Full life-cycle economic evaluation of integrated energy system with hydrogen storage equipment

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Abstract. Hydrogen energy storage, as a new type of energy storage with zero carbon emission, multi-energy federal reserve and combined supply, has a good development prospect in the integrated energy system. Based on the integrated energy system with hydrogen storage equipment, this paper proposes the operation mechanism of the integrated energy system with hydrogen storage equipment in the environment of electricity market and carbon market. On this basis, considering the time value of money, the life-cycle economic evaluation model of the integrated energy system with hydrogen storage equipment is constructed. The model is applied to calculate the investment benefit of a community integrated energy system with hydrogen storage equipment in the whole life cycle. The result of an example shows that the integrated energy system with hydrogen storage equipment is of good economic benefits.

Key words: Hydrogen Storage; Integrated Energy System; Electric Hydrogen Production; Full Life-cycle; Economic Evaluation

1. Introduction

In the context of "carbon peaking", "carbon neutral" and large-scale new energy applications, hydrogen energy storage has the characteristics of zero carbon emission,multi-energy federal reserve and combined supply, which help improve the utilization rate of new energy and the stability of power system operation[1]. In the integrated energy system, the use of hydrogen storage instead of traditional battery storage can not only supply hydrogen fuel to fuel cell vehicles and support the transformation of electrified transportation, but also convert electricity into natural gas with hydrogen as a carrier in a clean and efficient manner, realizing electrical synergistic operation and complementary transformation [2]. At present, the integrated energy system with hydrogen storage equipment is technically feasible, but whether can it generate considerable economic benefits in the market environment and its economic viability are worthy of in-depth study and exploration.

At present, a series of research on investment decision-making of integrated energy system containing hydrogen storage has been carried out at home and abroad. Literature [3] analyzes the economy of hydrogen production, storage and transmission from renewable energy by using the levelized hydrogen cost analysis model. Literature [4] puts forward the optimal allocation model of hydrogen energy storage units in the park integrated energy system with the optimization objectives of investment and operation cost and carbon emission. Literature [5] constructs a multi-objective programming model of electric thermal hydrogen integrated energy system considering uncertainty with the goal of minimizing economic cost and maximizing wind and solar energy consumption rate. In reference [6], aiming at minimizing the economic cost and potential cost of daily chemical system, a family comprehensive energy system planning model based on hydrogen energy storage is constructed. To sum up, most of the existing studies focus on the cost analysis of comprehensive energy systems containing hydrogen storage, and few studies analyze the income composition of such comprehensive energy systems in the market environment and calculate the economic benefits in the whole life cycle.

In summary, this paper proposes the operation mechanism of the integrated energy system with hydrogen storage equipment in the environment of electricity market and carbon market and establishes a model to evaluate the life-cycle economic benefits of the integrated energy system with hydrogen storage equipment, and then takes a community-based integrated energy system with hydrogen storage equipment as an example to calculate whether the integrated energy system with hydrogen storage equipment is economically feasible.

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2. Integrated energy system architecture and operation mechanism with hydrogen storage equipment

The integrated energy system with hydrogen storage equipment includes wind turbines, photovoltaics, cogeneration units, electrolytic cells, hydrogen storage tanks, hydrogen refueling stations, fuel cell vehicles, methanation devices, natural gas networks, gas boilers and other equipment. The system architecture is such as As shown in Figure 1.

The electrical load in the integrated energy system is supplied by wind turbines, photovoltaic and cogeneration units.When the electric energy generated by the fan and photovoltaic cannot meet the demand, the cogeneration unit will supplement the electricity; when the electric energy generated by the fan and photovoltaic has surplus in addition to the electricity sold, the surplus electric energy is electrolyzed into hydrogen through the electrolytic cell and stored in the hydrogen storage tank, the hydrogen refueling station provides hydrogen for fuel cell vehicles.When there is a surplus of hydrogen, the methanation unit is started to convert the surplus hydrogen into methane and input into the natural gas network.The heat load is mainly supplied by cogeneration units, and gas boilers are used as supplementary heat sources.

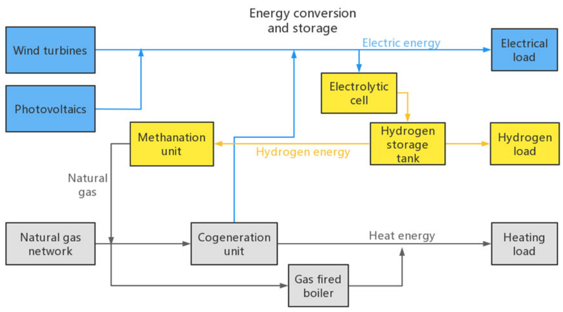

Fig 1 Architecture diagram of an integrated energy system with hydrogen storage equipment

3. Cost benefit analysis of integrated energy system with hydrogen storage equipment

3.1 Cost analysis

Assuming that the financial cost and facility exit cost are not considered, the life cycle cost of the integrated energy system including hydrogen storage equipment mainly includes investment cost, operation and maintenance cost and production cost. The investment cost includes the purchase, construction and installation costs of wind power, distributed photovoltaic, cogeneration units, electric hydrogen production, methane production units, gas-fired boilers, hydrogen storage tanks and other equipment; Operation and maintenance costs include repair costs, personnel salaries and welfare expenses; Production costs include fuel, water, etc.

3.2 Revenue analysis

In the environment of electricity market and carbon market, the integrated energy system with hydrogen storage equipment can supply electric energy, hydrogen energy, thermal energy and methane to users, and its carbon emission reduction can participate in carbon trading. Therefore, the life cycle income of the integrated energy system including hydrogen storage equipment mainly includes energy sales income, carbon emission reduction income and other income. Among them, energy sales revenue includes power supply revenue, hydrogen supply revenue, heating revenue and methane sales revenue. Carbon emission reduction revenue includes carbon emission reduction revenue from renewable energy power generation and carbon emission reduction revenue from methane production. As renewable energy, wind and light can obtain carbon emission reduction income by participating in the carbon emission reduction market. Compared with traditional coal chemical methane production, hydrogen production by electricity can reduce carbon emissions in methane production, so it can also obtain carbon emission reduction income. Other income includes equipment residual value recovery income, etc. The cost income composition of comprehensive energy system including hydrogen storage equipment is shown in Table 1.

4 Life cycle economic evaluation model of integrated energy system with hydrogen storage equipment

4.1 Life cycle NPV calculation model of integrated energy system with hydrogen storage equipment

Considering the time value of funds, the calculation of life cycle economic benefits of comprehensive energy system including hydrogen storage equipment is shown in formula (1).

$$NPV = \sum_{t=1}^{n} \frac{\left(R_t - \left(C_{t,2} + C_{t,3}\right)\right)}{\left(1+r\right)^t} - C_1 \tag{1}$$

Where, NPV is the present value of the net economic benefits of the comprehensive energy system with hydrogen storage equipment in the whole life cycle; n is the estimated service life of the project; t represents year t; R_t is the economic income of the integrated energy system in year t; C_1 is the investment cost for the construction of integrated energy system; $C_{t,2}$ is the operation and maintenance cost of the integrated energy system in year t; $C_{t,3}$ is the production cost of the integrated energy system in year t; r is the discount rate.

Table 1. Cost income composition of comprehensive energy system including hydrogen storage equipment

Cost and revenue category		Concrete content
Life cycle cost	Investment cost	Wind power
		Distributed photovoltaic
		CHP
		Electric hydrogen production
		Methane production unit
		Gas fired boiler
		Hydrogen storage tank
	Operation and maintenance cost	Repair cost
		Personnel salary
		Welfare funds
	Production costs	Fuel cost
		Charge for water
Life cycle revenue	Energy sales revenue	Power supply revenue
		Hydrogen supply revenue
		Heating revenue
		Methane sales revenue
	Carbon emission reduction revenue	Carbon emission reduction revenue from renewable energy power generation
		Carbon emission reduction revenue from methane production
	Other revenue	Equipment salvage value recovery revenue

4.2 Life cycle cost calculation model of integrated energy system with hydrogen storage equipment

(1) Investment cost of integrated energy system with hydrogen storage equipment

The investment cost of integrated energy system including hydrogen storage equipment mainly consists of seven parts: the purchase and installation cost of wind power equipment, distributed photovoltaic equipment, cogeneration equipment, electric hydrogen production equipment, methane production unit, gas-fired boiler and hydrogen storage tank. The calculation is shown in equation (2).

$$C_1 = C_f + C_p + C_c + C_e + C_m + C_g + C_h \quad (2)$$

Where, C_f, C_p, C_c, C_e, C_m, C_g and C_h are the investment costs of wind power equipment, distributed photovoltaic equipment, CHP Cogeneration Equipment, electric hydrogen production equipment, methane production unit, gas-fired boiler and hydrogen storage tank respectively. The investment cost of each equipment is directly related to the system scale, and the specific relationship is shown in equations (3) - (9).

$$C_f = U_f \times I_f \quad (3)$$

$$C_p = U_p \times I_p \quad (4)$$

$$C_c = U_c \times I_c \quad (5)$$

$$C_e = U_e \times I_e \quad (6)$$

$$C_m = U_m \times I_m \quad (7)$$

$$C_g = U_g \times I_g \quad (8)$$

$$C_h = U_h \times I_h \quad (9)$$

Where, U_f, U_p, U_c, U_e, U_m, U_g, U_h are the unit cost of each equipment; I_f, I_p, I_c, I_e, I_m, I_g, I_h are the installed capacity of each equipment.

(2) Operation and maintenance cost of integrated energy system with hydrogen storage equipment

The operation and maintenance cost of integrated energy system with hydrogen storage equipment is calculated as shown in equation (10).

$$C_2 = \sum \lambda C_i \alpha_i \quad (10)$$

Where, λ is the formation rate of fixed assets, C_i is the investment cost of class I equipment, and α_i is the freight rate of class I equipment.

(3) Production cost of integrated energy system with hydrogen storage equipment

The production cost of integrated energy system with hydrogen storage equipment is mainly composed of fuel and water. The calculation are shown in equation (11) - (13).

$$C_3 = C_u + C_w \quad (11)$$

$$C_u = Q_u P_u \quad (12)$$

$$C_w = Q_w P_w \quad (13)$$

Where, Q_u and Q_w are the annual gas consumption and water consumption of the integrated energy system respectively, P_u and P_w are the natural gas price and water price respectively.

4.3 Life cycle income calculation model of integrated energy system with hydrogen storage equipment

Life cycle income R mainly consists of six parts: power supply income R_e, hydrogen supply income R_h, heating income R_t, methane sales income R_m, carbon emission reduction income R_c and residual value recovery income R_s. The calculation is shown in equation (14).

$$R = R_e + R_h + R_t + R_m + R_c + R_s \tag{14}$$

(1) Power supply income of integrated energy system with hydrogen storage equipment
The power supply income is determined by the electricity sales (MWh) and the electricity sales price (yuan / MWh). The calculation is shown in equation (15).

$$R_e = Q_e P_e \tag{15}$$

Where, Q_e is the electricity sales; P_e is the selling price.
(2) Hydrogen supply income of integrated energy system with hydrogen storage equipment
Hydrogen supply revenue is determined by hydrogen sales volume (ton) and hydrogen sales price (10,000 yuan / ton). The calculation is shown in equation (16).

$$R_h = Q_h P_h \tag{16}$$

Where, Q_h is the hydrogen sales volume; P_h is the selling price of hydrogen.
(3) Heating income of integrated energy system with hydrogen storage equipment
The heating revenue is determined by the heat sold (MWh) and the heat sold price (yuan / MWh). The calculation is shown in equation (17).

$$R_t = Q_t P_t \tag{17}$$

Where, Q_t is the selling heat; P_t is the selling price.
(4) Methane sales revenue of integrated energy system with hydrogen storage equipment
Methane sales revenue is determined by methane sales volume (ton) and methane price (10000 yuan / ton). The calculation is shown in formula (18).

$$R_m = Q_m P_m \tag{18}$$

Where, Q_m is the sales volume of methane; P_m is the price of methane.
(5) Carbon emission reduction revenue of integrated energy system with hydrogen storage equipment
Carbon emission reduction revenue consists of carbon emission reduction revenue from renewable energy power generation and carbon emission reduction revenue from methane production, which is determined by carbon emission reduction (ton) and carbon price (yuan / ton). The specific relationship is shown in equations (19) - (21).

$$R_c = R_g + R_y \tag{19}$$

$$R_g = Q_g F_g P_c \tag{20}$$

$$R_y = Q_y F_y P_c \tag{21}$$

Where, Q_g and Q_y are respectively the annual power generation of renewable energy and the annual production of methane; F_g and F_y are carbon emission factors of electric power production and carbon emission factors of coal chemical industry to methane; P_c is the carbon price.
(6) Residual value recovery income of integrated energy system with hydrogen storage equipment
The residual value recovery income is determined by the investment cost and the residual value recovery rate. The calculation is shown in equation (22).

$$R_s = C_1 \beta \tag{22}$$

Where, β is residual value recovery.

5. Analysis of algorithms

In order to measure the economics of an integrated energy system with hydrogen storage equipment, this paper takes a community-based integrated energy system with hydrogen storage equipment as an example and conducts a full life-cycle cost-benefit calculation of an integrated energy system with hydrogen storage equipment participating in carbon trading.

5.1 Basic data

This integrated energy system with hydrogen storage equipment has a construction period of 1 year, an operation period of 20 years, a discount rate of 7.5%, a fixed asset formation ratio of 95%, a salvage recovery rate of 5% and a depreciable life of 15 years.

Table 2. Data sheet on investment costs and O&M costs

Equipment Type	Unit construction cost (million yuan/Mw)	Installed capacity (Mw)	O&M rate (%)
Wind energy	350.00	0.60	1.00
Distributed PV	950.00	2.10	1.00
CHP Combined Heat and Power	160.00	4.70	2.00
Electric hydrogen production	930.00	2.90	2.00
Methane production unit	470.00	1.90	1.00
Gas boiler	120.00	1.10	2.00
Hydrogen storage tank	128.73	7.20	2.00

Table 3. Data sheet on production costs and revenues

Specific categories of production costs and revenues	parameters
Natural gas price (Yuan/Nm^3)	3
Water price (yuan/ton)	3.15
Annual electricity sales (Mwh)	8957.1
Annual heat sales (Mwh)	5277.9
Annual hydrogen sales (tons)	22.70
Annual methane sales (tonnes)	45.69
Annual carbon emission reductions (tonnes)	4403.19
Sale price of electricity (yuan/Mwh)	800
Heat selling price (Yuan/Mwh)	330
Hydrogen sales price (million yuan/ton)	7
Methane selling price (million yuan/ton)	0.6
Carbon price (yuan/ton)	100

5.2 Results of the economic assessment

Substituting the data from Tables 2 and 3 into the integrated energy system with hydrogen storage equipment full life-cycle economics measurement tool, yields the financial indicators shown in Table 4.

Table 4. Financial indicators of integrated energy system with hydrogen storage equipment (million yuan)

Financial indicators	Parameters
Initial investment cost	76.06
Annual operation and maintenance costs	1.18
Annual production costs	2.64
Annual sales revenue	10.77
Annual carbon reduction revenue	0.44
Net present value (NPV)	0.12
Internal rate of return (%)	7.52%
Static payback period (years)	11.29
Dynamic payback period (years)	20.95

As can be seen from Table 4, the total initial investment cost is 76.06 million yuan, the annual operation and maintenance cost is 1.18 million yuan, and the annual production cost is 2.64 million yuan the annual sales revenue is 10.77 million yuan, and the annual carbon reduction revenue is 0.44 million yuan. The net present value is 0.12 million yuan, the internal rate of return is 7.52%, the static payback period is 11.29 years, and the dynamic payback period is 20.95 years. The NPV is greater than 0, the IRR is greater than the base rate of return, and the project is economically viable.

5.3 Sensitivity analysis

This section performs a sensitivity analysis on the economics of an integrated energy system with hydrogen storage equipment, and measures the impact on the NPV of the project when the price of hydrogen, the price of methane, the price of carbon, the cost of electric hydrogen production equipment, the cost of hydrogen storage equipment, and the cost of methane production equipment fluctuate in the range of -10% to 10% for each individual factor. The results of the analysis are shown in Figure 2. The results show that the NPV of the project is sensitive to the cost of electric hydrogen production equipment, the price of hydrogen followed. The cost of hydrogen storage equipment, the cost of methane production equipment, the price of carbon and the price of methane have a relatively small impact on the NPV of the project. The three items with the greatest sensitivity to NPV are all related to hydrogen, indicating that the cost of hydrogen production, hydrogen storage and the price of hydrogen sales are very important in the integrated energy system with hydrogen storage equipment which will have a large impact on the economics of the integrated energy system with hydrogen storage equipment. Therefore, with the development of technology, the cost of hydrogen storage decreases or the price of carbon is considered to increase while the economic benefits of integrated energy systems with hydrogen storage equipment will also increase.

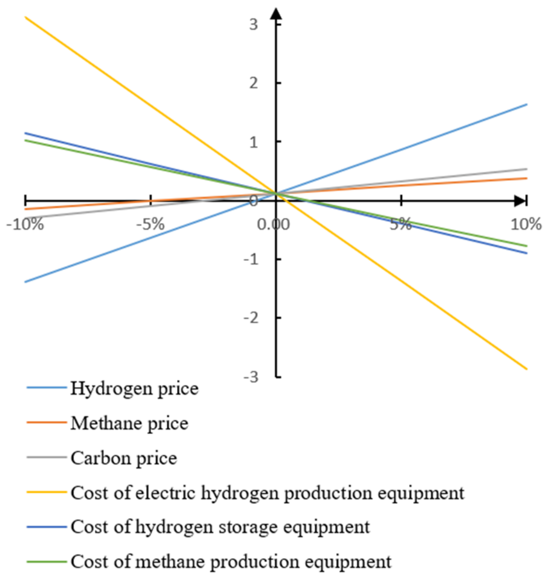

Fig 2 Sensitivity analysis of an integrated energy system with hydrogen storage equipment (million yuan)

6 Conclusion

In this paper, a community-based integrated energy system with hydrogen storage equipment is used as the research object, and a life-cycle economic evaluation model of the integrated energy system with hydrogen storage equipment is established. Under the premise of considering the time value of money, the evaluation system is measured in terms of NPV, IRR, payback period and other indicators. The calculation results yields that the integrated energy system with hydrogen storage equipment can generate investment benefits and has investment significance.

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