Inventory analysis of carbon footprint on greenhouse gas emission of large-scale biogas plants

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Abstract: Inventory analysis of greenhouse gas emission for large-scale biogas plants using carbon footprint method still needs to be improved. Based on the life cycle theory, the application of carbon footprint on four large-scale biogas plants was analyzed in this paper, which comprehensively considered project progresses of civil engineering construction, operation and comprehensive utilization of residues and slurry. Also the greenhouse gas emissions during the construction and waste removal stages were analyzed and estimated. The carbon footprint of those plants was analyzed in different types and scales. The results showed that the larger scale plant will produce relatively lower carbon footprint. The greenhouse gas emission of energy production, utilization during the period of anaerobic digestion accounted for more than 96% of the entire life cycle emission. The proportion of greenhouse gas emissions on equipment, demolition recycling and transportation phases was smaller, which was less than 1.5% and should be simplified in calculation. The greenhouse gas emission of building materials production can be ignored.

Keywords: biogas plant, carbon footprint, life cycle, greenhouse gas, emission reduction
DOI: 10.3965/j.ijabe.20160904.2076

Citation: Zhou Y G, Zhang Z X, Zhang Y X, Zhou J, Chen L, Yin X F, et al. Inventory analysis of carbon footprint on greenhouse gas emission of large-scale biogas plants. Int J Agric & Biol Eng, 2016; 9(4): 99－105.

1 Introduction

Currently, reduction of greenhouse gas emission has already become a worldwide hotspot of political, economic and academic research fields[1]. Most investigations of greenhouse gas emission focus on emission mechanism, emission and economic growth evolution, and the relations between emission and energy structure[2-4]. However, there are few researches focusing on the analysis of emission sources. Carbon footprint analysis method is suitable for analyzing the entire process of carbon emission in the view of life cycle, which comprehensively considers the source of greenhouse gas emission, analyzes the essential process of project emission, and develops scientific and reasonable emission reduction plan[5]. The calculation of carbon footprint could be used as guidelines for energy conservation and emission reduction for enterprises and organizations[6]. It helps them to analyze greenhouse gas emission during life cycle process and make it convenient to establish effective schemes for emission reduction[7].

Received date: 2015-07-26 **Accepted date:** 2016-04-28
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According to the report by the United Nations Food and Agriculture Organization (UNFAO), animal husbandry is one of the major greenhouse gas emission sources[8]. The greenhouse gases generated by animal husbandry accounted for 18% of the total greenhouse gas emissions around the world if calculated as per equivalent of CO_2. Construction of large-scale biogas plants in livestock and poultry farm is a key project of renewable energy construction in China and the key treatment of animal excrement and urine, and organic waste. It can provide clean energy, lighten environmental pollution in rural areas, and present favorable environmental benefit as well as reduce methane emission of excrements of livestock and poultry which can ease the global warming trend[9]. Currently, life cycle assessment method has already been used in environmental benefits analysis of household biogas projects[1,10-13], which can provide support for energy conservation and emission reduction. Greenhouse gas emission inventories should be improved although the life cycle assessment of large-scale biogas plant has already been widely applied[6,14]. Therefore, this study introduced carbon footprint into the environmental assessment of large-scale biogas plant, which comprehensively considered greenhouse gas emission in each phase of the project according to life cycle assessment method, defined cubic meters of biogas as a functional unit, analyzed footprint of large-scale biogas plant, and quantified greenhouse gas emissions of the project. The carbon footprint of the functional unit of the case project was compared and analyzed in the study, and the energy conservation and emission reduction scheme were selected and optimized. However, when calculating the carbon footprint of the selected plants, the carbon emission of a certain process accounted for less than 1%; and the carbon emission caused by human self-activities were excluded from the boundary[15-18]. This study would judge the effectiveness of carbon emission in each phase has also been considered.

2 Data sources and analytical methods

2.1 Data sources

This study adopted relevant standards and statistical technical data of existing biogas plants in China, combined relevant data including China Statistical Yearbook and Environment Statistical Yearbook. The authors also referred to related construction literatures, bids, project feasibility study reports, etc., and finally obtained relevant greenhouse gas emission data, involving energy consumption, transportation and construction processes. Furthermore, the emission type and coefficients of building materials were obtained from literatures, professional books and data base.

2.2 Analytical methods

Carbon footprint analysis methods include process analysis method (life cycle assessment method) and input/output analysis method, etc.[1,19] This study adopted process analysis method and calculated the carbon emission of each process in the life cycle by studying input and output data inventory of the life cycle, so as to obtain the carbon footprint. The calculations are consisted of flowchart, system boundary definition, data collection, calculation of footprint and inspection of results, etc.

3 Defining of system boundary

It is assumed that excrement and urine were collected and utilized within 24 h without greenhouse gas emission. The following process should be fully considered when defining of system boundary: production and acquisition of building materials and equipment, civil construction (earthwork leveling, etc.), acquisition of raw materials, the period of anaerobic digestion, utilization of biogas, comprehensive utilization of digested residues and slurry, recycling of wastes, transportation (transportation of raw materials, digested slurry and residues from/to the farmland, transportation of building materials and equipment to the plant site, and transportation of recycled materials to recycle station). The boundary did not include substances account for less than 5% of total building materials mass and materials with little environmental relevancy[15-18,20], such as the sand in building materials. For example, greenhouse gases generated by growth and development of livestock and the process of obtaining animal products are not included[21].

The calculation of carbon footprint is shown as follows:

$$CF=\sum CF_I=\sum\sum m_i\cdot EF_i \quad (1)$$

where, CF refers to carbon footprint, kg CO_{2e}; CF_I refers to greenhouse gas emission of biogas digester in the I^{th} phase of life cycle, kg CO_{2e}; m_i refers to the usage of the i^{th} substance; EF_i refers to emission factor of the i^{th} substance, kg CO_{2e}/kg.

4 Inventory analysis

Greenhouse gas emission generated from excrements of livestock and poultry breeding was not included in the scope of carbon footprint of biogas plant[7,22]. If starting from the perspective of carbon neutral, CO_2 emission absorbed and utilized by biomass cannot be taken into account[23]. Therefore, CO_2 emission absorbed and utilized by renewable biomass like straw and excrement was not included in the inventory analysis. Building materials mostly consumed included glass, ceramic tile, steel, cement and face brick[24-28]. Some data unavailable in China were extrapolated according to relevant references[29-31] plus 20%-30%[25]. As a result, greenhouse gas emission factors of building materials were listed in Table 1. Greenhouse gas emission of instruments and equipment was calculated as greenhouse gas emission produced by textures and materials of equipment. The emission during the plant construction phase was traditionally and roughly calculated by emission factor multiplying by the quantity of plant[25]. Another major source of greenhouse gas emission from biogas plants came from the process of obtaining daily power, such as the combustion of fuels in machines and electric generator[32]. Biogas leakage occurred during anaerobic fermentation process and biogas delivery phases. Demolition recycling process was studied by referring to the calculation steps during the construction phase. The specific process emission factors are shown in Table 2. Energy consumption including fossil energy and electricity needed during the operation of the plant. However, it did not include self-supplied part of biogas combustion and power generation. The estimation of greenhouse gas emission in transportation was related to the vehicle type, distance, fuels and the running power[29]. Diesel locomotive was usually adopted for transportation. Oil consumption of locomotive was 1.738×10^{-4} kg/(kg·km)[22] and the greenhouse gas emission factor was 74.037 kg CO_{2e}/MJ[33].

Table 1 Greenhouse gas emission factors of unit building material exploration and production

Type of building materials	Emission factor EF/g $CO_{2e}\cdot kg^{-1}$
Reinforcing steel bar	3755
Other steel	3589
Glass	1582
Cement	1169
Wood	200
Lime	1570
Face brick	131
Concrete block	216

Table 2 Greenhouse gas emission factors of demolition process

Process demolition item	Demolition process emission factor
Crushing and component demolition	7.78 kg $CO_{2e}\cdot m^{-2}$
Earthwork leveling	0.62 kg $CO_{2e}\cdot m^{-2}$
Crane handling	285 kg $CO_{2e}\cdot t^{-1}$

5 Case study

5.1 Project overview

The scale of pig farm where biogas plant A located was 6000 pigs/a, the excrement of breeding pigs was 1.3 kg/(pig·d). The entire TS volume was 1560 kg/d and the biogas output was calculated as 0.3 m^3/kg TS. Therefore, biogas output of this plant was 468 m^3/d in total, about 30 m^3 of the biogas production was used for cooking, and 438 m^3 was used for self-supported power generation. Annual power energy consumption of the plant for daily operation was 34010.1 kW·h, and the annual capacity of biogas power generation was 255792 kW·h. Therefore, the plant can provide electrical energy to the public besides the normal operation consumption of the biogas plant. It adopted USR reactor with the volume of 400 m^3. For biogas plant A, the daily coal consumption for heating was 58.6 kg/h, the equipment ran for 24 h/d, and the heating duration was calculated as 120 d/a. The operation period of the biogas project lasted for 20 years.

The amount of breeding pigs and piglets where biogas plant B located was 10000 pigs/a and 25000 piglets/a, respectively. For biogas plant B, the total wastewater treatment capacity was 200 t. The biogas output was 1274 m^3/d. Small part of biogas produced was used for cooking, and the remaining biogas was mainly used for biogas power generation. The remaining electric power generated would be sold besides meeting the electricity demand for daily operation of the biogas plant. Biogas plant B adopted two up-flow solid reactors (USR) which were suitable for high-suspension solid feedstock. The volume of each reactor was 490 m^3, the total volume was 980 m^3. Coal consumption for heating was 2345 kg/h; the equipment running for 24 h/d was with the efficiency of 75%; and the heating duration was calculated as 120 d/a. The operation period of biogas plant B lasts for 20 years.

On the livestock farm where biogas plant C located, the amount of breeding hens was 300000 hens/a; the amount of broiler breeders was 150000 breeders/a. The amount of cattle on the farm was 1000 cattles/a. There were totally four other farms within 5 km with 70000 hens/a and four pig farms with amount of sows 143 pigs/a, growing and fattening pigs 569 pigs/a in total. Continuous stirred tank reactor (CSTR) was adopted in large biogas plant C. There were two anaerobic tanks of 2500 m^3, one double-membrane dry-type gas storage tank with the volume of 500 m^3 and one set of biogas purification and compression equipment. Daily treatment volume of mixed excrements from hens, cattle and pigs reached 166 t and the daily biogas output was 5000 m^3. After purification, 3000 m^3/d of renewable natural gas could be obtained. The capacity of compressed natural gas could be 1 080 000 m^3 every year. The maximum annual income of selling compressed natural gas would reach 2 916 000 RMB according to the current market price of 2.7 RMB/m^3. The daily power consumption of the biogas plant itself was approximately 1150.0 kW·h. Biogas boiler was used for heating up the digestion tank. Besides, no coal consumption existed. The annual production period was calculated as 360 d and the plant operation period could last for 20 years.

There were 10000 cows/a fed where biogas plant D located. The fresh cow dung and urine treatment capacity was 350 t/d. Continuous stirred tank reactor (CSTR) was adopted by biogas plant C with the volume of 2500 m^3 in total. Daily biogas output was 10000 m^3. The daily power generation was 16000 kW·h and the annual generating capacity was approximately 5 760 000 kW·h. The energy used for heating up the digestion tank was waste heat of the generator. Furthermore, a thermal insulation layer was set up beyond the digester to satisfy the normal operation demand in winter. The annual operation period lasted for 360 d and the project operation period could last for 20 years.

5.2 Analysis of results

Through analysis of greenhouse gas emission conditions of four large-scale biogas plants, i.e. A, B, C and D, in the life cycle, carbon footprint of each plant and the proportion of each phase were shown in Table 3 and Figure 1.

Figure 1 indicated the greenhouse gas emission of biogas plant A during demolition recycling, equipment and building materials production phases were less than biogas plant B. Greenhouse gas emission during transportation phase accounted for very small part of the whole greenhouse gas emission of biogas plants. For the energy production and utilization phase, greenhouse gas emission of biogas plant B was 10% less than that of biogas plant A, while during anaerobic digestion phase biogas plant B was about 10% greater than that of biogas plant A. The difference proportion of greenhouse gas emission between biogas plant A and B mainly existed in construction phase. For biogas plant B, greenhouse gas emission result from the construction phase was less than 1% and this could be ignored, while that of plant A was greater than 1%. However, the final result was that the unit carbon footprint of biogas plant B less than that of biogas plant A. Therefore, under the condition of same power supply method and the same thermal insulation method of digestion tank, the bigger the scale of biogas plants are, the smaller the carbon footprint per unit will be.

When plant D and plant C’ (two same-scale plants C), given the same daily biogas output, the reasonable improvement of utilization rate of renewable energy in the biogas plant effectively reduced greenhouse gas emission. The carbon footprint of functional unit of the plant became lower and more energy-conservative and environmental-friendly.

Figure 1 indicated that the greenhouse gas emission of energy production and utilization, the period of anaerobic digestion accounted for more than 96% of the entire greenhouse gas emission of biogas plants. Greenhouse gas emissions of equipment, demolition recycling, transportation phase quite small, took up less than 1.5%. For building materials production phase, the greenhouse gas emission of the investigated four plants was lower than 1%. Therefore, during the calculation of the footprint of large-scale biogas plants, the greenhouse gas emission during building materials production stage can be ignored.

5.3 Uncertainty analyses

Greenhouse gas emission during construction and demolition process was estimated according to relevant data of the construction industry. For the transportation phase, greenhouse gas emission was estimated based on relevant data of national transportation industry as well as plant operation cost data. There were also some assumptions for transportation tools, total transportation volume and relevant emission factors. Therefore, indirect emission of carbon footprint of biogas plants was of relatively significant uncertainty. However, the proportion of this part of greenhouse gas emission was relatively low, which was less than 1%, therefore the uncertainty was acceptable.

Table 3 Results of the carbon footprint of large-scale biogas plants

Project	Scale/m^3	Daily biogas output/m^3	Electric power	Thermal insulation method of fermentation tank	Project total emissions/t CO_{2e}	Carbon footprint of functional unit/kg CO_{2e}
A	400	468	Self-supported power generation	Coal-fired boiler	13 150.01	3.86
B	980	1 274	Self-supported power generation	Coal-fired boiler	25 317.19	2.72
C	5 000	5 000	Purchased	Biogas boiler	46 169.86	1.28
C'(2C)	5 000×2	5 000×2	Purchased	Biogas boiler	92 339.72	1.28
D	10 000	10 000	Self-supported power generation	Biogas power generation residual temperature overheating	72 858.06	1.01

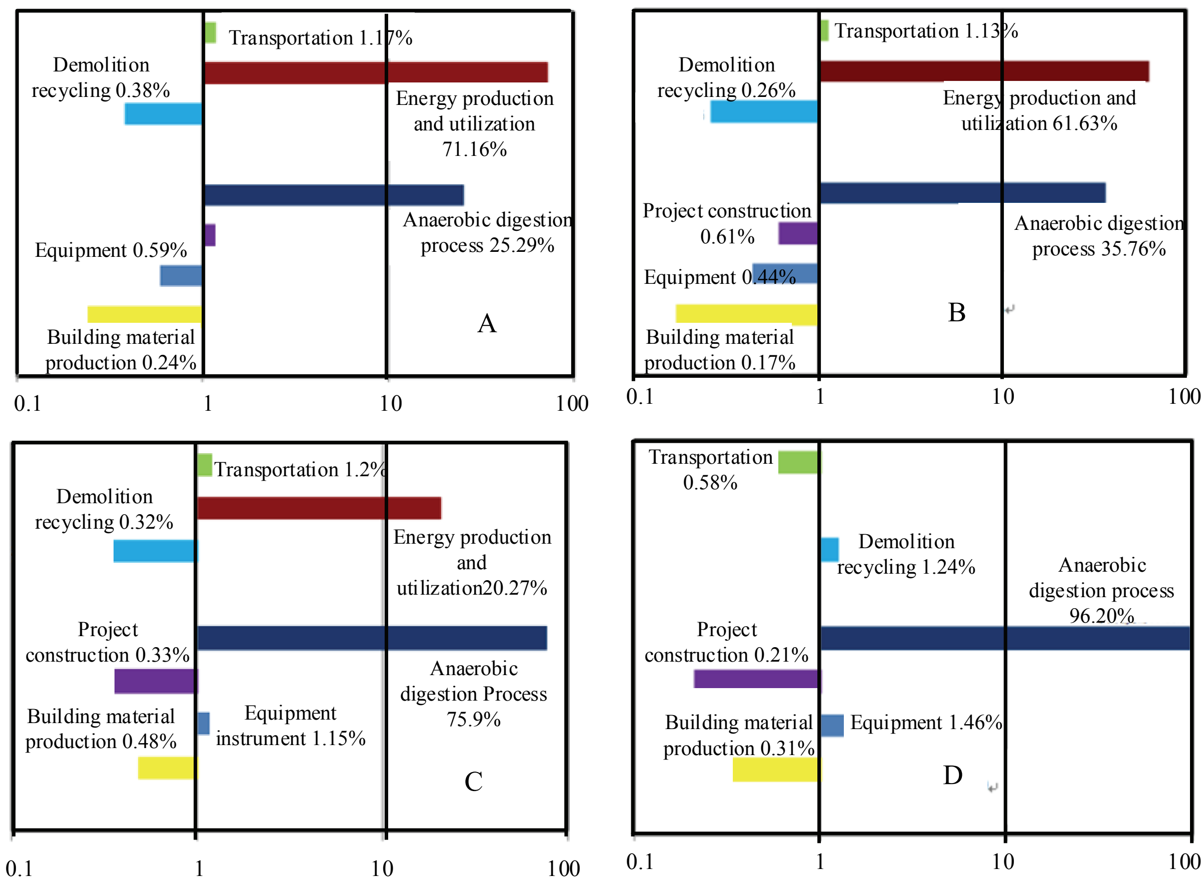

Figure 1 Emission percentage of various stages of four biogas plants

6 Conclusions

Under the condition of same power supply and thermal method of digestion tank, the carbon footprint could be reduced with the increase of biogas plant scale. Greenhouse gas emission of the plants could be effectively reduced by reasonably improving the utilization rate of renewable clean energy. Moreover, the carbon footprint of the biogas plants could become relatively lower, more energy-conservative and environmental-friendly.

The greenhouse gas emission of energy production and utilization accounted for more than 96% of the total emission during anaerobic digestion. The proportion of greenhouse gas emissions resulted from equipment, demolition recycling, transportation phase was lower than 1.5%. Since greenhouse gas emission of building materials production phase was less than 1%, it could be ignored when calculating the carbon footprint of the biogas plants.

Acknowledgments

This investigation was funded by China National 'The Twelfth Five-Year Plan' for Science & Technology Supporting Project (Grant No. 2012BAD47B03), Key Project for Agriculture Transformation of Scientific and Technological Achievements from the Ministry of Science and Technology of China (No. 2014GB2A400088, "Technical Transformation and Demonstration Project of High Efficiency Anaerobic Biogas Production in Breeding Farm of Dry Dejecta Collection Mode") and Beijing Municipal Key Discipline of Biomass Engineering.

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