Economic Analysis on Electrolytic Hydrogen Production by Abandoned Wind Power

Guoxin He, Hongshui Lv, and Dongmei Yang

***Abstract*—The rationing situation of abandoned wind power in the "Three North areas of China" (northeast, northwest and North China) is grim, and increasing the local electricity load is one of the exploring ways to promote the consumption for the nearest abandoned wind power. For water electrolysis power load with the grid adaptation, combined with domestic electric power system and market environment, we discuss economical efficiency in wind power direct supply mode, which put forward a general economical criterion. With consideration of the influence factors of wind power, such as intermittence and fluctuation, a comprehensive evaluation model of wind power hydrogen absorptive system has been established. Income returns have been calculated according to the general economical criteria, meanwhile, the sensitivity influence ofmain factors has been analyzed. A scheduling architecture is proposed from the perspective of power grid. Finally, a few suggestions about the construction of the demonstration project are given.**

***Index Terms*—Water electrolysis, hydrogen production, wind power, economical efficiency.**

I. Introduction

Wind abandon and power limit situation became further intensified in the whole country which is more serious especially in "Three North" area (northeast, northwest, north China). Taking Heilongjiang province as an example, by the end of 2015, accumulated grid-connected capacityof wind power installation has been up to 5.03 million kilowatts, however, wind abandon power capacity increased to 1.9 billion kilowatts. Wind abandon rate is 21% and annual average utilization hours are only 1520 hours. From the period and reason of wind power restrictions in the northeast area, contradictions between wind power and heat supply are serious mainly in valley load period through winter nights. In the condition of a certain power load, thermal power generating units have been operated at or even under the lower limit of rated power which still cannot meet power access of large-scale wind power. Prediction accuracy of wind power is relatively low at present, if wind force increased suddenly and wind power generating units exceeded rate limitation of retroregulation of conventional power units, the power grid will limit wind power output in order to keep real-time balance and safety of power. Adding local power load can effectively boost nearby absorption of renewable energy sources except building high voltage power grid for long-distance power transmission and building power storage station which provides an exploration idea to realize energy connection.

Hydrogen is an extremely predominant new energy and the cleanest energy in the world with high combustion heat and with water as its combustion product according to the literature [1]. Hydrogen can be produced through water electrolysis and the process can be disconnected. Hydrogen can be regulated within a certain range in the process of production and its economic operation range is 20% to 110%. Therefore, hydrogen production plant can be used as a kind of power load to meet power grid dispatching.

Existing literature has stretched discussion and research on economy of producing hydrogen by wind power. For example, literature [2] has presented four schemes, namely self-provided power plant and spot utilization of hydrogen, self-provided power plant and out transportation of hydrogen, direct supply and spot utilization of hydrogen, self-provided power plant and connecting hydrogen to natural gas pipeline network, and also has made estimation and contrastive analysis to economy of each scheme. Literature [3] has built NPV model of wind power coupling hydrogen system, made predication to inflow and outflow cash and analysis of net cash flow and sensibility according to specific examples. Literature [4], [5] has researched systematic evaluation for different hydrogen production technologies. In addition, literature [6]-[11] discussed the structure of the wind hydrogen coupling system. The application of hydrogen production system in the plant is discussed in [12], [13]. At present there is seldom systematic analysis of impact factors for economy of water electrolysis hydrogen generation absorbing abandon wind and power limit. Based on current power price system and electric power system situation in China, this article introduces the operation value of wind farm and hydrogen generation plant under direct supply of wind power, analyzes impact factors that influence revenue and cost, puts forward a judgment basis which can be used to comprehensively evaluate economy of schemes and build comprehensive evaluation model of absorption system. Through practical calculation and discussion on economy of water electrolysis hydrogen generation absorbing abandon wind and power limit, it draws relevant conclusions and makes suggestions of demonstration project construction.

II. Current Situation of Domestic Electricity Price Mechanism

Since the implementation of electricity system reform in 2002, Chinese electricity market has presented a diversified competition pattern and formation mechanism of the electricity price has been improved gradually. At present,

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power grid sales price is composed of three parts, namely feed-in tariff, transmission and distribution price and governmental funds and additional. Its computation formula is as follows:

$$P_S = P_{ON} + P_{T\&D} + P_F \quad (1)$$

In the formula: P_S is power grid sales price; P_{ON} is feed-in tariff; $P_{T\&D}$ is power grid transmission and distribution price; P_F is governmental funds and various additional.

Wind power feed-in tariff is the price of electricity generation enterprise selling to power grid and is generally regulated by the National Development and Reform Commission and other governments. The transmission and distribution power price are set by power grid company. Government funds and various additional are collected by grid company. Renewable energy sources such as wind power need to be checked by price administrative department under the State Council and add additional according to the collected price of actual power of users.

With the deepening reform of electric power system, relevant ministries and commissions of the state and local governments has further intensified the efforts to carry forward direct transaction between power generation enterprise and power users, establish electricity displacement mechanism of self-provided power plant to increase renewable energy resources and achieve nearby absorption. Some provinces will further explore pilot project construction of renewable energy resources absorption through adjustment of industrial structure and enlargement of absorption market. Power selling side competition mechanism will be gradually established in the future, trading market between power generation enterprise and users will be further expanded and relatively independent power trading platform will realize of realizing muliti-party transactions directly.

III. Evaluation of Consumptive System Model

A. Wind Power Operation Value

Wind power operation value is divided into four aspects: power generation income, power generation cost, auxiliary service cost and environmental benefit by a study in laboratory of electrical engineering department of Tsinghua University. The classification is as shown in Table I:

TABLE I: Operation Value of Wind Power Resources

category	Generating revenue	cost	ancillary services	Environmental benefits
factor	Installed capacity utilization factor on-grid price	Construction and operation repay a loan	Capacity cost Electricity cost	Emission allowance

1) Wind farm power generation income is expressed with W_1 and its main impact factors are: installed capacity refers to installed capacity of grid-connected wind power and is expressed with a_1; utilization coefficient refers to the ratio of annual effective utilization hours of wind farm and annual hours, or the ratio of actual annual feed-in power of wind farm operation and rated annual feed-in power(expressed in percentage) and is expressed with a_2; feed-in tariff refers to power price of wind farm selling to grid company an is expressed with a_3.

2) Wind farm power generation cost refers to the lowest power price required for wind farm operation and is expressed with W_2, and its main impact factors are: construction and operation cost and is expressed with a_4; repayment expense and is expressed with a_5.

3) Wind farm auxiliary service cost refers to the cost paid by grid company to power generation enterprises for purchasing spinning reserve capacity and other auxiliary services and is expressed with W_3, and its main impact factors are: capacity cost refers to cost of load operation and emergency reserve and is expressed with a_6; electricity cost refers to cost paid by grid company to maintain electricity balance of electric power system and is expressed with a_7.

4) Wind farm environmental benefit is expressed with W_4, referring to environmental benefit brought by wind power replacing traditional energy power: at present it is reflected through charging power users renewable energy power price additional through in our country and is expressed with a_8.

B. Operation Value of Hydrogen Production Plant

Operation value of hydrogen production plant can be divided into four aspects, namely product revenue, production cost, ancillary service, environmental protection benefit and its classification is as shown in Table II:

TABLE II: Operation Value of Hydrogen Plant

category	Product benefits	cost	ancillary services	Environmental benefits
factor	Production capacity Run time length Product selling price	Electricity price Construction and operation Period of depreciation	Electricity cost	Environmental protection subsidies

1) Product revenue of hydrogen production plant is expressed with H_1 and its main impact factors are: hydrogen production ability refers to total amount of hydrogen of the equipment in unit time considering on and off of hydrogen production equipment, intermittent electricity and other factors and is expressed with b_1; running time refers to the actual running time of hydrogen production equipment under the set operation condition and is expressed with b_2; product selling price refers to selling prices of hydrogen product and subsidiary products per unit volume(or weight) and is expressed with b_3.

2) Production cost of hydrogen production plant refers to the lowest cost required for the plant to maintain operation and is expressed with H_2, and its main impact factors are: electricity price refers to the actual purchasing price of hydrogen production plant and is expressed with b_4; construction operation cost is expressed with b_5; depreciation life refers to economic service life initially invested by hydrogen production plant and is expressed with b_6.

3) Ancillary service of hydrogen production plant refers to additional investment required for maintaining normal operation and is expressed with H_3, and its main impact factors are: series of costs of power distribution system and

dispatching management, etc added to guarantee electricity of hydrogen production plant by the power grid company and is expressed with b_7.

4) Environmental protection benefit of hydrogen production plant is expressed with H_4 and refers to environmental benefit brought by hydrogen energy replacing conventional energies; as hydrogen energy has not been applied in a large scale, there is no corresponding subsidy policy and its factor is expressed with b_8.

C. Economic Criterion

To evaluate the economy of water electrolysis hydrogen generation absorbing wind abandon and power limit, it should include the above-mentioned all the revenue of wind farm and hydrogen generation plant in revenue calculation. It should also include all the cost in cost calculation. To analyze economy of the scheme through the ratio S of revenue and cost:

$$S = \frac{R}{C} \tag{2}$$

$$R = R_W + R_H = W_1 + W_4 + H_1 + H_4 \tag{3}$$

$$C = C_W + C_H = W_2 + W_3 + H_2 + H_3 \tag{4}$$

In the formula: R_W and C_W represent the revenue of wind farm and hydrogen generation plant in the full life circle respectively, R_H and C_H represents their cost respectively. R and C represent revenue and cost of the whole absorption system in the full life circle respectively.

In this model, when S >1, revenue is higher than cost, then benefit will be made.

D. Comprehensive Evaluation of Consumptive System

Literature [4] has discussed systematic evaluation model of hydrogen generation technology and its basic ideas are: (1) build index system: primary election, inspection, nondimensionalization of index; (2) determination of index weight: Delphi direct weight making method; (3) system evaluation: select appropriate weighted model. This model is for scientific and reasonable evaluation of comprehensive benefit value of hydrogen generation scheme. To emphasize integral performance of water electrolysis hydrogen generation absorbing wind abandon and power limit and to highlight the function of impact factors and weighted factors, mixed weighted model is selected through analysis:

$$y = \lambda_1 y_1 + \lambda_2 y_2 = \lambda_1 \sum_{j=1}^{m} \omega_j^{(1)} x_j + \lambda_2 \prod_{j=1}^{m} x_j^{\omega_j^{(2)}} + \cdots \tag{5}$$

In the formula: y is integrated assessment value of a certain system, λ is proportionality coefficient of subsystems ($\lambda_1+\lambda_2=1$, $\lambda_1>0$, $\lambda_2>0$, constant). x_j is specific indicator, ω_j is weight coefficient of indicator x_j($0 \leqq \omega_j \leqq 1$, $j=1, 2,\ldots,m$).

Based on this model, whole life circle revenue of wind farm R_W can be expressed as:

$$\begin{aligned} R_W &= \lambda_1 W_1 + \lambda_2 W_4 \\ &= \lambda_1 (\lambda_3 \sum_{j=1}^{3} \omega_j^{(1)} a_j + \lambda_4 \prod_{j=1}^{3} a_j^{\omega_j^{(2)}}) + \lambda_2 a_7 \end{aligned} \tag{6}$$

In the formula: $\lambda_1+\lambda_2=1$, $\lambda_3+\lambda_4=1$.

In the same way, R_H, C_W, C_H in formula (3) (4) all can represent mixed weighted model of a_j and b_j. Bring the result into formula (2) and we will get a comprehensive evaluation result of water electrolysis hydrogen generation absorbing wind abandon and power limit system. Based on this model, it is necessary to analyze sensibility of each impact factor in evaluation system during analyzing the reasonability of water electrolysis hydrogen generation absorbing wind abandon and power limit.

IV. Example Analysis

A. Example Analysis

Referring to actual operation situation of wind power in some province, basic assumptions and parameters adopted in this article are as shown in Table III:

TABLE III: Basic Assumption and Parameter

category	Supposed Value
Hydrogen production unit power (consumption kWh/m^3)	4.5
Hydrogen production capacity(m^3/h)	10000
Hydrogen station at least(h)	1000
Unit price of hydrogen production (Million yuan/one)	650
Water price unit price(yuan/t)	4
Hydrogen production equipment depreciation period(year)	15
transmission-distribution price(yuan/kWh)	0.1
Government funds and additional(yuan/kWh)	0.05
Wind power subsidy price(yuan/kWh)	0.25

B. Sensitivity Analysis of Main Influencing Factors

To compare the influences of different impact factors to feasibility of water electrolysis hydrogen production absorbing wind abandon and power limit, now sensitivity analyses are being made in view of key factors such as wind power subsidy price a_8, hydrogen product selling price b_3, annual running time b_2, etc.

TABLE IV: Sensitivity Analysis Result of Wind Power Subsidy Price

a_8 (yuan/kWh)	R_W (Million yuan)	R_H (Million yuan)	S
0.25	1125	700	1.07
0.20	900	700	0.94
0.15	675	700	0.80
0.10	450	700	0.67
0.05	225	700	0.54

1) Sensitivity of wind power subsidy price

Set wind power subsidy price to different values and analyze the influence of wind power subsidy to absorption scheme economy, the calculation result is as shown in Table IV.

Since January 1, 2016, take Heilongjiang province as an example, most benchmark feed-in tariff in IV resources was 0.60 yuan/kWh and decreased to 0.58 yuan/kWh in 2008, the feed-in tariff shows downward trends. From now on the government tends to cancel subsidies gradually. The idea of renewable resources in the "13th Five years" plan makes it clear to realize grid-connected side parity of wind power by 2020 reaching 0.4 yuan/kWh. As the main source of income

of water electrolysis hydrogen production absorbing wind abandon and power limit, the decline of wind power subsidy price will become an important factor considered by investment developers to invest construction of hydrogen production station.

2) Sensitivity of hydrogen product selling price

Set hydrogen product selling price to different values and analyze the influence of product selling price to absorption scheme economy, the calculation result is as shown in Table V.

TABLE V: SENSITIVITY ANALYSIS RESULT OF HYDROGEN PRODUCT PRICE

b_3 (yuan / m^3)	R_W (Million yuan)	R_H (Million yuan)	S
0.70	1125	700	1.07
0.90	1125	900	1.18
0.11	1125	1100	1.30
0.13	1125	1300	1.42
0.15	1125	1500	1.54

Hydrogen energy can be applied in many fields and fields with relatively practical operation value at present are: (1) used for urban residents and as mixed hydrogen in industrial pipelines; (2) supply fuels for urban vehicles: synthetic HCNG new fuel for taxis; (3) adopt water electrolysis hydrogen production to replace part of decomposition hydrogen production in heavy chemical industries such as petroleum, petrochemical and coal chemical industry, etc. Advantages of water electrolysis hydrogen production are using fossil fuels indirectly, high purity hydrogen production and flexible operation; disadvantages are the cost is higher than traditional hydrogen production from coal and natural gas and economy is not good. Selling price of hydrogen product depends on demand of different hydrogen markets in the future.

3) Sensitivity of running time

Set running time to different values and analyzes the influence of annual running time of hydrogen production equipment to absorption scheme economy, the calculation result is as shown in Table VI.

TABLE VI: SENSITIVITY ANALYSIS RESULT OF RUN TIME LENGTH

b_2 (h)	R_W (Million yuan)	R_H (Million yuan)	S
1000	1125	700	1.07
1250	1406	875	1.21
1500	1688	1050	1.33
1750	1969	1225	1.44
2000	2250	1400	1.53

Considering volatility and intermittency of wind power and seasonality of wind abandon and to guarantee actual running time of hydrogen production plant, a hydrogen production station needs to sign direct power supply agreements with many wind farms. As the load changes a lot, power grid needs to participate timely to ensure that hydrogen production station can reach ideal running time.

4) Comprehensive sensitivity analysis

Wind farm revenue (ten thousand yuan) has no sensitivity to hydrogen product selling price and sensitivities to wind power subsidy price and running time are as shown in Fig. 1:

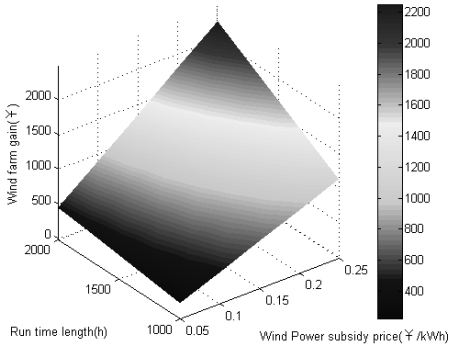

Fig. 1. Wind farm gain sensitivity.

Hydrogen production plant revenue (ten thousand yuan) has no sensitivity to wind power subsidy price and sensitivities to hydrogen product selling price and running time are as shown in Fig. 2:

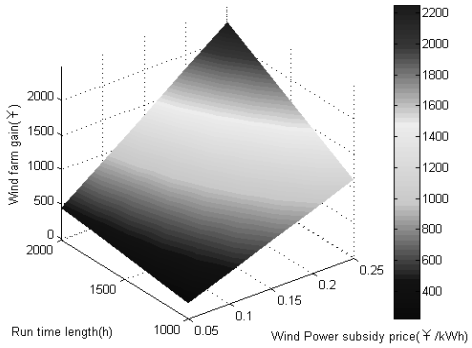

Fig. 2. Hydrogen production plant gain sensitivity.

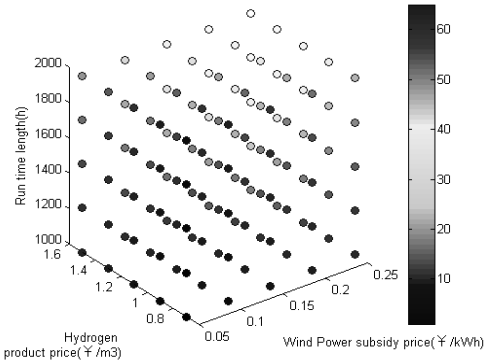

Fig. 3. Total return sensitivity.

Sensitivities of full life circle revenue R of Water electrolysis hydrogen production absorbing wind abandon and power limit to the three main above-mentioned impact factors are as shown in Fig. 3.

In conclusion, the absorption system is a complex system composed of wind farm, hydrogen production plant, hydrogen product users and power grid companies, etc. and its economy is influenced by many factors, among which wind power subsidy price, actual running time of the hydrogen station and selling price of hydrogen product have a greater influence on the economic benefits of absorption system.

V. Conclusion

This paper builds an evaluation model for economy of water electrolysis hydrogen production by absorbing wind abandon and power limit. Although the conclusion of this research is time-limited with the development of technology, ideas and methods used in the evaluation system have a long practicability which makes this model have a certain extension. Through numerical example analysis of the model, this paper discusses the sensitivities of multiple factors under direct supply model of wind power. Through the analysis, conclusions are drawn as follows: 1) adopting water electrolysis hydrogen production absorbing wind abandon and power limit, the opening of high purity hydrogen market helps further quantify hydrogen revenue and value; 2) to realize the improvement of overall acceptance ability of wide-area wind farm through dispatching and optimizing of power grid and at the same time improve operation efficiency of hydrogen production plant; 3) the security of absorption system and its influence to power grid need further study; 4) it needs more incentive policies to realize absorption of renewable resources through hydrogen production.

From the point of view of economy, this paper focuses on operation value of water electrolysis hydrogen production by absorbing wind abandon and power limit under direct supply model of wind power. Various factors could affect costs and benefits, which lead to a conclusion of the research through sensitivity analysis. Wind power hydrogen production is a comprehensive and complex system of renewable resources absorption system, more discussions and analyses are needed to finally get a propagable and practical solution. The next step is to combine the development of the hydrogen market and the reform of the electric power system and further explore complementary applications of hydrogen, wind power and solar energy from two aspects of technology and economy to provide reference for the construction of future energy Internet.

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