power from (6).

The mean relative error for the form of (6) is 1.46%, which is small enough and acceptable.

Instead of neglecting the temperature change and heat loss in the simple linear model, the paper considers these two terms above as well as the energy loss via the heat exchanger. Thus, the thermodynamic characteristics of the electrolytic cell can be formulated into:

\[
\frac{H_{out}^{ref}(t)}{\eta_h} - \frac{H_{in}^{ref}(t)}{\eta_h} = P_{fc}(t) - M_{fc}(t) - \frac{T_{fc}(t) - T_a(t)}{R_{fc}} - C_{el} \frac{T_a(t + 1) - T_{fc}(t)}{\Delta t}
\]

where, \( H_{out}^{ref}(t), H_{in}^{ref}(t) \) are real-time power for heat release and heat absorption, respectively. \( \eta_h \) is the efficiency of heat exchange, while \( \Delta t \) is time step for scheduling.

As for the fuel cell, the input-output relation is significantly nonlinear, and the influence of the electrolytic temperature increases with the increase of the input power. Therefore, the electrochemical characteristics of the fuel cell can be fitted by a quadratic function including a quadratic term of input power with a negative coefficient and a linear term between input power and electrolytic temperature. Similar to (6), the electrochemical characteristics of the fuel cell is also formulated in the per-unit form, as shown in (8).

\[
\frac{P_{fc}(t)}{P_{fc}^{ref}} = \beta_{fc} \frac{M_{fc}(t)}{P_{fc}^{ref}} + \eta_{fc} + \alpha_{fc} \frac{T_{fc}(t) - T_{ref}^{ref}}{T_{ref}^{ref}}
\]

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where \( P_{fc}(t) \), \( M_{fc}(t) \) are real-time output electrical power and input hydrogen power, respectively. \( \eta_{fc}, \alpha_{fc}, \beta_{fc} \) are coefficients for the linear term of power, bilinear term of power and temperature, and quadratic term of power respectively. \( T_{fc}(t) \) is the electrolyte temperature. \( P_{fc}^{ref} \) and \( T_{fc}^{ref} \) are basic values for power and temperature.

It is obvious that the fitting problem of (8) is similar to (6). The mean relative error for the form of (8) is 0.52%, which is so tiny and means the fitting equation (8) enjoys high accuracy. Further, simpler fitting equations are also tested. When the bilinear term of power and temperature is ignored from (8), the mean relative error is 3.31%. When the quadratic term of input power is ignored from (8), the mean relative error is 11.72%. It is obvious that bilinear term or quadratic term cannot be ignored, and (8) is the most simple fitting equation under enough accuracy.

Similar to (3) and (7), the thermodynamic characteristics of the fuel cell can be transformed into (9) from (5).

\[
\frac{\Delta t}{\eta_{fc}} - \eta_{t} H_{fc}^{in}(t) = P_{fc}(t) - M_{fc}(t) \\
- T_{fc}(t) - T_{\alpha}(t) - C_{fc} T_{fc}(t + 1) - T_{fc}(t) \\
R_{fc} \Delta t
\]

(9)

where \( H_{fc}^{out}(t) \) and \( H_{fc}^{in}(t) \) are real-time power for heat release and heat absorption, respectively.

Besides the electrolytic cell and the fuel cell, the last part in the HSS, i.e. the hydrogen storage tank is not involved in the multi-energy transformation. So the basic equation in the simple linear model can be followed, as shown below:

\[
\frac{S_{ht}(t + 1) - S_{ht}(t)}{\Delta t} = \eta_{ht} M_{ed}(t) - \frac{M_{fc}(t) + M_{id}(t)}{\eta_{ht}^{out}}
\]

(10)

where \( S_{ht}(t) \) is real-time stored energy in the hydrogen storage tank, and \( M_{id}(t) \) is the real-time power of hydrogen load. \( \eta_{ht}^{in} \) and \( \eta_{ht}^{out} \) are efficiency of hydrogen absorption and release.

To sum up, the proposed joint model for the HSS is composed of (6)~(10). Aside from two variables of electrolytic temperature, all variables are power variables. Through common power variables, characteristics equations of the certain energy type or the certain device are integrated into an entirely joint model for the HSS.

**B. OFF-DESIGN CHARACTERISTICS ANALYSIS OF THE OD-HSS MODEL**

Different from the simple linear model, the proposed joint model for the HSS fully considers the off-design characteristics, since the OD-HSS model is fitted based on simulated data at a large interval. Equations (6) and (8) manage to describe the influence of operating conditions on energy conversion efficiency between hydrogen energy and electricity. Two critical operating variables, the input power, and the electrolyte temperature are considered in the OD-HSS model.

According to (6) and (8), the influence of the input power on energy conversion efficiency is fully characterized. For the electrolyte cell, the influence is slight, as shown in Fig.2, and thus, the relationship between input power and output power is approximately linear in (6). However, for the full cell, the influence is significant, with the efficiency decreasing with the increase of the input power, as illustrated in Fig.3. Correspondingly, the relation between output power and input power is a quadratic function with negative coefficients in (8), reflecting the off-design characteristics with the change of the input power.

The influence of electrolyte temperature on energy conversion efficiency is also considered in (6) and (8). The electrolyte temperature change causes the overall shift of the input-output curve in Fig.2, and therefore, a linear item of electrolyte temperature is used in (6) to describe such an overall shift. The influence of the electrolyte temperature for the fuel cell is slightly complex, with the influence increasing with the increase of the input power. Therefore, a bilinear item of the input power and the electrolyte temperature is contained in (8) to reflect the influence of the temperature under different input power.

Equations (7) and (9) describe the influence of operating conditions on characteristics of heat supply and heat storage. Different from the mode of “fixing heat based on power” in the simple linear model, even if the electrical power and hydrogen power are fixed, thermal power can still be independently and flexibly regulated by adjusting electrolyte temperature. Objectively, both-way heat exchange and heat storage can be achieved by the electrolytic cell and the fuel cell.

**C. ENERGY COUPLING CHARACTERISTICS ANALYSIS OF THE OD-HSS MODEL**

Besides considering off-design characteristics, the OD-HSS model is also formulated in the type of a multi-energy model, to integrate three parts of the HSS and three types of energy. For each part of the HSS (the electrolytic cell, the hydrogen storage tank, or the fuel cell), the input and output variables are all power. Other operating variables include temperature (the electrolyte temperature of the electrolytic cell and the fuel cell) and energy (the stored hydrogen energy in the hydrogen storage tank).

Equations (6)~(9) describe the characteristics of both-way energy supply in the form of electricity and heat. Equation (10) and Equations (8)~(9) respectively describe the characteristics of energy storage in the medium of hydrogen and heat. The power of electricity, heat, and hydrogen are integrated via the rate of change of the stored energy in the medium of hydrogen and heat, i.e. \( C_{ht} T_{ht}(t) \), \( C_{fc} T_{fc}(t) \), and \( S_{ht} \) in (8)~(10). Thus, the OD-HSS model is characterized by multi-energy supply and storage.

All equations except (9) are linear. Equation (9) can be approximately linearized by introducing new binary variables, and thus the joint model can be transformed into a mixed-integer linear equation. Compared to the complex mechanism...
model, the OD-HSS model is more convenient to solve the optimal scheduling problem under different operating conditions.

V. CASE STUDIES

A. PARAMETERS OF CASE STUDIES

A real multi-energy system containing the HSS is chosen as the case study. The data of clean energy and load in a scheduling period is shown in Fig.4.

The electricity purchase price, heat purchase price, and environmental temperature are shown in Fig.5. The hydrogen purchase price is 0.924 RMB/kWh, i.e. 35.9 RMB/kg.

The capacity of the electrolytic cell, fuel cell, and hydrogen storage tank are respectively 200kW, 100kW, and 1000kWh. The OD-HSS model and the simple linear model are respectively used for optimal scheduling.

B. ACCURACY EVALUATION OF THE OD-HSS MODEL

To verify the accuracy of the OD-HSS model, the simulation data using the OD-HSS model and the simple linear model are respectively compared to the reference data by calculating the relative errors. The reference data is calculated from the OD-HSS model.

The efficiency fluctuation and causes the overestimation of the efficiency fluctuation for the fuel cell under different working conditions. The efficiency of the fuel cell keeps a high level of output power most of the time in its operating period, the mean efficiency (57%) is relatively lower than the efficiency constant (66%) in the simple linear model. The efficiency presents a significant fluctuation, with the relative error for the simple linear model reaches about 20%. Even for the same input power, the output power relative error under different electrolyte temperatures is up to 10%.

Based on the reference data, the fitting results of the OD-HSS model are summarized in Tab.1. For convenient comparison, the linear efficiency constant of the simple linear model adopts the calculated efficiency results from the OD-HSS model under the circumstances that the input power and the electrolyte temperature are set as the interval middle value.

The output power relative errors of the OD-HSS model and the simple linear model are demonstrated in Fig.6, with the input power varies from 40% to 100% of the rated power. In Fig.6(a), since the OD-HSS model has considered the influence of the electrolyte temperature on output power, the relative error is slight. In contrast, the relative error is great at a certain temperature in Fig.6(b) for the simple linear model. Only when the output power is relatively lower, the relative error for both models are relatively greater, but the relative error of the OD-HSS model varies from -1.5% to 1.5% in a large interval. The OD-HSS model for the electrolytic cell enjoys high accuracy.

The relative error for the output power of the fuel cell is shown in Fig.7. In Fig.7(a), having considered the nonlinear correlation between the electrolyte temperature, the input power, and the output power, the OD-HSS model keeps high accuracy in the whole interval. In contrast, owing to just considering linear input-output correlation, the simple linear model only keeps accuracy at several working points in Fig.7(b). When the output power is very high or low, the relative error for the simple linear model reaches about 20%. Even for the same input power, the output power relative error under different electrolyte temperatures is up to 10%.

As for the efficiency fluctuation in the scheduling results, the efficiency in each hour for the electrolytic cell and the fuel cell are set as 20%~100% of the rated power, while the electrolyte temperature varies between 60°C and 100°C.

Based on the reference data, the fitting results of the OD-HSS model are summarized in Tab.1. For convenient comparison, the linear efficiency constant of the simple linear model adopts the calculated efficiency results from the OD-HSS model under the circumstances that the input power and the electrolyte temperature are set as the interval middle value.

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As for the efficiency fluctuation in the scheduling results, the efficiency in each hour for the fuel cell is shown in Fig.8. In Fig.8(a), the OD-HSS model fully depicts the efficiency fluctuation for the fuel cell under different working conditions. The efficiency of the fuel cell increases with the increase of the electrolyte temperature and the decrease of the input power. Thus, as the fuel cell keeps a high level of output power most of the time in its operating period, the mean efficiency (57%) is relatively lower than the efficiency constant (66%) in the simple linear model. The efficiency presents a significant fluctuation, with the range up to 32%. The simple linear model neglects the efficiency fluctuation and causes the overestimation of the efficiency. On the contrary, the OD-HSS model reflects the efficiency fluctuation and corrects the overestimation of the efficiency, which can be used for more accurate multi-energy scheduling.

There just exists slight efficiency fluctuation for the elec-
The total cost of the multi-energy system containing the HSS is 2380.7 RMB when the proposed OD-HSS model is used, while that for the simple linear model is 2749.0 RMB. The daily cost under optimal scheduling reduces by 13.4% with the proposed OD-HSS model. It should be noted that the main cost of the multi-energy system lays in purchasing the electricity and heat, and heat purchase makes up the main cost of the multi-energy system.

C. PRACTICALITY EVALUATION OF OD-HSS MODEL

To verify the practicality in the practical scheduling, the OD-HSS model and the simple linear model are used for optimal scheduling. The energy and cost in a scheduling period are summarized in Tab.2.

The causes of its flexibility and economy can be inferred from Fig.9 and Fig.10, which illustrate thermal balance in a scheduling period using the OD-HSS model and the simple linear model.

Both the electrolytic cell and the fuel cell have two cycles in a scheduling period in Fig.9. When the heat purchase price is lower (1:00~5:00 and 13:00~17:00), they absorb heat from the heat network and store it in their electrolyte, with electrolyte temperature rising. When the heat purchase price is higher (6:00~12:00 and 18:00~22:00), they release heat to the network.
heat to the heat network and satisfy the thermal load, with electrolyte temperature lowering. The change of heat power of the electrolytic and the fuel cell is highly correlated to the heat purchase price instead of electrical power or hydrogen power. By regulating the electrolyte temperature, the heat power can be flexibly controlled to achieve a more economic heat supply.

In contrast, the both-way heat exchange is ignored using the simple linear model, as shown in Fig.10. Owing to the model of “fixing heat based on power” in the simple linear model, the heat power from the electrolytic cell and the fuel cell is independent of the heat purchase price, and determined by the hydrogen power or electrical power. Due to neglecting off-design characteristics, the heat supply cannot be flexibly regulated. When the heat purchase price is higher (8:00~12:00, 18:00~22:00), less heat is supplied but more heat is purchased. Similarly, when the heat purchase price is lower (0:00~5:00, 13:00~17:00), more heat is supplied but less heat is purchased. With higher heat produced and less heat purchased, the economy of the heat supply using the simple linear model is inferior.

The change of electrolyte temperature illustrated in Fig.11 further confirms the analysis of Fig.9. Using the proposed OD-HSS model, the electrolyte temperature in the electrolytic cell and fuel cell are directly correlated in the heat purchase price, displaying two cycles in a scheduling period. When the heat purchase price is higher (e.g. 6:00~12:00 and 18:00~22:00), the temperature decreases to supply the heat. When the heat purchase price is lower (e.g. 0:00~5:00 and 13:00~17:00), the temperature increases to store the heat. In contrast, the simple linear model neglects the change of the electrolyte temperature, ignoring the flexible heat supply and storage of the HSS.

The thermal balance of the multi-energy system using the proposed OD-HSS model is illustrated in Fig.12. Combining Fig.11 and Fig.12, the flexibility in integrated scheduling of electricity and heat can be clearly demonstrated.

In Fig.12, the electrolytic cell produces quantities of hydrogen for storage using abundant wind power and cheap purchased electricity from 0:00 to 7:00, and a small amount of hydrogen using abundant clean energy during 13:00~14:00, 16:00~18:00 and 23:00~24:00. The fuel cell provides electricity during peak times like 8:00~12:00 and 18:00~22:00, supplying the load when the clean energy is short. It should be noticed from equations (3) and (7) that, the efficiency has a positive correlation with the electrolyte temperature. Therefore, during the first cycle (about 5:00, the main operating period for the electrolytic cell) in Fig.11, the electrolyte temperature in the electrolytic cell keeps relatively high to ensure the high efficiency of electricity production. Similarly, during the second cycle (about 19:00, the main operating period for the fuel cell), the electrolyte temperature in the fuel cell keeps relatively high to ensure high efficiency of hydrogen production. Considering the influence of the electrolyte temperature, the proposed OD-HSS model can be used in practical scheduling to achieve efficient energy supply by regulating input power and electrolyte temperature.

To sum up, by considering the influence of the input power and the electrolyte temperature on the energy conversion efficiency between electricity and hydrogen, the proposed OD-HSS model avoids the model of “fixing heat based on power” in the simple linear model. The heat supply and heat storage can be independently and flexibly regulated according to heat purchase price. Besides, electricity and
hydrogen can also be efficiently transformed and supplied by regulating electrolyte temperature. The OD-HSS model can be used for more flexible and economical multi-energy scheduling.

**VI. CONCLUSION**

To achieve a compromise between accuracy and practicality in the modeling of the HSS, this paper analyzed the off-design characteristics of the electrolytic cell and the fuel cell and evaluated the influence of input power and electrolyte temperature on energy conversion efficiency. Furthermore, a multi-energy model for the HSS is proposed, considering the off-design characteristics. Three types of energy, i.e., electricity, hydrogen, and heat, and three parts of the HSS are integrated into the OD-HSS model. Applied in the practical scheduling, the advantages of the OD-HSS model are validated and demonstrated as below:

1) The OD-HSS model is convenient in practical scheduling, compared with the complex mechanism model. The simple form is easy for linearization and quick optimization. Besides, the model focuses on critical operating variables like power rather than the detailed process, and the parameters can be easily fitted using practical data.

2) The OD-HSS model also shows high accuracy under wide operation conditions. The OD-HSS model described the dispersion of efficiency under different operating conditions and efficiency decline under conditions of high input and low temperature. The fixed and optimistic estimation of efficiency in the simple linear model is corrected, and thus the model is more suitable for practical engineering.

3) The OD-HSS model has good flexibility and can effectively improve the scheduling economy. Independent electricity and heat supply can be realized to a certain extent. The ability to store and supply heat of the HSS can be fully utilized. Compared to the phenomena of fixing heat based on power in the simple linear model, the OD-HSS model is capable of flexible and economical scheduling.

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