Journal of Cleaner Production 112 (2016) 4107–4113

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Integrated substance and energy flow analysis towards CO_2 emission evaluation of gasoline & diesel production in Chinese fuel-refinery

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ARTICLE INFO

Article history:
Received 27 March 2015
Received in revised form
26 July 2015
Accepted 31 July 2015
Available online 8 August 2015

Keywords:
Carbon dioxide emission
Energy production
Substance flow analysis
Energy flow analysis
Fuel-refinery
Low carbon

ABSTRACT

In China, energy production in fuel refineries has a major problem: high emission of CO_2. The conventional method of CO_2 emission evaluation is based on substances flow analysis (SFA), which focuses on the cost control. However, as the importance of low carbon development in fuel refineries increases, CO_2 emissions control has become the main objective of evaluation. Moreover, it would be difficult for application of SFA to estimate CO_2 emission accurately because of the indirect CO_2 emissions in energy consumption that are ignored in SFA. In this study, a CO_2 emission evaluation method that combines SFA with energy flow analysis (EFA) is established. This method is applied to a Chinese fuel refinery, and the results indicated that the quantity of CO_2 emission evaluated by combined SFA and EFA was about 14.40% higher than emissions evaluated only by SFA. Also, the impacts of substance flow and energy flow on carbon dioxide emissions were analyzed, and some suitable suggestions are proposed for the low carbon development of the fuel-refinery.

1. Introduction

From 2000 to 2010, global greenhouse gas emissions began increasing at their fastest pace in history. The annual average growth rate has reached 2.2% (Gutowski et al., 2013; West et al., 2013). If this trend continues without major emissions-cutting measures, the Earth's average surface temperature will rise 3.7–4.8 °C by the end of the 21st century (Williams et al., 2012; Zhou et al., 2010). According to statistical data collected by British Petroleum Company (BP) in June 2011, China's energy consumption and CO_2 emissions have been growing significantly faster than this global rate since 2002, when heavy industrialization went through another wave of popularity. Their growth rates surpassed the USA in both 2006 and 2010. China has become the fastest-growing nation in terms of energy consumption and CO_2 emissions in the world (Chengzao et al., 2012; Olivier, 2012). According to statistical data collected by the U.S. Energy Information Administration (EIA), the CO_2 emissions of China were 8.38144×10^9 t in 2010, while the CO_2 emissions in the USA were 5.6006×10^9 t (EIA, 2011). China has become the largest emitter of CO_2 per capita in the world.

Chinese petrochemical industry is fourth in the world in terms of energy consumption and CO_2 emissions (Pao et al., 2012; Wang et al., 2011). As the sole producer of raw materials for petrochemical industry, the fuel-refinery is an energy-hungry source of CO_2 emissions. Since China announced a plan to reduce its carbon intensity (the amount of greenhouse gas emissions per unit of economic output) by at least 40% by 2020 at the 15th Conference of Parties of the United Nation Framework Convention on Climate Change (UNFCCC) in Copenhagen in December 2009, the fuel refining industry has been the main focus in the work to reduce greenhouse gas emissions. Production of cleaner gasoline and diesel, i.e. fuel with a lower sulfur content, leads to higher CO_2 emissions in fuel refineries (Szklo and Schaeffer, 2007). Pressure on the fuel refining industry has increased with the recent CO_2 emissions constraints (Glew et al., 2012; Ravanchi et al., 2011). The necessity of CO_2 emissions (the emissions of greenhouse gases such as CO_2, methane, nitrous oxide and so on) evaluation is twofold. First, it is important to evaluate emissions in order that they may be reduced. Second, it is also important to assess the opportunity cost of the reduction of CO_2 emission, which can be achieved with the help of emissions evaluation.

In the fuel-refinery production process, the materials proceed along the product life cycle of substance flow, and the energies proceed along the path of conversion, use, recycling and emission,

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http://dx.doi.org/10.1016/j.jclepro.2015.07.156
0959-6526/

Nomenclature

A_i	inflow raw material of unit i (t/a)
a_{fuel}	proportion of fuel in the energy consumption (%)
B_i	other energy inflows from production unit i (ton standard fuel)
$\overline{b}_{fuel}$	conversion coefficients of converting coal, fuel oil and natural gas to ton standard fuel
$\overline{b}_{other}$	conversion factor of electricity, steam or water
C_i	carbon fraction in the coke (%)
E_i	energy inflow from production unit $i-1$ to unit i (ton standard fuel)
E_{i+1}	energy inflow from production unit i to unit $i+1$ (ton standard fuel)
EC_{in}	input electrical energy consumption (kWh)
EC_{out}	output electrical energy power (kWh)
E_{ni}	total energy inflow into production unit i (ton standard fuel)
E_{ri}	energy recycle of production unit i (ton standard fuel)
$EF_{grid,OM,y}$	CO_2 emission factor of electricity (t/kWh)
EF_j	greenhouse gas j emission factor of the fuel i combustion
F_i	inflow substances of unit i (t/a)
GWP_j	global warming potential of the greenhouse gas j
G_{CO_2}	CO_2 emissions from input/output power process (t)
H_i	CH_4 content of the oil products in storage tanks (%)
L_i	total energy loss in the production process (ton standard fuel)
P_i	outflow product from unit i (t/a)
P_{ie}	outflow product from unit i (t/a)
R_i	the recycle substances (t/a)
S_i	energy outflow from production unit i to other units (ton standard fuel)
V_i	CO_2 emissions of production unit i
W_i	outflow waste discharge from unit i (t/a)
α_i	impact of inflow substances on production unit i
β_{i+1}	impact of outflow substances on the following production unit $i+1$
γ_i	impact of recycle substances on production unit i
ξ_i	energy consumption (ton standard fuel)
η_i	production coefficient of unit
ν_{CO_2}	CO_2 emissions per ton standard fuel (t)

i.e. energy flow. The substance flow is the main energy production process. However, the transformation and transmission of materials in the substance flow are promoted by the energy flow (Marta et al., 2012). In the fuel-refinery production process, both substance and energy are constantly dissipating (Zhang and Hua, 2007). The main goal of research into substance flow is to reduce the material lost, while the main goals of research into energy flow are to increase the recovery of energy in the recycling ratio and to achieve the highest possible energy conversion efficiency (Marianne et al., 2012; Chu-Long et al., 2014). The production process and energy conversion in the fuel-refinery are dictated by substance and energy flow.

As CO_2 emission is evaluated, there is a problem with navigating the complexity of substance and energy flow at the enterprise level. There have been some methods and guides proposed for CO_2 emissions evaluation in the literature, which are based on clearly identifiable emission sources. In this literature, the appropriate quantitative approach for each clearly identifiable emission source is selected, and the sources of CO_2 emissions are calculated one by one. Then, the industry CO_2 emissions can be calculated by the summation of the emissions from each of the sources (Donald et al., 2015; Pandey et al., 2011). These methods are time-consuming, laborious and impractical when applied to the refinery industry, for there are dozens or even hundreds of identifiable emission sources. In addition, feedstock routes and production processes are very complicated, and there are plenty of recovery, reuse and recycling processes of raw materials, fuels and by-products. All of these complications increase the sheer volume of test data to the point that it becomes impossible to ensure the validity of the data.

Conventionally, carbon dioxide emissions in Chinese refinery industry are evaluated by a compendium of greenhouse gas emissions methodologies drawn up by the American petroleum industry association (API) for the oil and gas industry, which was based on the material balance method. On the basis of fuel consumption and carbon content categorical data analysis, substances flow analysis (SFA) was carried out for CO_2 emission evaluation of stationary combustion sources in fuel refineries. However, there is not only substance flow but energy flow at work during the fuel refining process, and both flows directly influence CO_2 emission. It is nearly impossible to estimate CO_2 emissions accurately in the production process using just one SFA method.

In this study, research on CO_2 emissions evaluation methods in the fuel refining industry was conducted concerning technology-associated substance flows and energy flows. The approach integrated substance and energy, focusing on the production process rather than the industrial cluster. Additionally, the production process of the fuel refinery was divided into substance flow and energy flow. The CO_2 emission in the refining process was evaluated in terms of substance flow analysis combined energy flow analysis. Also, the impacts of substance and energy flow on CO_2 emissions were analyzed. Integrated substance and energy flow analysis was first used in Chinese fuel refineries as an emissions evaluation method at the enterprises level, and the approach may be used for similar projects in other petroleum refineries.

2. Methods

2.1. Emission sources definition

The CO_2 emission sources of the oil industry were divided into three types according to the GHG Emissions Guidelines of Oil Industry, which was compiled by the International Petroleum Industry Environmental Conservation Association (IPIECA) (Karin et al., 2005):

(1) Direct emission sources. CO_2 emissions of the stationary combustion sources were included, such as turbines, compressors, generators and furnaces.
(2) Indirect emission sources. CO_2 emissions produced by energy consumption process are included, such as electricity, steam and heating.
(3) Others, such as transportation, product use, waste disposal, and so on.

In the energy production process, direct and indirect activities occur, and other activities such as transportation, product use, and waste disposal are not included. The direct CO_2 emission sources in the Chinese fuel refinery include fuel combustion (natural gas, fuel