An Integrated Energy System Coupling Biomass Gas and Hydrogen produced by Wind Power

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Abstract. The integrated energy system is gaining increasing attention due to its remarkable superiority in modern energy system. Hydrogen and biomass are two commonly used energy sources in integrated energy systems, but both of them have shortcomings. This paper presents a new type of integrated energy system for coupling biomass with hydrogen produced by wind power. This system not only avoids the energy loss caused by hydrogen storage and transportation, but also can increase the burning value of biomass gas, thereby improving power generation efficiency. The investment of proposed system is calculated based on a case study, which shows that the system has a relatively high return of investment.

1. Introduction
The development of integrated energy system (IES) is one of the main carrier for energy innovation [1-4]. Owing to global warming and environment protecting pressure, energy development is facing unprecedented opportunities and challenges [1-2]. The large-scale replacement of traditional fossil energy by clean and low-carbon renewable energy will be an inevitable trend, leading to new types of energy supply and consumption [3]. At present, the planning and operation of various types of energy such as electricity, cooling/heating, and gas remain independent, and energy production, transmission, storage, and consumption have not been deeply integrated [4]. The independent energies will be unable to meet the requirements of energy development in the future [3].

Hydrogen energy may become a pivotal energy source on the world energy stage [5-6]. Hydrogen production, storage, transportation, and application technology have drawn much attention in decades [6-7]. Hydrogen has the characteristics of high calorific value, which is 3 times that of gasoline, 3.9 times that of alcohol, and 4.5 times that of coke [7]. Hydrogen can be produced by water combustion, and water is a clean and rich energy source in the world, which ensure the sustainable development for hydrogen energy [6].

Biomass refers to various organisms formed through photosynthesis [8-10]. And the so-called biomass energy is the solar energy stored in biomass in the form of chemical energy, that is, the solar energy using biomass as a carrier. Syngas is a vital way for biomass utilization. The world’s first complete integrated gasification combined cycle (IGCC) power plant utilizing wood was built in Sweden [8]. It was verified that adding syngas storing can increase the profit for IGCC utilizing biomass [9]. Siemens have applied a broad range of different syngas as the fuels for gas IGCC, CO2 capture and poly generation for decades [10].

Technologies such as new energy to hydrogen and syngas production are all relatively mature. The hydrogen transportation often uses compression/liquefaction technology, and the hydrogen is stored in high-pressure gas canister. This method needs to consume a large amount of energy in the process of
hydrogen compression and liquefaction, which will significantly reduce the utilization efficiency of hydrogen energy. At the same time, both hydrogen compression and liquefaction require special devices, which not only increases the cost, but also reduces the flexibility of hydrogen application. The syngas directly produced by biomass has low combustion value due to the mixed non-flammable carbon dioxide, and the efficiency of power generation and heating is not high.

In order to deal with the transportation issue of hydrogen and increase the combustion value of syngas, this paper presents a new IES coupling biogas and hydrogen produced by wind power.

2. System design
This paper proposes a new IES, mainly including the following parts: wind power generation units, hydrogen production unit (using proton exchange membrane (PEM) electrolytic cell), biomass fermentation unit, gas tanks and internal combustion engine (ICE).

2.1. Structure of the IES
The structure of new IES is shown in Fig. 1, where the energy is produced via two ways, i.e. wind power generation units and biomass fermentation unit. In the scene where wind power is surplus, part of wind power is directly transmitted to the main grid and the other is transferred to hydrogen. Then the hydrogen is stored in tank or transported to ICE.

Figure 1. Block diagram of the IES

In this IES, biomass is coupled with the hydrogen produced by surplus wind power via cogeneration in the ICE. The syngas from the gasifier is partly stored in a gas tank, and the other is burn in the ICE together with hydrogen. The ICE transfers the energy derives from the aforementioned fuels to electric power.

2.2. Advantages of the proposed system
Wind power hydrogen production can store large-scale renewable energy, which is an effective way to deal with wind power fluctuations. However, the hydrogen energy load is generally far away from the wind farm. It is difficult to deliver hydrogen and the cost is high. The most effective way of utilizing hydrogen energy is in-situ conversion and utilization. Biomass production is varying with seasons, and it is difficult for biomass power plants to achieve a higher utilization rate.

Wind power to hydrogen combined with biomass technology not only improves the burning value of syngas, but also eliminates huge energy consumption links such as compression/liquefaction of hydrogen. The above technology not only reduces the cost of the integrated energy system, but also improves the energy utilization efficiency of the entire system.

3. System modelling
A model based on Fig. 1 is built in this chapter, which is shown in Fig. 2. In this model, the installed capacity of the wind farm is \( P_{\text{wind}} \), of which the power integrated into the grid is \( P_{\text{wind}1} \), the power flowing to the electrolytic cell is \( P_{\text{wind}2} \).

**Figure 2.** System modelling for the IES

For ease of expression and calculation, all non-electrical variables are converted to power. The hydrogen generated by the electrolytic cell is divided to \( P_{\text{H11}} \) and \( P_{\text{H12}} \), \( P_{\text{H11}} \) is the power flowing into the hydrogen storage tank, and that \( P_{\text{H12}} \) is the power flowing into the ICE, \( P_{\text{H21}} \) is the power flowing into the ICE from the hydrogen tank. The biomass put into the gasifier is \( P_{\text{bio}} \), the syngas produced by the gasifier is divided to \( P_{\text{gas11}} \) and \( P_{\text{gas12}} \), the power of syngas directly flowing into the ICE is \( P_{\text{gas11}} \), the power stored in syngas tank is \( P_{\text{gas12}} \). The power of hydrogen flowing to ICE is compose of \( P_{\text{H11}} \) and \( P_{\text{H21}} \), where the former is from PEM and the latter is from hydrogen tank. The power of hydrogen flowing to ICE is compose of \( P_{\text{H11}} \) and \( P_{\text{H21}} \), where the former is from PEM and the latter is from hydrogen tank.

The relations among the aforementioned variables can be described according to the linear programming. The linear programming model mainly includes inequality constraints and equality constraints. The equality relations for the above variables are shown in (1) - (3)

\[
(P_{\text{H11}} + P_{\text{H12}}) \eta_h + (P_{\text{gas11}} + P_{\text{gas12}}) \eta_g = P_E
\]

\[
P_{\text{wind2}} k_{\text{P2H}} = P_{\text{H11}} + P_{\text{H12}}
\]

\[
P_{\text{bio}} k_{\text{b2g}} = P_{\text{gas11}} + P_{\text{gas12}}
\]

Where \( k_{\text{P2H}} \) is the conversion efficiency of electricity to hydrogen, and \( k_{\text{b2g}} \) is that of the gasifier. The efficiency of hydrogen and hybrid gas to electricity are \( \eta_h \) and \( \eta_g \), respectively. \( P_E \) is the power produced by the ICE.

The inequality relations are presented in (4) - (7)

\[
0 \leq P_E \leq C_{\text{ICE}}
\]

\[
\begin{align*}
0 & \leq P_{\text{wind1}} + P_{\text{wind2}} \leq P_{\text{wind}} \\
0 & \leq P_{\text{wind1}} + P_E \leq P_{\text{max}} \\
0 & \leq P_{\text{wind2}} \leq C_{\text{P2H}}
\end{align*}
\]

\[
\begin{align*}
0 & \leq P_{\text{bio}} \leq C_{\text{b2g}} \\
0 & \leq P_{\text{bio}} \leq C_{\text{bio, in}}
\end{align*}
\]

\[
\begin{align*}
0 & \leq \sum_{i=1}^{N} (P_{\text{H1}(i)} - P_{\text{H2}(i)}) \leq V_H \\
0 & \leq \sum_{i=1}^{N} (P_{\text{gas1}(i)} - P_{\text{gas2}(i)}) \leq V_g
\end{align*}
\]

Where \( V_H \) is the volume of hydrogen storage tank, and \( V_g \) is that of the syngas tank. The hydrogen production capacity of the electrolytic cell is \( C_{\text{P2H}} \), the gas production capacity of the gasifier is \( C_{\text{b2g}} \), and the rated power of the ICE is \( C_{\text{ICE}} \). The maximum power consumed by the grid is \( P_{\text{max}} \).
4. Case study
In this section, parameters of an actual system are selected, which is shown in table 1. The capacity of the wind farm $P_{\text{wind}}$ is 100MW, however the maximum consumption $P_{\text{max}}$ is only 50 MW. As a result, there would be a certain quantity of wind power to be abandoned without energy storage devices. A proper installing of electrolytic cell to transfer the surplus wind power to hydrogen will smooth the wind power integrated to the power grid.

**Table 1.** the parameters in the target IES

| Variables | Value | Unit | Variables | Value | Unit |
|-----------|-------|------|-----------|-------|------|
| $\eta_H$  | 0.45  | 1    | $k_{\text{H2}}$ | 0.4   | 1    |
| $\eta_E$  | 0.35  | 1    | $P_{\text{wind}}$ | 100   | MW   |
| $k_{\text{P2H}}$ | 0.8   | 1    | $P_{\text{max}}$ | 50    | MW   |

The 1-year operating data of the wind farm is selected. The data includes the output of the wind farm for 8760 hours. It can be concluded from Fig. 3 that the wind power output becomes relatively smooth due to the addition of the PEM electrolytic cell and a hydrogen storage device in the system, and the abandoned wind power can be stored and reused. Without the PEM, the fluctuation range of wind farm power is between 0MW and 80MW. After the implementation, the entire power generation power variation range is between 10MW and 45MW. In addition, the co-combustion of syngas and hydrogen in the ICE helps to increase the burning value of syngas and the efficiency of power generation [8].

![Abandoned wind power](image1)

**Figure 3.** Power generation in the study case (The unit of the ordinate in the figure is 10,000 kWh)

| Variables         | Value | Unit | Variables         | Value | Unit |
|-------------------|-------|------|-------------------|-------|------|
| Wind power revenue| 0.86  |      | Biomass power revenue| 0     |      |
| Biomass cost      | 0     |      | Depreciation cost | 0.6   | 0.75 |
| Other costs       | 0.11  |      | Total revenue     | 0.86  | 1.26 |
| Total expenses    | 0.71  | 0.22 | Net income        | 0.15  | 0.07 |
| Return of investment| 10%   | 11.7%|                   |       |      |

**Table 2 Investment analysis results**

| Scheme | Scheme 1 | Scheme 2 | Part of Scheme 2 |
|--------|----------|----------|------------------|
| Wind power revenue | 0.86 | 0.86 | 0 |
| Biomass power revenue | 0 | 0.4 | 0.4 |
| Biomass cost | 0 | 0.14 | 0.14 |
| Depreciation cost | 0.6 | 0.75 | 0.15 |
| Other costs | 0.11 | 0.15 | 0.04 |
| Total revenue | 0.86 | 1.26 | 0.4 |
| Total expenses | 0.71 | 1.04 | 0.34 |
| Net income | 0.15 | 0.22 | 0.07 |
| Return of investment | 10% | 11.7% | 18.2% |

The investment analysis is carried out in table 2. According to the table, Scheme 1 (wind farm only) has a total expenditure of 71 million RMB per year, a total income of 86 million RMB per year, and a net income of 15 million RMB per year. The return of investment (ROI) of scheme 1 is 10%, while that of scheme 2 (wind farm plus PEM and gasifier) is 11.7%. As to the part of Scheme 2 (wind power hydrogen production coupled biomass power generation system), the total investment is 192 million RMB per year, the capital is 388.4 million RMB per year, the total annual expenditure is 34 million
RMB per year, the annual total income is 40 million RMB per year, and the net income is 7 million RMB per year. As a result, the ROI is 18%, larger than that of scheme 1 and scheme 2, indicating that the proposed system has a relatively high ROI.

5. Conclusions

This paper presents a new type of integrated energy system for coupling biomass gas with hydrogen produced by wind power. Wind power to hydrogen combined with biomass technology not only improves the burning value of syngas, but also eliminates huge energy consumption links such as compression/liquefaction of hydrogen. This system not only avoids the energy loss caused by hydrogen storage and transportation, but also can increase the burning value of syngas, thereby improving power generation efficiency. In addition, the model of this system is built according to the linear programming method, which includes inequality constraints and equality constraints. At last, the investment analysis is carried out based on an 8760-hour data from practical wind farm, which indicates that the proposed system have a relatively high ROI.

6. References

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