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Full Cost Accounting for Renewable Natural Gas Produced from High Concentration Organic Wastewater

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High-concentration organic wastewater (HCOW) has great potential in the production of renewable natural gas. However, in the conversion process from HCOW to biofuel, many influencing factors are not yet included in the cost accounting. To address this issue, this work introduces the method of full cost accounting (FCA). This method first identifies potential environmental and social factors that may arise during wastewater treatment, and uses environmental impact assessment and monetary evaluation to each influencing factor. Then, the monetary evaluation shows that the unit cost of renewable natural gas is 3.71 CNY/m^3, which is 1.57 times of the economic cost that do not take into account environmental and social externalities. It provides a monetary indicator to enable calculating the hidden costs of unsustainable practices for sustainability assessment, which can comprehensively consider economic, environmental and social aspects.

1. Introduction

High concentration organic wastewater (HCOW) primarily originates from industries such as coking, pharmaceuticals, papermaking, petrochemicals, and, food processing. Due to its high-nutrient organic components, HCOW holds significant potential for the production of renewable natural gas (RNG), reducing environmental impacts (Olajire, 2020). However, previous studies on biogas production have primarily focused on economic aspects without adequately considering environmental and social costs. Dahl et al. (1993) explored the price of biogas in terms of development, supply, distribution, and, operation costs. This economic perspective was further refined by Zhang et al. (2019), who evaluated the cost of natural gas per unit product through exergetic and exergoeconomic assessments. Additionally, Keogh et al. (2024) examined the influence of biogas plant scale, location, and technology on biogas pricing. Despite these valuable insights, these studies often overlook the broader societal and environmental impacts associated with RNG production. To address these gaps, this paper introduces the full cost accounting (FCA) method to evaluate economic, environmental, and social costs.

FCA enables a more holistic understanding of the true costs of RNG production, allowing for the better allocation of direct economic and internal environmental costs and quantifies and monetizes external environmental and social impacts (von Braun et al., 2023). By using financial indicators to describe the effects of production processes on the environment and society (Burritt et al., 2021), FCA integrates both internal and external costs into the decision-making process. This integration helps combine economic, environmental, and social factors, facilitating the early identification and avoidance of future environmental costs and responsibilities. Consequently, this approach can enhance environmental performance and promote sustainable development (Plagiannakos et al., 1997). For RNG production from HCOW, FCA can demonstrate whether the process is sustainable and profitable by identifying costs that are not internalized and highlighting the risks and opportunities associated with natural resource and ecosystem depletion. By providing estimates of these external costs, as shown in Figure 1. this paper sheds light on the comprehensive environmental and social costs of RNG production, which often exceed the direct market prices of RNG.

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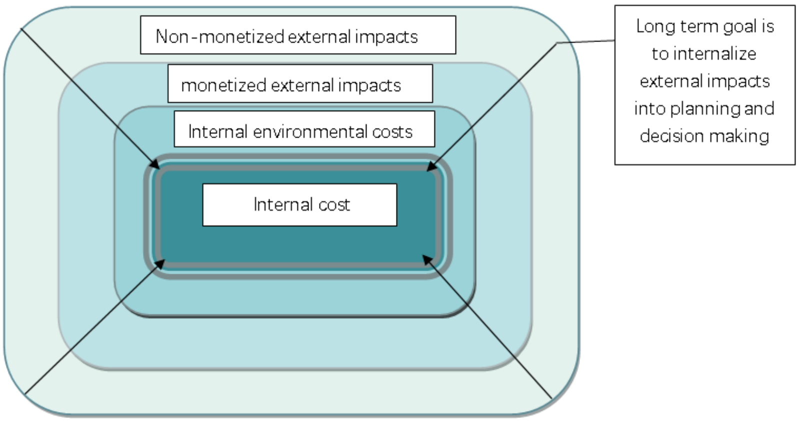

Figure 1: The concept of FCA

2. Methodology

2.1 Internal costs

Internal costs (ICs) are divided into direct economic costs and internal environmental costs. Firstly, ICs are determined based on the direct correlation between HCOW RNG production activities. To better link ICs with the main activities involved in RNG production, cost categories are established. The process of RNG production consists of three stages, namely pretreatment, anaerobic digestion, and biogas purification. Therefore, the main cost categories of direct economic cost are divided into pretreatment cost (PC), anaerobic digestion cost (ADC), and biogas purification cost (BPC). Internal environmental costs (IECs) can be divided into waste gas treatment cost (WGTC) and wastewater treatment cost (WWTC) according to the treatment content.

2.2 External cost

External costs (ECs) are divided into external environmental costs (EECs) and social costs (SCs), as shown in Eqs(1~8). The EECs are further divided into air and water pollution environmental costs. By modeling the calculation of the environmental cost of air pollution, we can directly obtain the environmental cost EC_1 caused by greenhouse gases, EC_2 caused by atmospheric pollutants other than greenhouse gases, EC_W caused by water pollution, mainly the part of sewage discharged into urban sewage treatment plants. The SCs consider the harm of environmental pollution caused by RNG production to human health.

$$EC_1 = \sum \beta \times Qa \times Pa \tag{1}$$

$$EC_2 = \sum 0.6Ma \tag{2}$$

$$Ma = La/Da \tag{3}$$

$$EC_{W=} \sum Ca \times Va \tag{4}$$

$$SC = C_1 + C_2 + C_3 \tag{5}$$

$$C_1 = \sum R_1 \times A \times W_A \tag{6}$$

$$C_2 = R_2 \times S \tag{7}$$

$$C_3 = \sum R_2 \times D \times W_D \tag{8}$$

Where β represents the warming potential of greenhouse gases relative to CO_2. Qa represents the total production of greenhouse gas emissions, The cost for carbon capture is expressed in Pa. Ma represents the equivalent number of pollutants. La represents the emission amount of pollutants, and Da for the equivalent value of pollutants. Ca represents the quantity of sewage, and Va for the value of sewage per cubic meter. C_1 represents the disease cost, and C_2 for the medical expenses. C_3 represents the lost labor cost of patients, in which R_1 represents the number of premature deaths caused by diseases, R_2 represents the number of patients suffering from a certain disease at the same time, A represents the average life expectancy remaining due to a certain disease, W_A represents the average annual salary of people, S represents the average cost spent in treating a certain disease, D represents the number of days lost due to a certain disease, and W_D represents the average daily salary of people.

3. Results

The COD concentration in HCOW from distiller's grains is 61 kg/m^3, considering the scope of the entire accounting for producing RNG, as shown in Figure 2, it includes three stages: pretreatment, anaerobic fermentation, and biogas purification. Firstly, transport the collected HCOW from distiller's grains to the biogas plant. After pretreatment, they are converted into biogas through anaerobic fermentation process (UASB), and then purified by HPWS process, all three stages will discharge pollutants into the environment during the operation process.

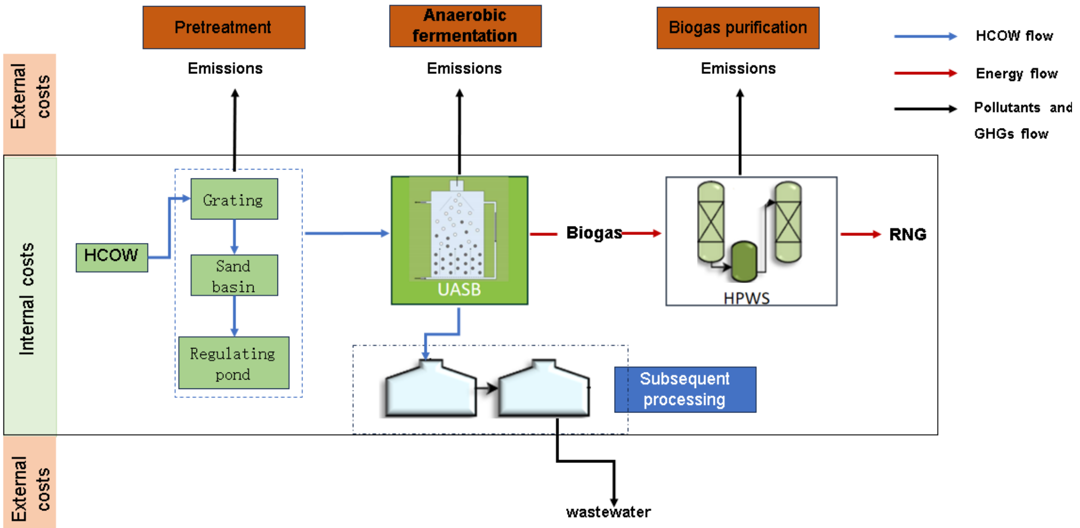

Figure 2: The scope of the accounting

3.1 Internal costs

The direct economic cost is calculated based on the three main activities involved in the HCOW RNG production process, namely pretreatment cost (PC), anaerobic digestion cost (ADC), and biogas purification cost (BPC). Therefore, the direct economic cost is CNY 7.87 M. The internal environmental costs include waste gas treatment cost (WGTC) and waste water treatment cost (WWTC). The internal environmental cost is CNY 1.07 M. The total of ICs is CNY 8.94 M.

3.2 External costs

From a process perspective, CH_4, H_2S, and NH_3 are emitted during the anaerobic fermentation stage and biogas purification stage. In addition, the residual COD, NH_3-N, and TP in the wastewater of the UASB system are discharged into the urban sewage treatment plant. The consumption of electricity in each stage will be accompanied by the emissions of CO_2, NOx, and SO_2. Calculate the indirect emissions of sulfur dioxide, nitrogen oxides, and carbon dioxide generated from electricity consumption based on the emission coefficients of sulfur dioxide and nitrogen oxides from various regional power grids in China (Cao et al., 2019) and the carbon dioxide emission factors released by the Ministry of Ecology and Environment of China.
As shown in Table 1, four environmental impact types were selected for research, namely CH_4, CO_2, which will have an impact on global warming potential (GWP 100 y), CH_4, NOx, SO_2 which will have an impact on photochemical ozone formation potential (POCP), NH_3, NOx, SO_2, H_2S which will affect acidification effect (AP), (AP), NH_3-N, NOx, COD, BOD which will affect eutrophication effect (EP). The weight of each stage's impact on the environmental impact categories is listed in Figure 3.

Table 1: Pollutant emission inventory

	Power/ substance	Pretreatment	Anaerobic fermentation	Biogas purificationn
Inputs	HCOW (m^3)	1,000	1,000	1,000
	Power (kWh)	5.20	14.10	196.39
Outputs	CH_4 (kg)		3.08	8.18
	H_2S (kg)		6.5×10^{-3}	10.55
	CO_2 (kg)	2.9	12.67	552.61
	NH_3 (kg)		0.01	0.93
	SO_2 (kg)	0.39×10^{-3}	0.84×10^{-3}	0.01
	NOx (kg)	0.18×10^{-3}	0.54×10^{-3}	6.84×10^{-3}
Drainage	COD (kg)		1.6	
	TP (kg)		0.04	
	NH_3-N (kg)		0.02	

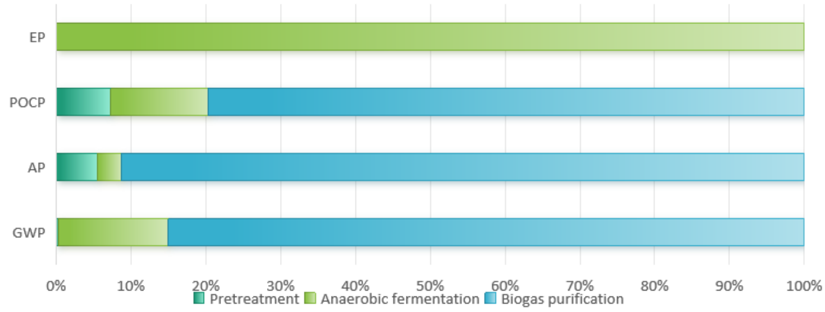

Figure 3: Environmental Impact Score

The biogas purification stage has the greatest impact on POCP, AP, and GWP in the process of producing high concentration organic waste from distiller's grains, while the anaerobic fermentation and pretreatment stages have a lower contribution. This is because the final exhaust gas in the biogas purification stage is completely discharged, and the pretreatment and anaerobic digestion stages only involve pollutant emissions caused by electricity consumption and gas leakage.

(a) Air pollution cost

The cost of CO_2 capture in China is approximately CNY 0.29 /kg. Therefore, the EECs cost generated by greenhouse gas emissions is approximately CNY 2.03 M. According to the table of taxable pollutants and equivalent values by the State Taxation Administration of China (2020), the equivalent values of NH_3, SO_2, H_2S, and NO_X are 0.95, 0.95, 0.29, and 0.95. The EECs added by the discharge of other pollutants is about CNY 0.18 M. The total environmental cost caused by air pollution is CNY 2.21 M.

(b) Water pollution cost

Water pollutants consist of COD, NH3-N, and TP respectively. It is discharged into the urban sewage treatment plant in the anaerobic digestion stage, with a daily output of 991.89 m^3. According to the concentration of COD, the sewage treatment charges 4.4 CNY /m^3 wastewater, and the value of sewage in a year is CNY 1.44 M.

(c) Social costs

The main atmospheric pollutants emitted during the production of biogas are H_2S and NH_3. H_2S is a highly toxic and corrosive gas, and exposure to H_2S increases the risk of sepsis (Gaddam et al., 2017). An increase in ammonia concentration can cause renal failure, which is a serious chronic disease (Le Maout et al., 2018). Renal function will be irreversibly lost. If these substances are present in people's living environment for a long time, it will increase the probability of people getting sick. The incidence of sepsis is 0.29% (Cavalcanti et al.,2018), According to the China Statistical Yearbook (2022a, 2022b), causing patients to lose labor force for 0.11 y, requiring medical expenses of about 9,956.51 CNY/person. The incidence of renal failure is 0.25% (De Pinho et al., 2022), causing patients to lose labor force for 0.12 y, requiring medical expenses of about 12,829.34 CNY/person; Spending 0.06 y and 0.10 y on bedtime and missed work, respectively, with a per capital annual income of CNY 6,250, results in a daily per capital income of about CNY 17. Assuming a permanent population of 50000, the probability of illness caused by the production of biogas is 25%. The ratio of the number of patients to the number of caregivers is 1:1, resulting in about 36 people suffering from sepsis and about 33 people suffering from kidney failure symptoms. Such people are absent for about 4993 days, so the cost of air pollution on human health is CNY 0.84 M.

3.3 Analysis of results

The ICs of producing RNG from HCOW, which is CNY 8.94 M, of which the direct economic cost accounts for 88.03% of the ICs. Figure 4 shows that the ADC and BPC account for the main part of the direct economic cost, which is closely related to the equipment used in the two stages. The internal environmental cost only accounts for 11.97 % of ICs, and the WGTC is relatively high. Wet denitrification and desulfurization process and activated carbon adsorption are mainly used for pollutant removal. The EC is CNY 4.48 M, with EECs accounting for 81.34%. Figure 5 shows the largest proportion of losses caused by air pollution. Equipment and technology upgrades and renovations can be carried out based on the specific emissions of pollutants. Although the proportion of social costs to external costs is not very high, it can still cause certain damage to the human body. The environmental pollution generated during the production of RNG is inevitable and can cause harm to human health. Producers can provide health benefits or subsidies based on their own situation, such as support for health examinations, disease prevention and control.

From the perspective of direct economic cost, the price of natural gas is 2.36 CNY/m^3. The greenhouse gas emissions, air pollution, and water pollution generated during the natural gas production stage will cause losses to the environment and human health. Taking these factors into account, the price of RNG has risen to 3.71 CNY/m^3. The government should formulate policies that are conducive to the development of the natural gas industry, such as tax incentives, subsidies, etc. To reduce production costs, RNG producers can improve the production efficiency of HCOW-producing RNG and reduce direct economic costs; At the same time, producers should strengthen their awareness of environmental protection to reduce environmental pollution during the production of RNG, thereby reducing external environmental and social costs.

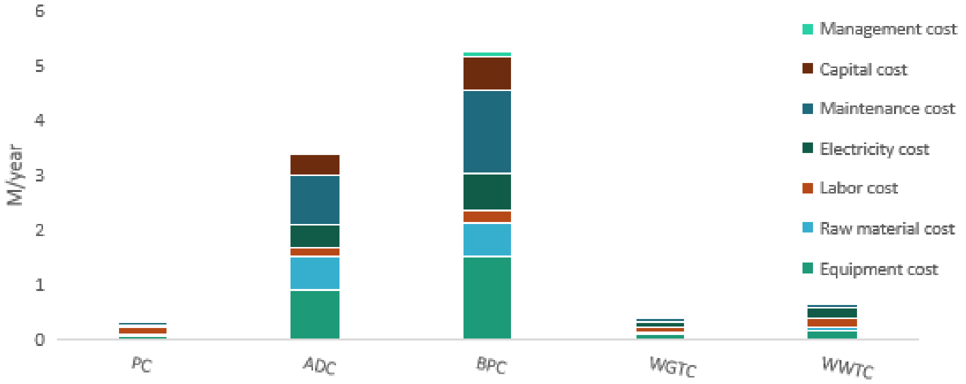

Figure 4: The detailed Internal Costs for the case study

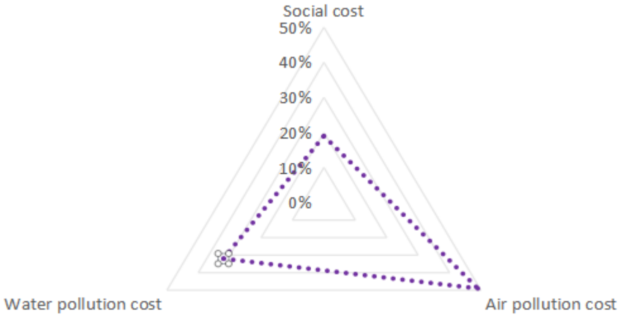

Figure 5: The proportion of losses caused by ECs

4. Conclusions

FCA is a useful tool for cost accounting, which can better understand and manage its environmental impact and costs. According to the accounting results, the RNG price is calculated to be 3.71 CNY/m^3. This approach requires good environmental impact and cost data. However, the implementation of FCA will face some challenges, as the internalization of externalities requires the participation of participants throughout the system, and more importantly, citizens and decision-making bodies. This involves policy tools such as differential taxation and subsidies to encourage fuel production to reduce pollution and save resources. This paper only focuses on measuring air pollution and water pollution losses in the EECs accounting. It is necessary to further develop and improve the existing data through field investigation and more extensive literature review, to study the loss of soil nutrients and yield reduction caused by soil erosion caused by water pollution, and to strengthen the research on the loss of biodiversity caused by phosphorus eutrophication. while exploring the adoption of appropriate pollution prevention and control measures to achieve a dual effect of reducing pollution, improving resource utilization, and enhancing economic benefits to achieve sustainable development.

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