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# Research on the Oxygen Eco-Compensation Benefit of Hydropower Station to Thermal Power Station

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The oxygen ecological compensation benefit is an attempt proposed on the premises of oxygen depletion theory. After proposing the definition of oxygen ecological compensation benefit of hydropower to thermal power, the CDM method is employed to obtain the carbon dioxide emission reduction of the reservoir and then calculate the reduction of oxygen consumption in cases where thermal power is replaced by hydropower to generate electricity. And finally, Liujiaxia hydropower station of the Yellow River is taken as an example to obtain that the oxygen ecological compensation benefit of the hydropower station in target year 2020 is 51.55 million yuan. The study provides scientific basis for water and electricity prices setting and also provides reference for China's electric power structure reform.

## 1. Introduction

Ecological compensation has gradually developed into the important means to protect the ecological environment and an academic focus at a global level. It is often referred to as Payments for Ecosystem/Environmental Services (PES) in foreign literature. Based on Coase's theory, Wunder (2005) first defines eco-compensation as a voluntary transaction on environmental services reached between purchasers and providers. In accordance with Pigou theory, Muradian et al., (2010) defines it as a resource transfer between the participants of social activities in natural resource management which provide incentives for the harmony between individual or/and collective land-use decision-making and social benefits. The research on ecological compensation by domestic scholars is mainly focused on forest protection, coal mining, water resources protection and other fields. For example, the team led by Huang Qiang from Xi'an University of Technology has carried out a comprehensive and systematic study on the compensation benefits of the cascade hydropower stations on the Yellow River. The research findings in this field by other scholars are also focused on the compensation for electricity generation between reservoirs or reservoir groups, lacking research on compensation benefit between hydropower and thermal power, which is also rare in foreign research. In this paper, the reduced oxygen consumption is adopted as the research object to calculate the oxygen ecological compensation benefit produced in the cases where hydropower conducts power compensation on thermal power, thus providing basis for scientific setting of water and electricity prices and ensuring the healthy development of hydropower.

## 2. The basic concept of oxygen ecological compensation benefit

### 2.1 Mechanism and definition of oxygen ecological compensation benefit

By the end of December 2015, China's installed power capacity has reached about 1.5 billion kW, among which thermal power occupies 66% and hydropower accounts for 21%. It can be seen that China's electricity supply mainly relies on thermal power, probably in the long term. Thermal power plants mainly generate power by coal combustion, which not only produces polluting gases but also consumes oxygen. It is generally believed that oxygen is "inexhaustible", but the actual situation is not the case. Chen (2008) points out that the harm caused by oxygen depletion is more serious than that by greenhouse effect. The burning of fossil fuels decreases the concentration of oxygen in the atmosphere, and the decline of oxygen concentration directly

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threatens the survival of living things because the survival of humans and other organisms requires a certain concentration of oxygen, which emphasizes the inevitability to reduce oxygen consumption.

Thermal power plants can bring about environmental pollution and damage during power generation, which will be imputed to the society in the form of economic losses. Hydropower as a kind of clean energy does not consume oxygen or produce polluting gases in the process of power generation, but these contributions are not reflected and rewarded but unfairly treated in the development of hydropower (Pan, 2004), which is not conducive to the healthy and sustainable development of hydropower. According to the theory of environmental economics, the economic externalities should be internalized to ensure the well-ordered economic development. Therefore, the oxygen ecological compensation benefit in this paper is defined as the economic benefit produced through the reduction of oxygen consumption of coal combustion due to the power compensation of hydropower, belonging to the scope of ecological compensation benefits (Zheng et al., 2009; Perrone and Ameli, 2016; Li et al., 2016; Zain et al., 2017; Chistyakov et al., 2017).

### 2.2 Quantification of oxygen ecological compensation benefits

*Table 1: Basic situation of CDM in China*

| Types of emission reduction | Ratified projects |  | Registered projects |  | Issued projects |  |
|---|---|---|---|---|---|---|
|  | quantity | Rate (%) | quantity | Pass Rate (%) | quantity | Rate (%) |
| New and renewable sources of energy | 1969 | 70.70 | 858 | 43.58 | 239 | 27.86 |
| Energy conservation and energy efficiency improvement | 493 | 17.70 | 90 | 18.26 | 35 | 38.89 |
| Methane recovery and utilization | 188 | 6.75 | 63 | 33.51 | 17 | 26.99 |
| $N_2O$ decomposition and elimination | 28 | 1.01 | 25 | 89.29 | 6 | 24.00 |
| Fuel replacement | 46 | 1.65 | 18 | 39.13 | 10 | 55.56 |
| HFC-23 decomposition | 11 | 0.39 | 11 | 100.00 | 11 | 100.00 |
| Garbage incineration power generation | 8 | 0.29 | 4 | 50.00 | 1 | 25.00 |
| afforestation and reforestation | 4 | 0.14 | 3 | 75.00 | 0 | 0 |
| Others | 38 | 1.36 | 7 | 18.42 | 1 | 14.29 |
| Total | 2785 | / | 1079 | / | 320 | / |

| Types of emission reduction | Expected average annual CERs from registered projects |  | Expected average annual CERs from Issued projects |  |
|---|---|---|---|---|
|  | quantity | Rate (%) | quantity | Rate (%) |
| New and renewable sources of energy | 105 649 590.386 | 40.21 | 29 337 440.6 | 19.95 |
| Energy conservation and energy efficiency improvement | 22 703 512.000 | 8.64 | 13 999 094.0 | 9.52 |
| Methane recovery and utilization | 22 415 096.000 | 8.53 | 9 292 280.0 | 6.32 |
| $N_2O$ decomposition and elimination | 24 600 966.000 | 9.36 | 17 923 987.0 | 12.19 |
| Fuel replacement | 17 362 226.000 | 6.61 | 9 147 883.0 | 6.22 |
| HFC-23 decomposition | 66 798 446.000 | 25.42 | 66 798 446.000 | 45.44 |
| Garbage incineration power generation | 1 159 812.000 | 0.44 | 150 158.0 | 0.10 |
| afforestation and reforestation | 116 272.000 | 0.04 | 0 | 0 |
| Others | 1 974 455.000 | 0.75 | 377 383.0 | 0.26 |
| Total | 262 780 375.386 | / | 147 026 671.6 | / |

The value of oxygen is difficult to measure at this stage because the reduction of oxygen has not brought about significant social impact, but the ecological compensation benefits of oxygen can be indirectly obtained. It is necessary to select the appropriate standard and basis to measure the value of oxygen ecological compensation in the replacement of thermal power with hydropower. Although the economic value of oxygen is unable to be estimated currently, coal combustion will consume oxygen and produce carbon dioxide. The international research on carbon trading has been launched and achieved some results, and many countries in the world, especially Sweden, the Netherlands, Italy and other countries in Europe have begun to impose carbon tax (EEA, 1996). Carbon tax is the internalization of the external cost of carbon dioxide emissions, and the right of carbon emission trading is to achieve the transfer of right to carbon emission through market mechanisms. The implementation of carbon taxes and carbon trading permit influences business decision-making by changing the corporate profit function (Pigou, 1992). Carbon trading is a trade of carbon emission permit in market conditions, aiming to reduce global greenhouse gas emissions, especially carbon dioxide emissions. The adoption of the Kyoto Protocol in December 1997 marked a consensus on environmental protection throughout the world. The Kyoto protocol is the first legally binding international treaty of the United Nations Framework Convention on climate change, the three flexible mechanisms proposed by protocol has promoted the formation and development of international carbon finance market. The Kyoto Protocol introduced a market mechanism that decided to trade carbon dioxide as a commodity, opening up a new path to reducing greenhouse gas emissions and forming a carbon trading market through transaction of carbon dioxide emission permits (Feng, 2016).

The clean development mechanism (CDM) is an important mechanism for the implementation of greenhouse gas emission reduction worldwide, and it is a form of project cooperation between developed and developing countries, it is a "win-win" policy. After the Kyoto Protocol came into effect, huge emission reduction potential and low emission reduction costs attracted investors from many developed countries to buy emission rights, CDM is developing rapidly in our country. As of November 12, 2010, the national development and Reform Commission approved the CDM project has reached 2785; As of December 13, 2010, China had registered 1079 CDM projects in the United Nations (Timilsina, 2006).

The CDM methodology is adopted in this paper to quantify the price of carbon dioxide, and the mass fraction of oxygen in the relative molecular mass of carbon dioxide is taken as the reduction factor λ, which is multiplied with the price of carbon dioxide to conduct a quantitative calculation of the unit price of oxygen. The formula is as follows:

$$P_{O_2} = \lambda P_{CO_2} \tag{1}$$

$Po_2$ is the ecological benefit price of a unit of oxygen; λ is the mass fraction of oxygen in the relative molecular mass of carbon dioxide, taking 0.73; $Pco_2$ represents the price of carbon dioxide obtained through quantitative calculation with CDM method.

## 3. Calculation of Oxygen Ecological Compensation Benefit

### 3.1 The selection of calculation method

Hydropower as a kind of clean energy is identified as an important part of the CDM project by international organizations (Li, 2007). Projects approved by the Executive Board (EB) of CDM can participate in the sale of greenhouse gas emissions in the carbon trading market. Therefore, the price of carbon dioxide can be quantitatively calculated with CDM method, and then the price of oxygen ecological compensation benefits can also be obtained. In the 97 approved methods of EB (Zhang and Li, 2008), AMS-I. D and ACM0002 apply to hydropower projects, which have different scopes of application. The power density is taken as the threshold value of their applicable range, and the formula is

ω= (the installed capacity of hydropower station)/(the inundated area at full water level) (2)

Different calculation methods are employed for different hydropower stations. The AMS-ID method is used when $\omega \leq 4W/m^2$ and the installed capacity of the power station is less than 15 MW. The ACM0002 method is adopted when $4W/m^2 \leq \omega \leq 10W/m^2$; and the carbon dioxide emissions from the reservoir are measured with the carbon dioxide emission factor being 90g/kW•h. When $\omega \geq 10W/m^2$, the ACM0002 method should be employed irrespective of carbon dioxide emissions from the reservoir.

### 3.2 Reduction of carbon dioxide emissions

According to the calculation method of CDM, the reduction of carbon dioxide in hydropower stations requires the calculation of the following aspects: the amount of carbon dioxide emissions $PE_y$ produced by hydroelectric power generation; the baseline emissions $BE_y$ of hydroelectric power generation; the leakage of carbon dioxide $L_y$ in hydropower; the carbon dioxide emission reduction $ER_y$ of hydropower projects.

(1) Carbon dioxide emissions $PE_y$ produced by hydroelectric power generation. The installed capacity of hydropower stations at the upper reaches of the Yellow River is relatively large, so ACM0002 method is employed to carry out the calculation exclusive of power plants whose installed capacity is less than 15MW. When $4W/m^2 \leq \omega \leq 10W/m^2$, $PE_y$ =90g/kW•h; when $\omega \geq 10W/m^2$, $PE_y$ = 0.

(2) The baseline emissions $BE_y$ of hydroelectric power generation. Provided that there is no hydropower project in a power grid, all the hydropower in the power grid needs to be replaced by thermal power to meet the normal operation of the grid and the needs of users, in which cases the thermal power project is called the baseline project. The reduced amount of carbon dioxide emitted by the hydropower project relative to the baseline (i.e. thermal power project) is the emission reduction of hydropower, with which the reduction of oxygen consumption by hydropower can be obtained. The ACM0002 method is adopted to conduct the following calculation:

$$BE_y = EG_y \times 0.5 \times (OM + BM) \tag{3}$$

$$CM = \omega_{OM} \times OM + \omega_{BM} \times BM \tag{4}$$

In the formulas, $EG_y$ is the electricity capacity of the hydropower project in the year of y; CM is the emission factor of the power grid which the hydropower project belongs to; OM is the power emission factor; BM is the capacity emission factor; $\omega_{OM}$ and $\omega_{BM}$ are the weight of OM and BM, respectively, and $\omega_{OM}= \omega_{BM}= 0.5$ in this paper. The value of emission factors in our country is region-based, and the baseline emission factors for different regions in 2013 are shown in Table 1.

*Table 2: The baseline emission factors of the power grids in 2013*

| Name of the power grid | *OM*/t(MW·h)$^{-1}$ | *BM*/t(MW·h)$^{-1}$ |
|---|---|---|
| North China | 1.030 2 | 0.577 7 |
| Northeast region | 1.112 0 | 0.611 7 |
| East China | 0.810 0 | 0.712 5 |
| Central China | 0.977 9 | 0.499 0 |
| Northwest region | 0.972 9 | 0.511 5 |
| Southern China | 0.922 3 | 0.376 9 |

(3) The leakage of carbon dioxide $L_y$ in hydropower. It is negligible in this calculation method, i.e. $L_y = 0$.
(4) The carbon dioxide emission reduction $ER_y$ of hydropower projects. It can be calculated according to the following formula

$$ER_y = BE_y - PE_y - L_y \tag{5}$$

### 3.3 Reduction of oxygen consumption through replacement of thermal power with hydropower

Under the carbon trading mechanism, the ACM0002 method is used to calculate the reduced amount of carbon dioxide emission through replacement of thermal power with hydropower. Coal combustion will produce carbon dioxide, sulfur dioxide and other gases, which may consume oxygen. In the composition of coal, carbon takes a percentage of 80%, and the oxygen consumption of other elements is negligible. Thus, the amount of carbon dioxide produced by the reaction of carbon and oxygen is used to quantitatively calculate the oxygen consumption during the thermal power generation process. The average carbon content of 1kg coal is 0.8kg, so 1kg of coal will consume about 2.13kg of oxygen, producing 2.93kg of carbon dioxide.

### 3.4 The price of carbon dioxide

*Table 3: Carbon trading prices (yuan/t)*

| Date | Opening price | The highest price | The lowest price | Closing price | Average price |
|---|---|---|---|---|---|
| 2015-07-06 | 29.00 | 29.00 | 28.87 | 28.87 | 29.00 |
| 2015-07-07 | 25.98 | 25.98 | 25.98 | 25.98 | 25.98 |
| 2015-07-08 | 23.38 | 23.38 | 23.38 | 23.38 | 23.38 |
| 2015-07-09 | 21.04 | 25.72 | 21.04 | 25.72 | 21.47 |
| 2015-07-10 | 23.15 | 28.29 | 23.15 | 28.29 | 23.16 |
| 2015-07-13 | 25.46 | 30.00 | 25.46 | 30.00 | 25.51 |

At present, China does not establish a real significance of the carbon trading market, and therefore does not establish a corresponding price system, the research on price is still in its infancy. The carbon trading market price of China's Shenzhen Emission Rights Exchange is adopted in this paper. According to the average price of the carbon trading transaction price of Shenzhen Emission Rights Exchange from July 6, 2015 to July 13, 2015 (see Table 2), the price of carbon trading can be obtained and recorded as $P_{CDM}$.

The carbon trading price $P_{CDM}$ in this paper is calculated by the following formula:

$$P_{\mathrm{CDM}} = \frac{\sum_{i=1}^{n} \overline{P}}{n} \tag{6}$$

where $\bar{P}$ is the average price of everyday carbon trading for Shenzhen Emission Rights Exchange.

In accordance with the formula (6) and Table 1, it can be calculated that the carbon trading price is 24.75 yuan/t.

### 3.5 Standards of oxygen ecological compensation benefit

The standard of oxygen eco-efficiency can be calculated in three steps: (1) select the power generation capacity $EG_y$ of a hydropower station; (2) calculate the reduced carbon dioxide emission in the year by replacing the generated power of hydropower station with that of thermal power; (3) calculate the oxygen ecological compensation benefit standards according to the price of carbon trading developed in this paper.

According to the formula (1), it can be obtained that the standard of oxygen ecological compensation benefit is 18.07 yuan / t.

## 4. Practical applications

Liujiaxia reservoir is a large-scale reservoir mainly serving to generate power, which also serves for the comprehensive benefits including flood control, irrigation, ice prevention and aquaculture. Liujiaxia hydropower station possesses an installed capacity of 1.16 million kW with a guaranteed output of 489.9 thousand kW; its normal water level is 1 730m with the corresponding submerged area of 106.7km$^2$, according to which the power density of Liujiaxia reservoir is obtained to be 10.87W/m$^2$. The baseline emissions $EB_y$ can be calculated with formula (3), and the carbon dioxide emission reduction $ER_y$ can be obtained through formula (4). So, the reduction of oxygen consumption $S_y$ through replacement of thermal power with hydropower is:

$$S_y = 0.73 \times ERy = 0.73 EG_y \times 0.5 \times (OM + BM) - PE_y - L_y \tag{7}$$

Based on the carbon trading price mechanism, the ecological compensation benefit of oxygen is the product of the oxygen consumption reduction and the price of oxygen ecological compensation benefit in the replacement of thermal power with hydropower.

$$B_{O_2} = S_y \times P_{O_2} \tag{8}$$

After literature [10] presents the optimal operation of hydropower station for 2020 level year, the power generation capacity of the Liujiaxia Hydropower Station is 5.431 billion kW•h.

Liujiaxia hydropower station is located in the northwest region, so the generated electricity is incorporated into the northwest power grid. It can be seen from Table 1 that OM=0.9729, BM=0.5115 and the carbon dioxide emissions of hydroelectric power $PE_y$=0. It can be calculated that the annual $CO_2$ emission reduction of Liujiaxia Hydropower Station in 2020 is 3,908,691t and that the oxygen consumption reduction reaches 2,853,342t. Therefore, the oxygen ecological compensation benefit of Liujiaxia Hydropower Station in 2020 is 51.56 million yuan.

## 5. Conclusion

(1) In this paper, an indirect method is employed to calculate the ecological compensation benefit of oxygen, and the oxygen ecological compensation benefit for Liujiaxia Hydropower Station in 2020 is calculated to be 51.56 million yuan, aiming to prove that hydropower is of vital importance in the development of national economy and to remind people to pay attention to oxygen depletion and actively protect the environment in the meantime.

(2) Hydropower exerts huge oxygen ecological compensation benefit on thermal power. Under the environment of energy saving and emission reduction, the proportion of hydropower in power grid needs to be raised to enhance the oxygen ecological compensation benefit of hydropower. Related policies beneficial to the sustainable development of hydropower should be introduced to promote the healthy development of hydropower.

(3) The method used in this paper is only an attempt for oxygen ecological benefits, and the ecological value of oxygen needs to be further studied.

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