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A Feasible and Green Approach for Developing Hydrogen Energy

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ABSTRACT

Hydrogen is recognized as the green energy with the greatest potential for future development, but currently, China's hydrogen production is highly dependent on raw fossil materials, which conflicts with the original intention of developing hydrogen energy. As the abandoned hydropower problem in Southwestern China is serious. The current strategy can be focused using surplus hydropower to produce hydrogen in a green way. In this study, the technical cost and advantage of hydrogen produced using surplus hydropower using the levelized cost of energy model was analyzed. The results show that cheap surplus hydropower will considerably reduce the cost of hydrogen produced using electrolyzing water, and the cost is comparable to that of coal gasification hydrogen production. The hydropower to be abandoned by Southwestern China annually can drive the hydrogen production with 1.2 million tons per year, providing a technically and economically feasible approach to developing hydrogen energy.

INTRODUCTION

Hydrogen is recognized as the most promising type of secondary energy due to its high calorific value, clean emissions, and huge prospective reserves on earth. The development and use of this clean energy is strategically important for solving the two major crises, energy shortages and environmental pollution, currently plaguing humankind.

Since 2011, China has been the world's largest producer and consumer of hydrogen energy. However, the hydrogen energy production process in China is not green; more than 80% hydrogen energy is produced using raw fossil materials, especially coal and natural gas. Using coal and natural gas to produce hydrogen not only requires a large quantity of raw fossil materials and large amounts of heat, but also produces environmental pollutants through waste residue and waste liquid. This obviously conflicts with the original intention of developing clean hydrogen energy.

Two kinds of clean raw materials for hydrogen production have not been fully used in Southwestern China: water and the electric power generated by hydro power. As the capability of installed hydro power generation is far higher than the local demand, a large amount of water and the hydro power are abandoned every year. If the to-be-abandoned water and hydro power were used to produce hydrogen using the electrolysis water method, the redundant hydro power energy could be stored in the form of hydrogen, and the hydrogen-producing process would be greener.

The major problem is that when using the industrial electricity price, the cost of hydrogen produced using the electrolysis water method is much higher than using raw fossil materials (Cao 2017). The cost of producing hydrogen with the electrolysis water method is about USD $5.2/kg, whereas the cost of using raw fossil materials to produce hydrogen is about USD $1.67/kg (Cao 2017). As the to-be-abandoned water and hydro power can be sold much cheaper than the industrial electricity price and raw fossil materials, the cost of hydrogen produced by the electrolysis water method can hopefully be reduced to a competitive level. In this study, we focused on whether it is feasible to lower the cost of hydrogen production using the to-be-abandoned water and hydro power in Southwestern China.

STATE OF ART

Developing hydrogen energy has been a common goal in most developed countries. Japan has announced a national strategy to build a hydrogen society by 2040 (Mao 2016), Germany and France planned to develop hydrogen industry for a greener traffic system (Mao 2016), the USA planned to substitute hydrogen for fossil energy by 2030. China has introduced a strategy to develop hydrogen energy and become the world's largest hydrogen producer (Mao 2016).

As the hydrogen process in China is not green, and environmental pollution continues to increase, some scholars are calling for hydrogen to be produced with renewable energy and materials (Zou et al. 2019, Yi et al. 2018). For example, Yi et al. (2018) stated that hydrogen can be produced by water electrolysis with solar or wind power. However, this idea is not without its issues. In China, wind and solar energy resources are concentrated in the northwest, where water resources are in extremely short supply. Long-distance electric power transport will increase the hydrogen production costs. Thus, using solar or wind power in water electrolysis is not appropriate, but the sufficient hydro power and water in Southwest China can be used for hydrogen production.

Few studies have focused on the issue of whether producing hydrogen using the to-be-abandoned hydro power in Southwest China is technically and economically feasible. The levelized cost of energy (LCOE) model is a useful method for evaluating the cost of energy per unit in production (Lina et al. 2018), and it has been widely used in evaluating energy cost, such as: Ioannou et al. (2017) use it in accounting the cost of a wind farm, Vazquez & Iglesias (2015) use it in tidal resource cost accounting, Mikel et al. (2016) use it to account a solar project's cost. In this study, we built a cost accounting model and prove the feasibility of this new approach to producing hydrogen.

METHODOLOGY

Modeling for Accounting Levelized Cost of Energy

According to the definition of LCOE, a project's net present value cost is equal to the net present value of profit. The equation can be written as

$$I_0 - V_R \cdot (1+r)^{-N} + \sum_{n=1}^{N} C_n \cdot (1+r)^{-n} = \sum_{n=1}^{N} P_n \cdot E_n \cdot (1+r)^{-n} \quad \ldots(1)$$

Where, I_0 indicates the initial investment amount of the project, V_R indicates the residual value of the asset, n indicates the years of project operation, N indicates the project's operational life, C_n indicates the project's annual expenditure cost in year n, r indicates the discount rate, P_n indicates the energy price in the year n, and E_n indicates the quantity of energy produced in the year n. Then, the LCOE can be obtained from Equation (1) and written as

$$\text{LCOE} = P_n = \frac{I_0 - \dfrac{V_R}{(1+r)^N} + \sum_{n=1}^{N} C_n \cdot (1+r)^{-n}}{\sum_{n=1}^{N} E_n \cdot (1+r)^{-n}} \quad \ldots(2)$$

Where, C_n includes the costs of initial fixed asset investment, taxes, asset depreciation, and project operation and maintenance. C_n can be expressed as

$$C_n = OPE_n + TAX_n - I_{dn} \quad \ldots(3)$$

Where, OPE_n indicates the project's operation and maintenance costs, TAX_n indicates the tax costs, and I_{dn} indicates the asset depreciation costs. E_n in Equation (2) can be written as

$$E_n = W_s \cdot H_n \cdot (1 - R_n) \quad \ldots(4)$$

Where, W_S indicates the project's production capability per hour, H_n is the project's production hours in year n, and R_n indicates the project's production loss rate in the year n.

The variables I_{dn}, OPE_n, and TAX_n can be specifically written as

$$\begin{cases} I_{dn} = I_0 (1-v) \cdot N^{-1} \\ T_{an} = E_n \cdot P_n \cdot \tau_a \\ T_{bn} = T_{an} \cdot \tau_b \cdot \\ T_{cn} = (E_n \cdot P_n - T_{an} - T_{bn} - I_{dn} - OPE_n) \cdot \tau_c \\ TAX_n = T_{an} + T_{bn} + T_{cn} \\ OPE_n = E_n \cdot (w_1 \cdot g + w_2 \cdot l_n) \end{cases} \quad \ldots(5)$$

Where, v is the asset's residual value rate, T_{an} is the project's value added tax paid in year n, T_{bn} is the project's surtax paid in year n, T_{cn} is the project's income tax paid in year n, τ_a is the value added tax rate, τ_b is the surtax rate, τ_c is the income tax rate, w_1 is the cost of electric power used in water electrolysis, w_2 is the project's variable cost per unit hydrogen output, g is the quantity of electricity needed per unit hydrogen output, and l_n indicates the increasing coefficient for project's operation and maintenance. Substituting Equations (3)–(5) into Equation (2), the LCOE is:

$$LCOE = \frac{I_0 - V_R \cdot (1+r)^{-N} - I_0 (1-v) \cdot N^{-1}}{\sum_{n=1}^{N} E_n \cdot (1+r)^{-n}} + \frac{E_n \cdot (w_1 \cdot g + w_2)}{\sum_{n=1}^{N} E_n \cdot (1+r)^{-n}} + \frac{T_{an} + T_{bn} + T_{cn}}{\sum_{n=1}^{N} E_n \cdot (1+r)^{-n}} \quad \ldots(6)$$

From Equation (6), the LCOE can be obtained by the rolling years' iteration calculation.

Modeling for Cost Sensitivity Analysis

The purpose of cost sensitivity analysis is to analyze the influence on hydrogen production cost when relative parameters change. The cost sensitivity of hydrogen production can tell that, which parameters should to be exogenously regulated, for the proper cost control. Consider the equation (6) as a function:

$$LCOE(x_1, x_2, \cdots x_i) \quad \ldots(7)$$

Where, $x_1, x_2, \ldots, x_i$ indicate the relative parameters in the cost calculation of hydrogen production. Then the sensitivity analysis can be written as:

$$F_j = \frac{\Delta LCOE_j}{LCOE_0} \cdot \frac{x_{j0}}{\Delta x_j} \qquad \ldots(8)$$

Where, $1 \leq j \leq 1$. x_{j0} indicates the initial value of parameter x_j. Δx_j indicates the change value of parameter x_j. $LCOE_0$ indicates the cost of hydrogen production when all the parameters are set as the initial values. $\Delta LCOE_j$ indicates the change rate of hydrogen production cost when the parameter x_j changes with the value Δx_j. F_j indicates the sensitive value when the parameter x_j changes.

RESULTS AND DISCUSSION

Parameters Setting

According to actual tax amounts and, raw materials and hydrogen output prices in China, the parameters for LCOE calculation were set as following: I_0 = USD $1.1 billion; N = 30 years; V_R = 5%; the depreciation rate of assets = 4.75%; W_s = 162 kg/hour; H_n = 2400 hours/year; w_1 = USD $21.43/MWh (Lin, et al. 2016), w_1 = USD $0.71 /kg; g = 0.05 MWh/kg (Lin et al. 2016); τ_a =17%, τ_a =8%, τ_c =25%, r=6.5%. l_n was set to 0 when $0 \leq n \leq 5$; l_n was set as 1.05 when $6 \leq n \leq 15$; l_n was set as 1.08 when $16 \leq n \leq 25$; and l_n was set as 1.10 when $26 \leq n \leq 30$. R_n was set to 0 when $0 \leq n \leq 5$, 3% when $6 \leq n \leq 15$, 6% when $16 \leq n \leq 25$, and 9% when $26 \leq n \leq 30$.

Calculation and Comparison of Hydrogen Production Costs

By bringing the parameters above into Equation (6), we obtained the following: First, if using traditional electricity to produce hydrogen by water electrolysis with the industrial electricity price, the LCOE of hydrogen would be USD $4.87/kg. This result is close to the result reported by Cao (2017). This means the model built in this study is accurate. Second, if using the to-be-abandoned water and hydro power in Southwestern China, the LCOE of hydrogen would be reduced to USD $1.90/kg. Compared with the costs of other hydrogen producing methods, the advantage of this result is shown in Fig. 1.

Fig. 1 shows that the LCOE of hydrogen obtained using to-be-abandoned water and hydro power is significantly lower. The accumulated after-tax cash flow can be obtained from the rolling years' iteration calculation. Compared to the same project using traditional industrial electricity, the accumulated after-tax cash flows are shown in Fig. 2.

Fig. 2 shows that during the project's life, using to-be-abandoned water and hydro power can result in project profitability, whereas the use of traditional industrial electricity results in project losses.

In summary, Figures 1 and 2 prove that using to-be-abandoned water and hydro power can water electrolysis can be competitive in the hydro market.

COST SENSITIVITY ANALYSIS

In the reality, the parameters of value-added tax rate and assets depreciation rate are relatively fixed, while the parameters of hydrogen price and project's surtax rate may fluctuate. Thus, in this study, six parameters are selected as the investigation objects, and the change rates are set as 10% and -10%. Then the sensitivity coefficients of hydrogen production' LCOE to the parameters are obtained according to the equation (8). The results are depicted in Table 1.

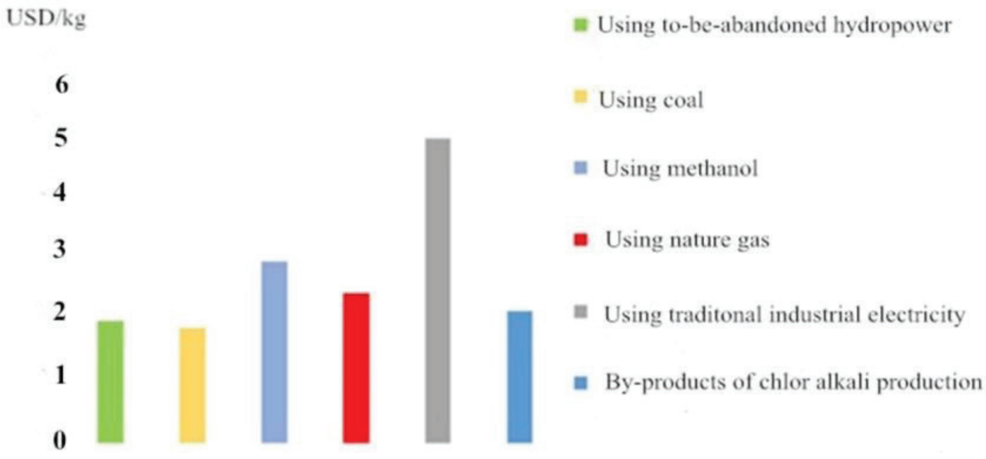

Fig. 1: Cost comparison of different hydrogen production methods.

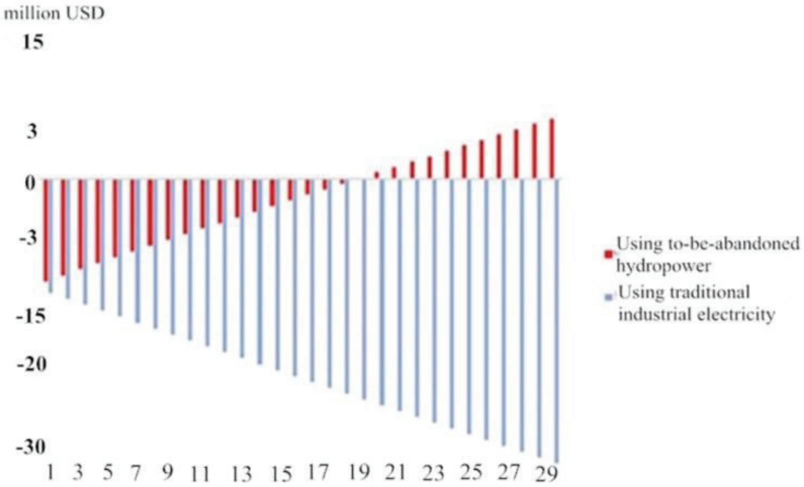

Fig. 2: Comparison of accumulated after-tax cash flows.

Table 1: Sensitivity analysis.

Parameters	LCOE (USD/kg)		Sensitivity Coefficient	
	+10%	-10%	+10%	-10%
Annual hydrogen production quantity	13.965	12.942	0.478	0.290
Discount rate	13.032	14.008	-0.222	-0.510
Project’s variable cost per unit hydrogen output	13.720	12.937	0.294	0.294
Hydrogen price	14.407	12.261	0.809	0.801
Price of to-be-abandoned hydropower	13.891	12.766	0.422	0.422
Surtax rate	13.354	13.303	0.019	0.019

It can be found from Table 1 that, the LCOE of hydrogen production project is most sensitive to the hydrogen price, followed by the parameters of price of to-be-abandoned hydropower, discount rate and annual hydrogen production quantity. The LCOE is least sensitive to the parameters of surtax rate and project’s variable cost per unit hydrogen output. The specific analyses are as following:

First, the hydrogen price is positively related to project’s to-be-paid value-added tax, which is vital to the LCOE. If the hydrogen price rises, LCOE will be also pulled up. But the change rate of LCOE is smaller than that of hydrogen price. This phenomenon is implying that, hydrogen price rigidity will be more welcomed by the project.

Second, as the project’ LCOE is sensitive to the price of to-be-abandoned hydropower, it is vital to minimize the potential cost of power transmission. Therefore, it is necessary for the project to be built adjacent to hydropower plants.

In addition, as the LCOE is not sensitive to surtax rate and project’s variable cost per unit hydrogen output, the cost fluctuation in human resources and equipment maintenance will not shock the LCOE significantly.

Since 2014, the amount of annual abandoned hydro power in Southwestern China was more than 60 million MWh, and a single project could use 0.019 MWh/year. So, more than 3000 projects can be built for fully using the energy and more than 1.2 million tons of hydrogen could be produced every year. Therefore, developing this green hydrogen production method is technically and economically feasible. In this case, the wasted energy in Southwestern China can be fully used.

CONCLUSIONS

This study provides a feasible approach to solving the energy waste and green hydrogen production problems in Southwest China. Using the LCOE model, we proved that the cost of hydro production can be significantly reduced when using the to-be abandoned water and hydro power, and the cost would be competitive in the hydrogen market. The to-be-abandoned hydro power is capable of producing more than 1.2 million tons hydrogen annually. We predicted that this feasible approach to hydrogen production will have positive environmental and social benefits.

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