Coordinated Control of a Wind-Methanol-Fuel Cell System with Hydrogen Storage

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Abstract: This paper presents a wind-methanol-fuel cell system with hydrogen storage. It can manage various energy flow to provide stable wind power supply, produce constant methanol, and reduce CO2 emissions. Firstly, this study establishes the theoretical basis and formulation algorithms. And then, computational experiments are developed with MATLAB/Simulink (R2016a, MathWorks, Natick, MA, USA). Real data are used to fit the developed models in the study. From the test results, the developed system can generate maximum electricity whilst maintaining a stable production of methanol with the aid of a hybrid energy storage system (HESS). A sophisticated control scheme is also developed to coordinate these actions to achieve satisfactory system performance.

Keywords: coordinated control; energy storage; fuel cell; hydrogen; methanol production; wind power

1. Introduction

In order to curb global warming, international efforts have been devoted to developing renewable energy sources as well as utilizing conventional energy in a cleaner way. Wind energy, as a renewable source of energy, attracts much attention from research community and industry. As the largest CO2 emitter, China had installed 150 million kW of wind turbines by the end of 2016 [1]. However, wind power is intermittent and its increasing penetration in the power network can create power stability issues. Therefore, much research is focused on the integration of wind energy in the power system for a resilient energy supply [2–5]. On the other hand, China is also the world’s largest coal producer. Coal is a primary source of energy and accounts for 90% of China’s CO2 emissions from fossil fuels [6]. How to use coal in a cleaner way is always a challenge facing the successive Chinese governments.

Methanol is a clean-burning liquid that requires only minor modifications to existing engines and fuel-delivery infrastructure. Manufacturing it could even make use of carbon dioxide, which is the main cause for global warming. While methanol’s benefits have long been understood, recent advances in methanol synthesis and methanol fuel cells could make this fuel even more attractive [7]. Conventionally, methanol is a by-product of mining coal through a hydrocarbylation reaction. In this process, 1.526 times of CO2 could be produced with one unit of methanol. This has led to a significant increase in CO2 emissions to the environment. In order to tackle this issue, a new representative
process has been developed [8] to produce methanol from hydrogen, oxygen and coal which is used in this study.

Energy storage is important to maintain the stable operation of energy systems. Reference [9] presented a new energy storage design to support energy flow in a hybrid wind-hydrogen system. Reference [10] proposed a hybrid energy system consisting of a wind turbine generator, a fuel cell with a water electrolyser and a battery energy storage system. Typically, these energy components are divided into two groups and two PI controllers were used to manage energy flow. By combining wind energy with fuel cells, reference [11] discussed the feasibility of a hybrid system satisfying residential demands when connected to the power grid. Reference [12] proposed an optimal method for sizing a grid-connected wind farm with a hydrogen system. Fuel cell systems with wind energy were also investigated in references [13–16] in order to find an optimal structure in the hybrid system. New concepts for optimal applications for wind energy were proposed [17,18]. These hybrid energy systems were integrated with integrating wind energy and coal-based methanol production, so as to provide an effective method to utilize local energy resources. Energy management and control methods in multi energy sources are critically important also important. Fuzzy logic control is a popular option for hybrid energy systems. Reference [19] presented a particle swarm-based fuzzy logic control for a hybrid wind-fuel cell-battery system to decrease total harmonic distortion of the power sources. A maximum power point tracking (MPPT) algorithm was used in a wind-fuel cell system [20] to meet variable load. Reference [21] adopted a probability distribution function to manage a wind-fuel cell-turbine with energy storage. The test results for different scenario of load or demand uncertainty. These systems are effective but have their limitations. It is the author’s review that using systematic approaches to integrate the developed techniques will increase multiple functions in the loop of energy generation, utilization, operation, clean environment and so on.

The research project uses Xinjiang, the large territory province in China, as a case background. It is an important energy base in China, it connects advanced provinces in East China eastward, and links to the Central Asia countries westward. Xinjiang is regarded as a strategic hub on the “Silk Road Economic Belt”. It is rich in coal resources and wind energy, which is a perfect match for the project as generated electricity from wind can be used for water electrolysis to produce hydrogen and oxygen. Xinjiang has been one of the five national integrated energy bases [22,23]. Therefore, how to effectively utilise coal sources and wind energy in Xinjiang is one of the crucial issues in China’s national agenda. In national perspective, China has been a major contributor to global warming and thus is committed to play a significant role to cut down its CO\textsubscript{2} emissions. In June 2014, China proposed a radical measure for managing its energy consumption and for developing renewable energy technologies. China has become the largest renewable producer in 2016, according to British Petroleum Statistical Review of World Energy [24].

This study proposes a hybrid system including a wind turbine, hydrogen/oxygen storage tanks through water electrolysis, a coal-base methanol device and a fuel cell. In this multi-source system, energy is managed into different forms: kinetic energy in a turbine; chemical energy in hydrogen/oxygen and fuel cells; electrical energy in the wind turbine/generators and the fuel cells. The hydrogen production through water electrolysis and the charging/discharging of the fuel cells provide flexibility when the intermittent wind power cannot match the energy requested. Meanwhile, methanol production with the new technology reduces the CO\textsubscript{2} emission for the system [17,25] which also in turn increase the revenue from the carbon trading scheme according to the national policy [26,27]. In this system, energy flow is managed by a coordinated control strategy. It determines the electricity generation and methanol production, with a target of maximising utilisation of wind energy. The feasibility and the performance of the strategy are tested through modeling and simulation in the MATLAB/Simulink environment. The novelty and contribution of the study are listed below.

1. Integration wind energy into the grid has resulted in degradation of the inertia response, which in turn seriously affects the stability of the power system’s frequency. This problem can be solved by
using an active power reserve to stabilize the frequency. Hydrogen/oxygen fuel cell technology is one of solution as a power reserve for this purpose.

(2) Hydrogen/oxygen production from water electrolysis could provide the resource for fuel cell applications. As typical electricity-to-hydrogen conversion devices, electrolyzers are regarded as deferrable loads with the ability to operate under a flexible schedule on the demand side.

(3) The coal-based methanol production is one of research challenges of clean energy applications of fossil fuels. This study adopts a “greener” process. The oxygen is fed to the gasifier as the gasification agent and then the hydrogen is mixed with the CO-rich gas to adjust $H_2/CO$ so as to produce methanol. However, it requires local supplies of hydrogen/oxygen continuously. Therefore, this kind of applications are limited. However, specific geometry advantages of Xinjiang province is perfect for this kind of applications.

(4) This innovative application integrates wind power, hydrogen from water electrolysis, hydrogen/oxygen fuel cells and a coal-based methanol production by a “greener” process. The system proposed has advantages of both the renewable sources and sustainable coal industries in China. Methanol receives hydrogen/oxygen to balance the local loads and to increase the overall profits. However, the hybrid construct would increase the system complexity. Therefore, it is necessary to investigate the possible energy management strategy and control mechanism before physical complicated system is build up.

The rest of the main studies are arranged as follows: Section 2 introduces the configuration of the hybrid system; Detailed discussion associated with the control scheme is carried out for energy management of this system; Section 3 provides the simulation outcomes and analysis; Section 4 summarises the main findings and suggests future work.

2. The Hybrid System and Its Control Scheme

The schematic diagram of the system is shown in Figure 1. The system includes a doubly-fed induction generator (DFIG) of a wind turbine, coal-based methanol production sub-system, a water electrolyser for hydrogen production, hydrogen and oxygen storage tanks, fuel cells, a DC link, DC/AC or AC/DC converters. The coal chemical process comprises gasification, mixing, purification, reaction, separation and rectification.

![Figure 1. Schematic diagram of the proposed system.](image-url)
This system is operated on the following basis:

i. Wind power is used to generate electricity for supplying the grid and for producing hydrogen through water electrolysis.

ii. Normally, the generated electricity is fed into the power grid. If the wind power is plenty, the additional power is used for water electrolysis and the energy is stored in hydrogen.

iii. Hydrogen and oxygen produced are stored in separate tanks and are controlled to be within a range (upper limit 90% and lower limit 20%).

iv. Fuel cells absorb hydrogen and generate electricity to supply the grid.

v. Methanol is produced constantly (from coal, hydrogen and oxygen) at a set value regardless of wind power input.

Figure 2 shows the operation of the proposed system.
2.1. State Index of the Hybrid Energy Storage System (HESS)

In this paper, the HESS consists of a water electrolyser, a hydrogen and an oxygen tank, and fuel cells. The energy flow in the HESS is bi-direction. However, methanol production is single direction and cannot be fed back. Therefore, coal-based methanol production is not involved in the storage system in this study. In the HESS, the equivalent state of charge (ESOC) is evaluated by the state of the hydrogen and oxygen tanks:

\[ ESOC = \frac{p_{\text{ore}}}{p_{\text{cap}}} \]  

(1)

where \( p_{\text{ore}} \) and \( p_{\text{cap}} \) are the current pressure and full pressure of the tanks, respectively. Based on the average weighting method, the ESOC is calculated as follows:

\[ ESOC_H = \frac{p_{\text{Hre}}}{p_{\text{Hcap}}} \]  

(2)

\[ ESOC_O = \frac{p_{\text{Ore}}}{p_{\text{Ocap}}} \]  

(3)

\[ ESOC_S = \frac{ESOC_H \times V_{\text{Hcap}} + ESOC_O \times V_{\text{Ocap}}}{V_{\text{Hcap}} + V_{\text{Ocap}}} \]  

(4)

where \( ESOC_H \) is the ESOC level of the hydrogen storage tank, \( p_{\text{Hre}} \) is the pressure of the hydrogen tank, \( p_{\text{Hcap}} \) is the full pressure of the hydrogen tank, \( ESOC_O \) is the ESOC level of the oxygen tank, \( p_{\text{Ore}} \) is the pressure of the oxygen tank, \( p_{\text{Ocap}} \) is the full pressure of the oxygen tank, \( V_{\text{Hcap}} \) and \( V_{\text{Ocap}} \) are the volumes of hydrogen and oxygen tanks, respectively.

In order to operate the HESS effectively, the indicators of \( ESOC_H, ESOC_O, ESOC_S \) should be controlled within reasonable range. Basically, they are divided into two intervals and three situations, as shown in Figure 3. Each interval can be determined by Equation (5):

\[ \begin{align*}
\text{Normal interval: } & ESOC_{X, \text{min}} \leq ESOC_X \leq ESOC_{X, \text{max}}, N_{\text{H}_2\text{O}} = N_{\text{fc}} + N_{\text{mhg}} \\
\text{Warning interval: } & \begin{cases} 
ESOC_X < ESOC_{X, \text{min}}, N_{\text{H}_2\text{O}} > N_{\text{fc}} + N_{\text{mhg}}, X = H, O, S \\
ESOC_X > ESOC_{X, \text{max}}, N_{\text{H}_2\text{O}} < N_{\text{fc}} + N_{\text{mhg}}
\end{cases}
\end{align*} \]  

(5)

where \( ESOC_{X, \text{min}} \) represents the minimal of ESOC and \( X \) represents hydrogen, oxygen and HESS states, respectively. \( ESOC_{X, \text{max}} \) is the maximal of hydrogen, oxygen and HESS. \( N_{\text{H}_2\text{O}} \) is the hydrogen flow rate in water electrolyser. \( N_{\text{fc}} \) is the hydrogen flow rate in the fuel cell. \( N_{\text{mhg}} \) is the hydrogen flow rate used in coal chemical system when producing methanol.

![Figure 3. The capacity range of the HESS.](image-url)
When the tank or ESOC level is in the normal range, the coal chemical system operates normally to produce methanol. The ideal operation state of the system is that hydrogen generated by the water electrolysis is equal to the sum of hydrogen consumption in the methanol production and in the fuel cells discharging while the ESOC of the HESS is still within the normal range.

In the control scheme, ESOCs is considered as the priority factor in the operation. And the relationship among the wind power output \( P_{\text{wind}} \), the cluster power dispatch demand \( P_{\text{fl}} \), local load demand \( P_{\text{load}} \) is defined as follows:

1. When \( \text{ESOC}_s > \text{ESOC}_{s \text{ max}} \), let \( i = 1 \) and \( P^{(i)}_{\text{re}} = P_{\text{wind}} - \left( P_{\text{load}} + P_{\text{fl}} \right) \)
2. When \( \text{ESOC}_{s \text{ min}} \leq \text{ESOC}_s \leq \text{ESOC}_{s \text{ max}} \), let \( i = 2 \) and \( P^{(i)}_{\text{re}} = P_{\text{wind}} - P_{\text{load}} \)
3. When \( \text{ESOC}_s < \text{ESOC}_{s \text{ min}} \), let \( i = 3 \) and \( P^{(i)}_{\text{re}} = P_{\text{wind}} \)

### 2.2. Operation Scheme of the Hybrid System

The system converts energy between electrical, chemical and mechanical. Hydrogen/oxygen reaction is an integral part of the energy flow. The processes involve several reactions as follows [28,29]:

- **Water electrolysis**: \( H_2O \rightarrow \frac{1}{2}O_2 + 2H^+ + 2e^- \), therefore, \( n(H_2):n(O_2) = 2:1 \)
- **Coal based methanol production**: \( CO + 2H_2 = CH_3OH \), therefore:
  \[
  n(H_2) : n(O_2) = 1 : 1
  \]

Electrochemical reactions in a fuel cell: \( H_2 + \frac{1}{2}O_2 \rightarrow H_2O \), therefore, \( n(H_2):n(O_2) = 1:0.5 \)

For the constant production of methanol at set power \( P_{\text{fl}} \), the hydrogen and oxygen are the same. The flow rate of hydrogen \( N_{\text{mhg}} \) and power demand \( P^{(i)}_{\text{re}} \) are given in Table 1.

#### Table 1. Interval scheme of power \( P^{(i)}_{\text{re}} \) with the flow rate \( N_{\text{H}_2} \).

<table>
<thead>
<tr>
<th>( N_{\text{H}_2} )</th>
<th>( P^{(i)}_{\text{re}} )</th>
<th>( fl_1 )</th>
<th>( fl_2 )</th>
<th>( fl_3 )</th>
<th>( fl_4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 0, N_{\text{mhg}} )</td>
<td>( (0, P_{\text{mhg}}) )</td>
<td>([P_{\text{mhg}}, 2P_{\text{mhg}}] )</td>
<td>([2P_{\text{mhg}}, 4P_{\text{mhg}}] )</td>
<td>([4P_{\text{mhg}}, +\infty) )</td>
<td></td>
</tr>
<tr>
<td>( 0, N_{\text{mhg}} )</td>
<td>( (0, N_{\text{mhg}}) )</td>
<td>([N_{\text{mhg}}, 2N_{\text{mhg}}] )</td>
<td>([2N_{\text{mhg}}, 4N_{\text{mhg}}] )</td>
<td>([4N_{\text{mhg}}, +\infty) )</td>
<td></td>
</tr>
</tbody>
</table>

When \( P_{\text{H}_2O} \) and \( N_{\text{H}_2O} \) are in interval \( \gamma_1 \), hydrogen from water electrolysis is not sufficient to sustain the required methanol production, as a result, the stored hydrogen in the tank is also consumed and ESOCs slowly reduces. When \( P_{\text{H}_2O} \) and \( N_{\text{H}_2O} \) are in interval \( \gamma_2 \), the generated hydrogen is more than the needed for methanol. Extra hydrogen is consumed by fuel cells to generate electricity. In \( \gamma_3 \) or \( \gamma_4 \), when the hydrogen is much more than needed, extra hydrogen is used for fuel cells and methanol and increasing tank levels. Table 2 gives detailed explanations.

#### Table 2. Operational regulation for different scenarios.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Scenario</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P^{(i)}_{\text{re}} &lt; 0 )</td>
<td>( \text{ESOC}_s ) is over the upper limit. ( \text{The wind power is insufficient to satisfy both local demands and cluster power requested by the grid.} )</td>
<td>The total wind power is fed into the grid. The fuel cells discharge. Water electrolysis suspends, ( P_{\text{fl}} ) = 0.</td>
</tr>
<tr>
<td>( P^{(i)}<em>{\text{re}} = P</em>{\text{wind}} - \left( P_{\text{load}} + P_{\text{fl}} \right) )</td>
<td>( \text{ESOC}_s ) is over the upper limit. ( \text{The wind power is sufficient to satisfy both local and cluster power, the rest of the wind power is equal to} 0 )</td>
<td>The wind power is completely transferred to the grid. Water electrolysis suspends, ( P_{\text{fl}} ) = 0.</td>
</tr>
<tr>
<td>( P^{(i)}_{\text{re}} \in \gamma_1 )</td>
<td>( \text{ESOC}_s ) is over the upper limit. ( \text{The wind power is sufficient to satisfy both local and cluster power. The rest of the wind power is within} \gamma_1 )</td>
<td>The wind power fed into the grid is set ( P_{\text{load}} ) = ( P_{\text{fl}} ). ( P_{\text{fl}} ) = ( P^{(i)}_{\text{re}} ).</td>
</tr>
</tbody>
</table>
2.3. Electrical Power and ESOC Control

Based on the control priority and the operating state of the system, a power distribution strategy is proposed. Its flow chart is shown in Figure 4. The power consumed by water electrolysis is obtained as follows:

\[ P_{H_2O} = \begin{cases} 0 & P_{re}^{(i)} \leq 0 \\ P_{re}^{(i)} & 0 < P_{re}^{(i)} \leq 2^{i-1}P_{mg} \\ 2^{i-1}P_{mg} & P_{re}^{(i)} > 2^{i-1}P_{mg} \end{cases} \]  \hspace{1cm} (7)

The fed-in wind power to the grid is given by:

\[ P_S = P_{wind} - P_{H_2O} \]  \hspace{1cm} (8)

All hydrogen is generated by water electrolysis and is consumed by either fuel cells or methanol production. Thus, the hydrogen distribution can be expressed by:

\[ \begin{align*} n_{H_2O,H} + n_{AH} &= n_{mg,H} + n_H \\ n_{H_2O,O} + n_{AO} &= n_{mg,O} + n_O \end{align*} \]  \hspace{1cm} (9)

where \( n_{H_2O,H} \) and \( n_{H_2O,O} \) are the amount of the hydrogen and oxygen produced by electrolysis of water respectively. \( n_{AH} \) and \( n_{AO} \) are the amount of the hydrogen and oxygen consumed in the tank respectively. \( n_H \) and \( n_O \) are the amount of hydrogen and oxygen that fed into the fuel cell respectively.

The hydrogen flow rate \( N_{H_2} \) from the electrolysis of water power \( P_{H_2O} \) is obtained:

\[ N_{H_2} = \eta_e N_e \frac{I_e}{2F} = \frac{P_{H_2O}}{N_e U_e} \frac{P_{H_2O}}{2U_e F} = \frac{\eta_e P_{H_2O}}{2U_e F} \]  \hspace{1cm} (10)

where \( \eta_e \) is the electrolysis efficiency of water electrolyser, which is generally between 60\% and 80\% [30], \( N_e \) is the number of electrolytic cells in series, \( F \) is the Faraday constant, \( I_e \) is the operating current of the cell which is given by dividing the consumption power \( P_{H_2O} \) by the electrolyser voltage \( U_e \).
Figure 4. Control diagram of electric energy allocation.
Thus:

\[
\begin{align*}
\dot{n}_{H_2O,H} &= N_{H_2} \Delta t \\
\dot{n}_{H_2O,O} &= 0.5 \dot{n}_{H_2O,H} = 0.5 N_{H_2} \Delta t
\end{align*}
\]

(11)

Assuming the operation process is ideal, the amount of hydrogen and oxygen consumed in the coal chemical system during \( \Delta t \) can be written as:

\[
\dot{n}_{\text{mgg},H} = \dot{n}_{\text{mgg},O} = N_{\text{mgg}} \times \Delta t
\]

(12)

\[
N_{\text{mgg}} = 207 \times 0.2 \times \frac{M_W}{3.6V_m}
\]

(13)

where \( M_W \) is the wind turbine output power (MW), and \( V_m \) is the hydrogen molar volume 22.4 L/mol.

From Equation (8), \( n_{rO} \) can be derived from \( n_{\Delta H} \) and \( n_{\Delta O} \), and vice versa. Thereby the state of the hydrogen storage system at the end of each cycle can be obtained. Therefore, the hydrogen distribution control is simplified to study the operation state of the fuel cells. The cases for the fuel cells discharging can be summarised as the follows:

1. If \( P_{re}^{(1)} \geq 0 \), reduce \( \text{ESOC}_H \) by consuming more hydrogen and oxygen for electricity generation, Let flag1 = 1. Logical order is to derive \( n_{rH}, n_{rO}(P_{fc}) \) from \( n_{\Delta H}, n_{\Delta O} \).

At this moment, the amount of hydrogen and oxygen can reach the upper limits of the tank pressure \( n_{\Delta H}, n_{\Delta O} \):

\[
\begin{align*}
\dot{n}_{\Delta H}' &= \frac{p_{Hcap} V_{Hcap} (\text{ESOC}_H - \text{ESOC}_{H\text{, max}})}{R_H} \\
\dot{n}_{\Delta O}' &= \frac{p_{Ocap} V_{Ocap} (\text{ESOC}_O - \text{ESOC}_{O\text{, max}})}{R_O}
\end{align*}
\]

(14)

The calculations of the parameters \( n_{\Delta H}, n_{\Delta O} \) are shown in Table 3.

Table 3. Parameter selection for the calculation.

<table>
<thead>
<tr>
<th>( n_{\Delta O} )</th>
<th>( n_{\Delta H} )</th>
<th>&lt;0</th>
<th>=0</th>
<th>&gt;0</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;0</td>
<td>-</td>
<td>-</td>
<td>select ( n_{\Delta H} = n_{\Delta H}' )</td>
<td></td>
</tr>
<tr>
<td>=0</td>
<td>-</td>
<td>-</td>
<td>select ( n_{\Delta H} = n_{\Delta H}' )</td>
<td></td>
</tr>
<tr>
<td>&gt;0</td>
<td>Select ( n_{\Delta O} = n_{\Delta O}' )</td>
<td>Select ( n_{\Delta O} = n_{\Delta O}' )</td>
<td>( \begin{cases} n_{\Delta H} = n_{\Delta H}' &amp; \text{if } n_{\Delta H}' \geq 2.3 n_{\Delta O}' \ n_{\Delta O} = n_{\Delta O}' &amp; \text{if } n_{\Delta H} &lt; n_{\Delta O}' \end{cases} )</td>
<td></td>
</tr>
</tbody>
</table>

The molar flow rate of the hydrogen and the oxygen in the fuel cell is:

\[
1 < \gamma_{H-O} = \frac{n_{rH} \Delta t}{n_{rO} \Delta t} < 1.25
\]

(15)

i. The actual stock of the hydrogen is calculated by:

\[
\begin{align*}
\dot{n}_{rH} &= n_{H_2O,H} + n_{\Delta H} - n_{\text{mgg},H} \\
\dot{n}_{rO} &= \frac{n_{H_2O,O}}{\gamma_{H-O}}
\end{align*}
\]

(16)

ii. The actual stock of the oxygen is calculated by:

\[
\begin{align*}
\dot{n}_{rO} &= n_{H_2O,O} + n_{\Delta O} - n_{\text{mgg},O} \\
\dot{n}_{rH} &= \gamma_{H-O} \dot{n}_{rO}
\end{align*}
\]

(17)
The partial pressures of hydrogen and oxygen \( p_{fc,H}, p_{fc,O} \) are obtained:

\[
\begin{align*}
    p_{fc,H} &= \left( \frac{n_H}{N} - \frac{d p_{fc,H}}{d t} \right) - \frac{10^5 V_a}{RT} - \frac{N f c_H}{4 F} / 10^5 K_{H_2} \\
    p_{fc,O} &= \left( \frac{n_O}{N} - \frac{d p_{fc,O}}{d t} \right) + \frac{10^5 V_c}{RT} - \frac{N f c_O}{4 F} / 10^5 K_{O_2}
\end{align*}
\]  

(18)

where \( N \) is the number of the fuel cell units, \( V_a \) and \( V_c \) are anode and cathode volumes per unit hydrogen fuel cell respectively, \( T \) is the operating temperature of the fuel cell, \( I_{fc} \) is the current of the fuel cell, \( K_{H_2} \) and \( K_{O_2} \) are the molar constant of hydrogen (anode) and oxygen (cathode) respectively.

Based on a fuel cell model, the power of the fuel cell \( P_{fc} (P_{fc} \geq 0) \) can be obtained:

\[
P_{fc} = \begin{cases} 
    P_{fc, \min}, & \eta_f \left( U_{fc} \cdot I_{fc} \right) < P_{fc, \min} \\
    \eta_f \left( U_{fc} \cdot I_{fc} \right), & P_{fc, \min} \leq \eta_f \left( U_{fc} \cdot I_{fc} \right) \leq P_{fc, \max} \\
    P_{fc, \max}, & \eta_f \left( U_{fc} \cdot I_{fc} \right) > P_{fc, \max}
\end{cases}
\]

(19)

where \( U_{fc} \) is the output voltage of the fuel cell, \( \eta_f \) is the power generation efficiency of the fuel cell, \( P_{fc, \max} \) and \( P_{fc, \min} \) are the upper and lower limits of the fuel cell stack, respectively. Based on double electric layer phenomenon, the output voltage of the hydrogen fuel cell is calculated as follows [31–33]:

\[
U_{fc} = N \cdot U_{cell} = N \cdot (E_{nernst} - U_{ohmic} - U_c)
\]

(20)

where \( U_{cell} \) is the output voltage of a single fuel cell, \( E_{nernst} \) is the thermodynamic potential, \( U_{ohmic} \) is the ohmic polarization overvoltage, and \( U_c \) is the equivalent voltage.

The thermodynamic potential can be calculated by Equation (21):

\[
E_{nernst} = 1.229 - 8.5 \times 10^{-4} (T - 298.15) + 4.3085 \times 10^{-5} T \times (\ln p_{fc,H} + 0.5 \ln p_{fc,O})
\]

(21)

The ohmic polarization overvoltage is obtained by:

\[
U_{ohmic} = I_{fc} (Z_m + Z_e) = I_{fc} \left( \frac{181.61 \left[ 1 + 0.03 \frac{I_{fc}}{A} + 0.062 \left( \frac{I_{fc}}{A} \right)^2 \left( \frac{I_{fc}}{A} \right)^{2.5} \right]}{A \left( \varphi - 0.634 - 3 \frac{I_{fc}}{A} \right) \times \exp \left( 4.18 \left( \frac{T - 303}{T} \right) \right)} + Z_e \right)
\]

(22)

where \( Z_m \) is the equivalent membrane impedance; \( Z_e \) is the impedance which represents the proton through the exchange membrane; \( \rho_M \) is the resistivity; \( I \) is the film thickness; \( A \) is the activation area of proton exchange membrane; and \( \varphi \) is the proton exchange membrane moisture content. The cell equivalent voltage can be given by:

\[
U_c = \left\{ \begin{array}{ll}
-B \times \ln(1 - \frac{I_{max}}{I_{fc}}) - [\varepsilon_1 + \varepsilon_2 T + \varepsilon_3 T \ln\left( \frac{p_{fc,O} \times 10^2}{5.08 \times 10^8 \exp(-\frac{395}{T})} \right)] & (23)
\end{array} \right.
\]

where \( B \) is the equation coefficient; \( J \) is the active current density of the cell; \( I_{max} \) is the maximum current density; \( C \) is the equivalent capacitance; and \( \varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4 \) are the empirical parameters of fuel cell.

(2) If \( (p_{rel}^{(2)} < 0) \) and \( (ESOC_S \geq ESOC_{soc}) \) or \( (P_{rel}^{(1)} < 0), ESOC_S \) level is operated within ideal range but the wind power cannot meet the demand. The hydrogen fuel cell discharges to assist wind power with flag1 = 1. \( n_{H} \) and \( n_{O} \) can be obtained by the \( P_{fc} \) and then \( n_{\Delta H} \) and \( n_{\Delta O} \) can be derived.

\[
P_{fc} = \begin{cases} 
    \left| P_{fc, \min} \right|, & \left| P_{rel} \right| < \left| P_{fc, \min} \right| \\
    \left| P_{rel} \right|, & \left| P_{fc, \min} \right| \leq \left| P_{rel} \right| \leq \left| P_{fc, \max} \right| \\
    \left| P_{fc, \max} \right|, & \left| P_{rel} \right| > \left| P_{fc, \max} \right|
\end{cases} \quad i = 1, 2
\]

(24)
The above equation can be simplified as:

\[
\begin{align*}
    n_{rH} &= \begin{cases}
        \frac{N_{rH,\text{min}} \times \Delta t}{|P_i^{\text{re}}|}, & P_{fc} < P_{fc,\text{min}} \\
        \frac{|P_i^{\text{re}}| \times \frac{N_{rH,\text{max}}}{P_{fc,\text{max}}} \times \Delta t}{P_{fc}} , & P_{fc} = |P_i^{\text{re}}| \\
        \frac{N_{rH,\text{max}} \times \Delta t}{P_{fc}}, & P_{fc} > P_{fc,\text{max}}
    \end{cases} 
\end{align*}
\]

(25)

where \(N_{rH,\text{min}}\) is the flow rate of the hydrogen when the fuel cell operates at minimum power output:

\[
n_{rO} = n_{rH}/1.2
\]

(26)

(3) If \((P_i^{\text{re}}) < 0\) & \((\text{ESOC}_s < \text{ESOC}_{\text{Sa}})\), or \(P_i^{\text{re}}(2) \geq 0\) or \(P_i^{\text{re}}(3) \geq 0\), the hydrogen fuel cell suspends with flag1 = 0.

Let \(P_{fc} = 0\), \(n_{rH} = n_{rO} = 0\, \text{then} \, n_{\Delta H} = n_{\text{mHG},H} - n_{\text{H}_2\text{O},H}, n_{\Delta O} = n_{\text{mHG},O} - n_{\text{H}_2\text{O},O}.

According to the above control rules, the HESS pressure \(P_{Hre}\) is obtained:

\[
\begin{align*}
    P_{Hre} &= P_{H0} + \Delta P_{H,1} + \Delta P_{H,2} - \Delta P_{H,3} - \Delta P_{H,4} \\
    \Delta P_{H,1} &= n_{\text{H}_2\text{O},H} \Delta RT_H/V_{H_{\text{cap}}} \\
    \Delta P_{H,2} &= 10^5k'K_{\text{H}_2} P_{fc} H_{\Delta RT_H}/V_{H_{\text{cap}}} \\
    \Delta P_{H,3} &= n_{\text{mHG}} \Delta RT_H/V_{H_{\text{cap}}} \\
    \Delta P_{H,4} &= n_{\text{H}_2\text{O}} \Delta RT_H/V_{H_{\text{cap}}} \\
\end{align*}
\]

(27)

where \(P_{H0}\) is the initial pressure of the hydrogen tank; \(\Delta P_{H,1}\) is the pressure increment of the hydrogen caused by water electrolysis; \(\Delta P_{H,2}\) is the pressure increment of the hydrogen caused by incomplete consumption from the fuel cells. \(\Delta P_{H,3}\) is the pressure decrement of the hydrogen caused by methanol production. \(\Delta P_{H,4}\) is the pressure decrement of the hydrogen recovery rate caused by the fuel cell discharging. \(k'\) is the hydrogen recovery rate.

The pressure of the oxygen tank \(P_{Ore}\) is calculated by:

\[
P_{Ore} = P_{O,0} + \frac{(n_{\text{H}_2\text{O},O} + 10^5k'K_{\text{O}_2} P_{fc, O} \Delta t - n_{\text{mHG}} - n_{rO})RT_O}{V_{O_{\text{cap}}}}
\]

(28)

where \(P_{O,0}\) is the initial pressure of the oxygen tank.

2.4. Overall Control Scheme

This study is focused on the optimal operation of the hybrid system. When the cluster power is required by the cluster control center, the power from the hybrid system is sent to the grid after the local demand is satisfied. In order to communicate with the cluster control center, a specific indicator “flag2” is used.

By changing flag2, the operation states and the request of the local hybrid system are recorded.

The specific actions are as follows:

- If \(P_s + P_{fc} < P_{\text{load}} + P_{\text{Hr}}, \text{flag2} = -1\), the local system does not satisfy with the grid plan and the local system requests the cluster control center to provide power assistance;
- If \(P_s + P_{fc} = P_{\text{load}} + P_{\text{Hr}}, \text{flag2} = 0\), the local system operates in an ideal state and the established target is realised;
- If \(P_s + P_{fc} > P_{\text{load}} + P_{\text{Hr}}, \text{flag2} = 1\), the local system requests assistance from cluster control center and the more power from the local system is sent to the grid.

In order to prevent the amounts of hydrogen and oxygen from reaching their tank limits, an additional control action is developed, as shown in Figure 5.
i. As shown in Figure 5a,c, when ESOCH or ESOCO is lower than ESOCH\_min or ESOCO\_min, the hybrid system produces the hydrogen/oxygen in maximum and consumes the hydrogen/oxygen in minimum. \( \Delta t_a \) should select the smaller one between \( \Delta t_{aH} \) and \( \Delta t_{aO} \):

\[
\Delta t_a = \begin{cases} 
\min(\Delta t_{aH}, \Delta t_{aO}) \\
\text{s.t.} & \Delta t_{aH} = \frac{(ESOC_{H,\text{max}} - ESOC_{H,\text{min}})V_{Hcap}V_{Hcap}}{(4N_{\text{mHg}} - N_{\text{mHg}})RT_H} \\
& \Delta t_{aO} = \frac{(ESOC_{O,\text{max}} - ESOC_{O,\text{min}})V_{Ocap}V_{Ocap}}{(2N_{\text{mHg}} - N_{\text{mHg}})RT_O} 
\end{cases}
\] (29)

ii. As shown in Figure 5b,d, when ESOCH or ESOCO is over than ESOCH\_max or ESOCO\_max, the hybrid system produces the hydrogen/oxygen in minimum and consumes hydrogen/oxygen in maximum. \( \Delta t_b \) should select the smaller one between \( \Delta t_{bH} \) and \( \Delta t_{bO} \):

\[
\Delta t_b = \begin{cases} 
\min(\Delta t_{bH}, \Delta t_{bO}) \\
\text{s.t.} & \Delta t_{bH} = \frac{(ESOC_{H,\text{max}} - ESOC_{H,\text{min}})V_{Hcap}V_{Hcap}}{(N_{\text{mHg}} + N_{\text{H,\text{max}}})RT_H} \\
& \Delta t_{bO} = \frac{(ESOC_{O,\text{max}} - ESOC_{O,\text{min}})V_{Ocap}V_{Ocap}}{(N_{\text{mHg}} + N_{\text{O,\text{max}}}/S_{H-O})RT_O} 
\end{cases}
\] (30)

Therefore, the time interval \( \Delta t \) is controlled to be:

\[
\Delta t < \min(\Delta t_a, \Delta t_b) 
\] (31)

3. Simulation Results

The simulation of a local hybrid system with 10 MW wind power has been carried out by using MATLAB/Simulink. The key parameters of the system are shown in Table 4.
After a control period, ESOC restores normal. From 26 s to 27.5 s and from 31.5 s to 34.5 s, the ESOC is set 0.31. The input and the output power curves are shown in Figures 6 and 7, respectively. The wind power data are from a real wind power integration, and ensure the output power of the hybrid system to meet the tied-grid demand.

In the simulation, ESOC_S is set 0.31. \( P_{mhg} \) and \( N_{mhg} \) are set 2.48 MW and 5.134 mol/s respectively. According to Equations (28) and (29), \( \Delta t \) is less than 3.75. Therefore let \( \Delta t = 0.5 \) s. The input and the output power curves are shown in Figures 6 and 7, respectively. The wind power data are from a real 10 MW wind turbine model and the time duration is reduced from 15 min to 1 s. ESOC_S exceeds the upper limit (0.9) at 11 s as shown in Figure 7, the fuel cell discharges and the ESOC_S reduces. After a control period, ESOC_S restores normal. From 26 s to 27.5 s and from 33 s to 34.5 s, the ESOC_S is in the normal range and the storage state is normal. The fuel cells discharge to assist wind power integration, and ensure the output power of the hybrid system to meet the tied-grid demand.

Table 4. Key parameters of the hybrid system.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>( U_e )</td>
<td>2 V</td>
<td>( A )</td>
<td>50 cm^2</td>
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<tr>
<td>( \eta_e )</td>
<td>80%</td>
<td>( \varphi )</td>
<td>14</td>
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<tr>
<td>( R )</td>
<td>8.3145 J/mol K</td>
<td>( C )</td>
<td>3 F</td>
</tr>
<tr>
<td>( V_{Heap} )</td>
<td>60 m^3</td>
<td>( \epsilon_1 )</td>
<td>-0.9514</td>
</tr>
<tr>
<td>( V_{Oxap} )</td>
<td>60 m^3</td>
<td>( \epsilon_2 )</td>
<td>3.12 \times 10^{-3}</td>
</tr>
<tr>
<td>( p_{Heap} )</td>
<td>( 5 \times 10^6 ) Pa</td>
<td>( \epsilon_3 )</td>
<td>7.4 \times 10^{-5}</td>
</tr>
<tr>
<td>( p_{Oxap} )</td>
<td>( 5 \times 10^6 ) Pa</td>
<td>( \epsilon_4 )</td>
<td>-1.87 \times 10^{-4}</td>
</tr>
<tr>
<td>( p_{H,0} )</td>
<td>( 4.499 \times 10^6 ) Pa</td>
<td>( B )</td>
<td>0.016</td>
</tr>
<tr>
<td>( p_{O,0} )</td>
<td>( 4.499 \times 10^6 ) Pa</td>
<td>( J_{max} )</td>
<td>1.2 A/cm^2</td>
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<td>( T_H )</td>
<td>298 K</td>
<td>( \eta_f )</td>
<td>90%</td>
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<tr>
<td>( T_O )</td>
<td>298 K</td>
<td>( I_{fc} )</td>
<td>25 A</td>
</tr>
<tr>
<td>( K_{H_2} )</td>
<td>( 6.781 \times 10^{-2} ) mol/s-atm</td>
<td>( V_1 )</td>
<td>0.005 m^3</td>
</tr>
<tr>
<td>( K_{O_2} )</td>
<td>( 6.781 \times 10^{-2} ) mol/s-atm</td>
<td>( V_{ca} )</td>
<td>0.01 m^3</td>
</tr>
<tr>
<td>( k' )</td>
<td>0.9</td>
<td>( P_{fc, max} )</td>
<td>0.2 MW</td>
</tr>
<tr>
<td>( N )</td>
<td>400</td>
<td>( P_{fc, max} )</td>
<td>2 \times 10^{-4} MW</td>
</tr>
<tr>
<td>( T )</td>
<td>350 K</td>
<td>( N_{H_2, max} )</td>
<td>27,140 mol/s</td>
</tr>
<tr>
<td>( I )</td>
<td>( 5.1 \times 10^{-3} ) cm</td>
<td>( N_{H_2, min} )</td>
<td>1.357 mol/s</td>
</tr>
</tbody>
</table>

![Figure 6. Output power, load and scheduled power curves.](image-url)
Therefore, actual tied-grid power and tied-grid demand curves of the hybrid system are shown as Figure 8.

It can be seen from Figure 8 that when actual tied-grid power of the hybrid system does not meet the tied-grid demand, that is $P_s + P_{fc} < P_{load} + P_{jh}$, flag2 is set $-1$ and the hybrid system requests the cluster center for assistance. Otherwise, flag2 is set 1, the local hybrid system power is excess. If the system power equates the tied-grid demand, the flag2 is set 0. The control objective is achieved. In the above process, the states of the hydrogen/oxygen tanks and HESS are shown in Figures 8–11.
It can be seen from Figures 9 and 10 that the ESOC₅ is in the normal range at the beginning. \( P_{H,O} \) equates \( 2P_{mhg} \) from 0 s to 4 s and from 6 s to 11 s. The ESOC₇ and the ESOC₈ rise slowly and the ESOC₉ remains unchanged. From 4 s to 6 s, from 11.5 s to 16 s and from 17.5 s to 23 s, \( P_{mhg} < P_{H,O} < 2P_{mhg} \). The ESOC₇ and the ESOC₈ rise slowly and the ESOC₉ decreases slowly. At 11 s, ESOC₉ exceeds the upper limit, and the control priority changes. The fuel cells start, and ESOC₇, ESOC₉ and ESOC₊ drop rapidly. The ESOC₅ restores to the normal range. From 23 s to 26 s, \( P_{H,O} < P_{mhg} \). The ESOC₇, ESOC₉ and ESOC₊ decrease slowly.

It can be seen from Figure 7 that \( P_{H,O} \) drops rapidly since 26 s. From 26 s to 36 s, \( P_{H,O} \) is less than \( P_{mhg} \) and even reduces to zero at 31 s. From 26 s to 27.5 s and from 31 s to 34.5 s, the fuel cells discharge, and the ESOC₇, ESOC₉ and ESOC₈ decrease rapidly as can be seen in Figure 11. From 27.5 s to 31.5 s, the fuel cells suspend and the hydrogen produced by water electrolysis is less than the hydrogen used for coal chemical process. The ESOC₇, ESOC₉ and ESOC₈ decrease slowly. At 34.5 s, ESOC₈ < ESOC₉a and the fuel cells suspend. The downward trend of the ESOC₇, ESOC₉ and ESOC₈ has been curbed.

It can be seen from Figures 7 and 12 that ESOC₅,₉ₐ < ESOC₈ < ESOC₉ between 35 s and 60 s while the fuel cells suspend. From 35 s to 50 s, \( P_{H,O} = 0 \) and the hydrogen/oxygen for the coal chemical process are provided by the tanks. ESOC₈ decreases slowly. From 50 s onwards, \( P_{H,O} \) rises slowly. However, it does not reach \( 2P_{mhg} \) until 60 s. Therefore, ESOC₈ is seen decreasing in this period.

In Figure 13, when the hydrogen for the methanol production is zero, ESOC₅ decreases 0.0004 within 15 s. It is at 1 s that ESOC₅ decreases from ESOC₉a to ESOC₅,₉ₐ under unchanged condition. Therefore, let:

\[
p_{H,0} = 1268049.26 P_a \tag{32}
\]

and:

\[
p_{O,0} = 732049.26 P_a \tag{33}
\]
The simulations when $ESOC_S$ below the low limit is carried out based on this model. The hydrogen tank and the $ESOC$ of the HESS are shown in Figures 14 and 15. In Figures 14 and 15, the $ESOC_S$ reach the lower limit and the control priority changes. The wind power is used for the water electrolysis at 1 s. The $ESOC_S$ recovers to the normal range at 3 s. After that, the power for the water electrolysis increases and maintains $2P_{mlq}$ until 5.5 s. The $ESOC_H$, $ESOC_O$ and $ESOC_S$ increase slowly.
4. Conclusions

This paper has presented a new hybrid system involving wind turbines, hydrogen energy storage, water electrolyser, and fuel cells. The novelty lies in the coordinated control scheme to maximize the utilisation of wind power with a constant methanol output whilst still reducing CO₂ emissions. All the symbols used in the paper can refer to Table A1 in Appendix A. The main contributions of the study can be concluded as follows:

(1) This work takes advantage of wind power for electricity generation and for energy storage. In addition, coal-based energy systems for methanol production in a cleaner manner. This is critically important for China as well as many coal-dependent economies.

(2) It integrates some interdisciplinary techniques into a multi-functional dynamic system to effectively manage various energy sources to enhance stable power supply stability, increase energy efficiency in utilization, and reduce CO₂ emissions.

(3) It proposes a concept prototype and then implements the structured system in a simulation environment, which significantly reduces the real test cost.

(4) The simulation results have confirmed the technical feasibility of the proposed system. It paves the way for next stage progression in small scale real tests and future commercialization of the technology.

(5) Because of the optimal design and control of the hybrid system, energy efficiency and cost efficiency will be improved. This has a significant economic implications. Moreover, the reduction in CO₂ emissions will have an additional benefit from Carbon Trading Scheme in China.

As this is just a theoretical study in pioneering stage in China, there are several pertinent aspects need to be fully investigated before real system implementation and applications. These are:

(1) Development of a full-scale simulation with hardware-in-loop real-time simulator for feasibility investigation.

(2) Development of a full scale demonstration experimental setup of the system.

(3) Conduction economic analysis, costs and gains, energy trading and carbon trading.

(4) Carrying out a study on other social, environmental, legal impacts to minimize the uptake of the proposed technology.

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Author Contributions: In this article, T. Yuan and Q. Duan conceived and designed the system; J. Hu and X. Yuan performed the experiments; Q. Zhu built the simulation models; X. Chen and W. Cao analysed data and wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.
## Appendix A

### Table A1. Symbols.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>Active area of the membrane</td>
</tr>
<tr>
<td>$B$</td>
<td>Equation coefficient</td>
</tr>
<tr>
<td>$C$</td>
<td>Equivalent capacitor of fuel cell</td>
</tr>
<tr>
<td>$E_{\text{therm}}$</td>
<td>Thermodynamic potential</td>
</tr>
<tr>
<td>$E_{\text{SOC}}$</td>
<td>Equivalent state of charge</td>
</tr>
<tr>
<td>$E_{\text{SOC}}H$</td>
<td>Equivalent state of charge of the hydrogen tank</td>
</tr>
<tr>
<td>$E_{\text{SOC}}S$</td>
<td>Equivalent state of charge of the HESS</td>
</tr>
<tr>
<td>$E_{\text{SOC}}S_{\text{H}}$</td>
<td>Threshold of $E_{\text{SOC}}$</td>
</tr>
<tr>
<td>$E_{\text{SOC}}S_{\text{O}}$</td>
<td>Equivalent state of charge of the oxygen tank</td>
</tr>
<tr>
<td>$E_{\text{SOC}}X_{\text{max}}$</td>
<td>The upper limit of the $E_{\text{SOC}}$</td>
</tr>
<tr>
<td>$E_{\text{SOC}}X_{\text{min}}$</td>
<td>The low limit of the $E_{\text{SOC}}$</td>
</tr>
<tr>
<td>$F$</td>
<td>Faraday constant</td>
</tr>
<tr>
<td>$I_e$</td>
<td>Current in water electrolyser</td>
</tr>
<tr>
<td>$I_{fc}$</td>
<td>Discharge current of fuel cell</td>
</tr>
<tr>
<td>$J$</td>
<td>Ampere density in fuel cell</td>
</tr>
<tr>
<td>$J_{\text{max}}$</td>
<td>Maximum ampere density in fuel cell</td>
</tr>
<tr>
<td>$k'$</td>
<td>Fuel recovery rate</td>
</tr>
<tr>
<td>$k_{H_2}$</td>
<td>Hydrogen constant</td>
</tr>
<tr>
<td>$K_{O_2}$</td>
<td>Oxygen constant</td>
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<tr>
<td>$l$</td>
<td>Thickness of the membrane</td>
</tr>
<tr>
<td>$M_W$</td>
<td>Nominal capacity of the wind farm</td>
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<td>$n_{H_2O,H}$</td>
<td>Hydrogen production amount by water electrolysis in $\Delta t$</td>
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<tr>
<td>$n_{H_2O,O}$</td>
<td>Oxygen production amount by water electrolysis in $\Delta t$</td>
</tr>
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<td>$n_{\text{mbg,H}}$</td>
<td>Hydrogen consumption by methanol production in $\Delta t$</td>
</tr>
<tr>
<td>$n_{\text{mbg,O}}$</td>
<td>Oxygen consumption by methanol production in $\Delta t$</td>
</tr>
<tr>
<td>$n_{H}$</td>
<td>Hydrogen consumption by fuel cell in $\Delta t$</td>
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<tr>
<td>$n_{O}$</td>
<td>Oxygen consumption by fuel cell in $\Delta t$</td>
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<td>$n_{\Delta H}$</td>
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<tr>
<td>$n_{\Delta O}$</td>
<td>Oxygen consumption in $\Delta t$</td>
</tr>
<tr>
<td>$n'_{\Delta H}$</td>
<td>Hydrogen amount when the pressure of the hydrogen tank is over the upper limit</td>
</tr>
<tr>
<td>$n'_{\Delta O}$</td>
<td>Oxygen amount when the pressure of the oxygen tank is over the upper limit</td>
</tr>
<tr>
<td>$N_e$</td>
<td>The serial units of fuel cells</td>
</tr>
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<td>$N_{fH}$</td>
<td>Flow rate of the hydrogen fed in the fuel cells</td>
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<td>$N_{H_2O}$</td>
<td>Hydrogen flow rate in water electrolysis</td>
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<td>$N_{H_2O,H}$</td>
<td>Flow rate of the hydrogen by water electrolysis</td>
</tr>
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<td>$N_{\text{mbg}}$</td>
<td>Hydrogen flow rate consumed by methanol production at the rated power</td>
</tr>
<tr>
<td>$N_{\Delta H_{\text{max}}}$</td>
<td>Hydrogen consumption at full discharging of the fuel cells</td>
</tr>
<tr>
<td>$N_{\Delta H_{\text{min}}}$</td>
<td>Hydrogen flow rate when fuel cell discharging in minimum</td>
</tr>
<tr>
<td>$p_{\text{cap}}$</td>
<td>Tank pressure when fully charged</td>
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<tr>
<td>$p_{\text{fc,H}}$</td>
<td>Hydrogen pressure in a fuel cell</td>
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<tr>
<td>$p_{\text{fc,max}}$</td>
<td>Maximum power output of fuel cell discharging</td>
</tr>
<tr>
<td>$p_{\text{fc,min}}$</td>
<td>Minimum power output of fuel cell discharging</td>
</tr>
<tr>
<td>$p_{\text{fc,O}}$</td>
<td>Oxygen pressure in a fuel cell</td>
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<td>$p_{H_{\text{cap}}}$</td>
<td>Full pressure of the hydrogen tank</td>
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<td>$p_{H_{\text{H}}}C$</td>
<td>Current pressure in the hydrogen tank</td>
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<td>$p_{H_{\text{H,0}}}$</td>
<td>Initial pressure in hydrogen tank</td>
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<td>$p_{O_{\text{cap}}}$</td>
<td>Full pressure of the oxygen tank</td>
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<td>$p_{O_{\text{re}}}$</td>
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<tr>
<td>$p_{O_{\text{O,0}}}$</td>
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<tr>
<td>$p_{\text{re}}$</td>
<td>Current pressure in storage tank</td>
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<tr>
<td>$P_{fc}$</td>
<td>Discharging power of fuel cell</td>
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<tr>
<td>$P_{H_{\text{H}}}$</td>
<td>Power for water electrolysis</td>
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<td>$P_{jH}$</td>
<td>Cluster power demand dispatched by cluster control center</td>
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Table A1. Cont.

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<td>$V_{\text{m}}$</td>
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<td>73</td>
<td>$\epsilon_{1}, \epsilon_{2}, \epsilon_{3, 4}$</td>
</tr>
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<td>$\eta_{W}$</td>
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<td>78</td>
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<td>82</td>
<td>$\Delta t$</td>
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References

8. Li, Q.; Wei, Y.N.; Chen, Z.A. Water-CCUS nexus: Challenges and opportunities of China’s coal chemical industry. Clean Technol. Environ. Policy 2016, 18, 775–786. [CrossRef]


