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Carbon footprint analysis of a combined cooling heating and power system

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ABSTRACT

Combined Cooling, Heating and Power (CCHP) systems are safe, efficient, and environmentally friendly systems, which have been widely used all over the world. However, the greenhouse gas emission problems of CCHP systems have not been fully studied. This research adopted a multi-product carbon footprint (MPCF) method to assess the greenhouse gas emissions of a CCHP system. Activity data, mass and energy balances were checked to ensure the accuracy of the assessment. To solve the allocation problems, the authors introduced the concept of carbon footprint contribution rate, x_j, and presented an applicable expression of x_j for CCHP systems. The MPCF calculations showed that without optimization the total MPCF of the CCHP system is 8.071 kg-CO_2e/kW h-prod and direct MPCF occupies the carbon footprint overwhelmingly. Moreover, an optimization thought that MPCF can be decreased by increasing the amount of cooling output was proposed theoretically. To corroborate the thought, a dehumidifier unit has been incorporated into the original CCHP system. Compared with the original system, results show that the MPCF of the optimized CCHP system drops by 7.5% while the total carbon emissions rise only by 0.5%, which means the CCHP system after optimization can produce more products than before but only with a small increase of environmental costs.

1. Introduction

In recent decades, the utilization of Combined Cooling, Heating and Power (CCHP) systems has drawn increasing attention from scientists and researchers [1–5]. CCHP systems which produce power and use waste heat for cooling and heating have been widely used in distributed energy supply systems [6–9]. Due to their advantages in improving energy efficiency and in reducing greenhouse gas (GHG) emissions [10–13], CCHP systems have developed rapidly in the last ten years. Studies concerning CCHP systems reside in various aspects, and the problem of how to reduce the GHG emissions of CCHP systems has already become a hot topic. Generally, the utilization of CCHP systems is more likely to produce less GHG emissions than those from conventional systems, since CCHP systems usually consume less resources than traditional ones. Mago et al. [14] pointed out that operation strategies can result in different CO_2 emissions. Thus, Fumo et al. [15] proposed an emission operational strategy to minimize the emissions of CO_2 from CCHP systems. Under the guidance of the strategy, CO_2 emissions declined by 22.3% in a Minneapolis building-CCHP case. Thereafter, more and more researchers began to consider the GHG emissions as an indispensable index to comprehensively assess CCHP systems. For example, Han et al. [16] regarded CO_2 emissions as such an important index as operation cost and exergy efficiency to assess CCHP system performance of different load strategies. Mohan et al. [17] also compared the normalized CO_2 emissions between systems with and without waste heat recovery unit, and results showed that the normalized CO_2 emissions per MW h had been reduced by 51.5% by implementation of waste heat recovery tri-generation system.

In the current studies, the index of total GHG emissions, rather than carbon footprint, is mainly used to evaluate the CCHP systems from the environmental respects. However, authoritative institutes and organizations tend to adopt carbon footprint to assess a system. The carbon footprint assessment is a professional methodology concerning all life-cycle processes that incorporate carbon [18], and the assessment is more objective and comprehensive than a total emission evaluation. There are a series of international standards and regulations [19–22] to help users with different backgrounds better conduct the carbon footprint calculation and thereby find breakthroughs in decreasing carbon emissions. ISO

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Nomenclature

a	economic value(standard coal conversion factor), kgce/kW h	MPCF	multi-product footprint
c	carbon footprint, kg-CO_2e/kW h-prod	P	product amount, kW
C	carbon emission, kg-CO_2e/h	x	carbon footprint contribution rate
CCHP	combined cooling, heating, and power		
GHG	greenhouse gas	*Subscript*	
		i or j	index (choose from cooling, heating and power)

14067 specifies principles, requirements and guidelines for the quantification and communication of the carbon footprint of a product [20], based on ISO 14044 [19] for quantification and on environmental labels. Similarly, PAS 2050 was introduced in 2008 with the aim of providing a consistent internationally applicable method for quantifying product carbon footprints [21]. Intergovernmental Panel on Climate Change (IPCC) provides a clear scientific view on the current state of knowledge in climate change and its potential environmental and socio-economic impacts [22], and IPCC convenes conferences at fixed time to collect the newest development of carbon footprint.

Moreover, an effective CCHP system can be regarded as a multi-product or co-product system since it usually produces electricity, heat and cooling simultaneously [2,5]. In multi-product systems, using total carbon emissions as an assessment index cannot help understand contributions to emissions by each product. Therefore, to assess the system objectively, allocation problems [20,21] of carbon emissions should be considered among different products. It has been stated in ISO 14067 [20] that input and output data might be allocated between co-products in proportion to the economic value of the products. In CCHP systems, the co-products, i.e. electricity, cooling and heat, have different energy levels [23–26], so allocation principles should be claimed in carbon footprint assessment of CCHP systems. However, there is no further information can be referred to in ISO 14067 for executing allocations.

In this research, a multi-product carbon footprint (MPCF) method has been adopted to assess the carbon emissions of a typical CCHP system with power capacity of 1183 kW and natural gas consumption rate of 303.85 m^3/h. To ensure the accuracy of the assessment, the boundary of the CCHP system has first been clarified in detail, followed by activity data, mass and energy balances being checked. Moreover, a definition of carbon footprint contribution rate has been proposed for fair allocation of carbon footprint in CCHP systems. Based on the expression of the contribution rate, MPCF of the CCHP system has been calculated and analyzed. Finally, a potential method to reduce the MPCF has been proposed for system optimization and the feasibility of the method has been demonstrated.

2. Combined Cooling, Heating and Power systems

Generally, a typical CCHP system is composed of three units, i.e., power generation (U1), absorption refrigeration (U2) and heating supplying (U3), as shown in Fig. 1. However, for the stable operation of a CCHP system, utilities are also indispensable. Utilities provide natural gas, cooling water and electricity, to ensure the normal operation of the CCHP system. When calculating the carbon footprint of a CCHP system, both the CCHP system and the affiliated utilities should be considered as carbon emission sources.

In terms of masses, the main input of the system comprises air and natural gas from the utilities. After combustion, the exhausted gas flows out of the system as output.

When it comes to the energy flow, the CCHP system is powered by natural gas and electricity. In the internal combustion engine (ICE), the thermal energy generated from the natural gas combustion is converted to electricity. When the ICE is operating, hot exhausted gas and hot jacket water are generated. After combustion, the hot exhausted gas is first used to drive the absorption refrigeration unit (U2). In U2, the hot exhausted gas can provide heat for adsorption refrigerator before its cooling down and then is emitted out of the system. After heat transfer in the internal combustion engine, hot jacket water (green[1] solid line) from the internal combustion engine acts as an energy resource for the heat supply. Through all the processes of combustion, energy conversion and exchange, the outputs of the system are power, cooling and heat in U1, U2 and U3, respectively. Fig. 1 illustrates the energy flow in the CCHP system itself, so chilled water and hot water from the customers are not depicted for simplification.

3. Methods of MPCF calculation

In this section, a specific case will be used to show the process of calculating carbon footprint of a CCHP system. The CCHP system uses natural gas and electricity from utilities as energy input in this case.

3.1. Activity data

The system consumes CH_4 with the rate of 303.85 m^3/h and electricity of 36 kW from utility subsystem, but produces 1183 kW of electricity, 688 kW of cooling and 53 kW of heat from the system.

GHG emission factors are given here for calculating the multi-product carbon footprint of the CCHP system, and the values of these factors used in this case are listed in Table 1.

3.2. Mass and energy balances

In the CCHP system, substances cover the input methane and air and the output waste gas. This system can be regarded as mass balance due to the only output of waste gas.

The CCHP system consumed natural gas of 303.85 m^3/h which is equal to 3000 kW by low heat value. Detailed information of energy input and output are listed in Table 2. Values in Table 2 were site data obtained from an existing CCHP system for an industrial park in the southern part of China, and the data were collected through our field research. Corresponding to each input or output stream of the CCHP system, in Table 2, data in the first column are the input energy to drive the CCHP system. Meanwhile, data in the second column of Table 2 shows the energy distribution of the CCHP system. In the output column, power, cooling and heat are the three kinds of products of the system. Based on the 1st Law of Thermodynamics, cooling can be obtained by incorporating heat

[1] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.