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Life-cycle GHG emission factors of final energy in China

Jiang Lixue[a], Ou Xunmin[b], Ma Linwei[a]*,Li Zheng[a], Ni Weidou[a]

[a]State Key Laboratory of Power Systems, Department of Thermal Engineering, Tsinghua-BP Clean Energy Center, Tsinghua University, Beijing 100084, China

[b]Institute of Nuclear and New Energy Technology, Tsinghua University, Beijing 100084, China

Abstract

In this manuscript, a model for the estimation of the life-cycle GHG emission factors of final energy and an empirical study of China is presented. A linear programming method is utilized to solve the problem that several forms of final energy are utilized in the life-cycle of one certain type of final energy. Nine types of final energy are considered, including raw coal, crude oil, raw natural gas, treated coal, diesel, gasoline, fuel oil, treated natural gas, and electricity. The results indicate that the life-cycle GHG emission factors of final energy in China slightly decreased in recent years.

Keywords: Life-cycle; GHG emissions; final energy; fossil energy; model

1. Introduction

China makes a great contribution to the greenhouse gas (GHG) emissions all over the world mainly due to its huge amount of energy consumption and heavily reliance on fossil fuels, especially on coal [1,2]. Therefore, it is of importance to understand the life-cycle GHG emissions of final energy in China. Although a number of related studies have been published, most methods neglected the upstream GHG emissions [3-11], while life-cycle based analyses being either limited in a certain industry [12-15] or based on commercial models [16]. Seldom studies presented an overview of the life-cycle GHG emissions of final energy in China. In this paper, a general model for estimating life-cycle GHG emission factors of final energy is developed and used to conduct on an empirical study of China. A linear programming method is utilized in this model to solve the problem that several forms of final energy are utilized in the life-cycle of one certain type of final energy and it is difficult to integrate them in one life-cycle emissions

* Corresponding author. Tel.: +86 10 62795734-302; fax: +86 10 62795736.
E-mail address: malinwei@tsinghua.edu.cn.

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estimating model. In the following, we introduce firstly the methodology, followed by an introduction to the data input, and finally the results and discussions.

Nomenclature

$EF_{LC,j}$	Life cycle primary fossil energy consumption for process fuel *j* (MJ/MJ)
$EI_{m,j}$	Amount of total process fuel consumption for 1 MJ process fuel *j* at stage *m* (MJ/MJ)
NG	Natural gas
RA_n	Share of the nth power generation route in the total electricity supply
$SH_{m,j,z}$	Share of process fuel *z* consumption among total process fuel consumption for 1 MJ process fuel *j* at stage *m*
γ_j	Characterized if primary fossil energy used as raw material directly for process fuel *j*
$\eta_{m,j}$	Energy conversion efficiency factor for process fuel *j* at stage *m*
ζ_j	Conversion factor in the feedstock production and transportation sub-stage

2. Methodology

2.1. Key definitions and system boundary

The energy system boundary of this study is illustrated in Figure 1.

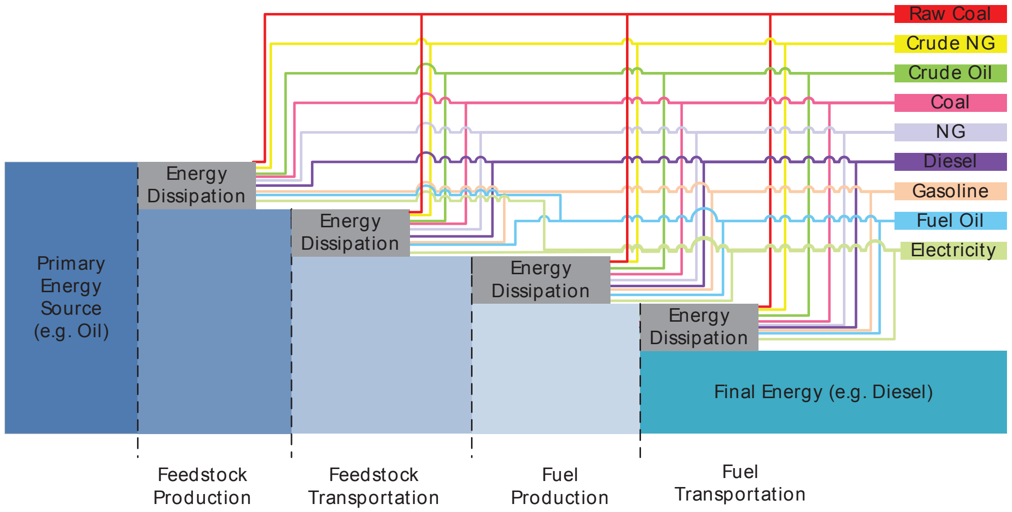

Figure 1. Structure representation of calculation method of fossil fuel intensity

It is divided into four sub-stages: (1) feedstock production for the fossil energy source, (2) feedstock transportation, (3) fuel production, and (4) fuel transportation [5,18-24].Three key types of GHG emissions (CO2, CH4, and N2O), three types of fossil energy (coal, oil, and natural gas), and nine types of final energy (raw coal, crude NG, crude oil, coal, NG, diesel, gasoline, fuel oil, and electricity) are considered. These types of final energy totally account for 68.6% of all final energy consumption in China [17], and are also process fuels in the calculation. Table 1 summarized the definitions of the primary fossil energy, final energy, and sub-stages.

Table 1. The definitions of the primary fossil energy, final energy, and sub-stages.

	i (primary fossil energy)	*j* (final energy)	*m* (sub-stages)
1	Coal	Crude coal	Feedstock Production
2	Natural Gas	Crude natural gas	Feedstock Transportation
3	Oil	Crude oil	Fuel Production
4		Coal	Fuel Transportation
5		Natural gas	
6		Diesel	
7		Gasoline	
8		Fuel oil	
9		Electricity	

2.2. Calculation of fossil energy consumption intensity

The fossil energy consumption (FEC) intensity of final energy is defined as the total life-cycle primary fossil energy input per 1 MJ (low heating value) final energy obtained (EF_{LCA}, MJ/MJ), and the GHG emissions intensities is defined as the total life-cycle GHG emissions per 1 MJ final energy obtained and utilized (GHG_{LCA}, gCO_2,e/MJ). $EF_{LC,\,j}$ is defined as the sum of three primary fossil energy (i) consumption in the life cycle of final energy j, and can be calculated by the total process fuel consumption $(EI_{m,j})$ at each sub-stage, referring to equation 1 and 2. $EI_{m,j}$ can be calculated by η_j (energy conversion efficiency factor) and ζ_j (Conversion factor of feedstock to resource), referring to equation 3-7. In equation 7, RA_n, $\eta_{3,9,n}$, and $\eta_{4,9,n}$ respectively represents the proportion of the nth power generation route in the total electricity supply, power generation efficiency and transmission efficiency of this route.

$$EF_{LC,j} = \sum_{i=1}^{3} EF_{LC,j,i} \tag{1}$$

$$\begin{cases} EF_{LC,j} = \sum_{i=1}^{3}\sum_{m=1}^{4}(EI_{m,j}\sum_{z=1}^{9}(SH_{m,j,z}EF_{LC,z,i})) + \gamma_j \\ \gamma_j = \begin{cases} 0 & j = 9 \\ 1 & j \neq 9 \end{cases} \end{cases} \tag{2}$$

$$EI_{1,j} = (1/\eta_{1,j} - 1)/\xi_j \tag{3}$$

$$EI_{2,j} = (1/\eta_{2,j} - 1)/\xi_j \tag{4}$$

$$EI_{3,j} = 1/\eta_{3,j} - 1 \tag{5}$$

$$EI_{4,j} = 1/\eta_{4,j} - 1 \tag{6}$$

$$EI_{m,9} = \begin{cases} \sum_{n=1}^{4}(RA_n/\eta_{3,9,n}/\eta_{4,9,n}) & m = 3 \\ 0 & m \neq 3 \end{cases} \tag{7}$$

2.3. Calculation of GHG emissions

The GHG emissions are calculated and convert to the CO_2 equivalents according to their Global Warming Potential (GWP), referring to equation 8, where $GHG_{LC,j}$, $CO_{2,LC,j}$, $CH_{4,LC,j}$, and $N_2O_{LC,j}$ stand for the emission intensity of GHG, CO_2, CH_4, and N_2O of final energy j, respectively. The life cycle CO_2 emissions of final energy j comprehend 2 parts: direct emission and upstream emission (indirect emission), and the calculation is according to equation 9-10. The calculation of CH_4 and N_2O emissions is similar to CO_2. However, non-combustion CH_4 emissions of final energy j are considered (equation 11 and 12).

$$GHG_{LC,j} = CO_{2,LC,j} + 25CH_{4,LC,j} + 298N_2O_{LC,j} \quad (8)$$

$$CO_{2,LC,j} = CO_{2,up,j} + CO_{2,direct,j} \quad (9)$$

$$CO_{2,up,j} = \sum_{m=1}^{4}\sum_{x=1}^{9}(EI_{m,j}SH_{m,j,x}(CO_{2,direct,x} + CO_{2,up,x})) \quad (10)$$

$$CH_{4,up,j} = \sum_{m=1}^{4}\sum_{x=1}^{9}(EI_{m,j}SH_{m,j,x}(CH_{4,direct,m,x} + CH_{4,up,x})) + CH_{4,j,noncomb} \quad (11)$$

$$CH_{4,j,noncomb} = CH_{4,j,resource} / \xi_j \quad (12)$$

3. Data input

3.1. Feedstock and fuel production

It comprises the extraction and processing of coal, natural gas, and oil, whose data are shown in Table 2. For electricity, coal, natural gas, and oil account for 78.1%, 1.8% and 0.6% of total electricity generation, while the emissions of other electricity supply routes (hydro, nuclear, wind, etc.) is ignored. The electricity generation efficiency ($\eta_{3,9,n}$) of coal power, natural gas power and oil power are assumed as 36.5%, 45% and 36.5% respectively[27]. We assume the efficiency of electricity transmission and distribution is 93.3%.

Table 2. Data of feedstock production, feedstock transportation, and fuel production

		Coal	Crude oil	Natural gas	Diesel	Gasoline	Fuel oil
Production efficiency (η)		97%	92.3%	92.3%	91.5%	90.8%	94.0%
Conversion factor (ζ)		99%[26]	-	99.6%	95%	95%	97%
Processing fuel mix[a][17] [21]	Raw Coal	75%	0%	0%	0%	0%	0%
	Crude Gas	0%	42%	42%	2%	2%	2%
	Crude Oil	0%	25%	25%	60%	60%	60%
	Coal	6%	4%	4%	20%	20%	20%
	Natual Gas	1%	0%	0%	0%	0%	0%
	Diesel	3%	12%	12%	1%	1%	1%
	Gasoline	1%	1%	1%	1%	1%	1%
	Fuel Oil	0%	1%	1%	4%	4%	4%
	Electricity	14%	15%	15%	12%	12%	12%

a: processing fuel mix is based on the calorific value calculation, thus the proportion of electricity here might be lower than other research.

3.2. Feedstock and fuel transportation

Five modes of transport are considered: rail, sea tanker, water way, pipeline and road. In the sub-stage of feedstock transportation, we consider coal, natural gas and crude oil. For coal, it is 62% by rail, 4% by sea, 16%by water and 18% by road. For oil, it is 3% by rail, 48% by sea, 15% by water, 42% by pipeline, and 1% by road. Natural gas is assumed as 100% by pipeline [17, 28]. In the sub-stage of fuel transportation, only coal, crude oil, and product oil are considered, referring to Table 3 [17, 26, 28, 29]. The electricity transmission and distribution is included in the third sub-stage, considering the specialty of the electricity route.

Table 3. Process fuel mix of coal, crude oil, and product oil transportation

	Diesel	Gasoline	Fuel Oil	Electricity
Coal	45%	6%	23%	26%
Crude oil	2%	0%	84%	14%
Diesel	40%	5%	30%	25%
Gasoline	40%	5%	31%	24%
Fuel oil	49%	6%	15%	30%

4. Result and discussion

All types of fossil energy consumption and GHG emissions of these final energy forms, when 1 MJ fuel is achieved, are shown in Table 4. As Figure 2 shows, GHG emissions are mainly generated in the process of feedstock and fuel production, especially for product oils because their supply chains are longer than others'. For electricity, the life-cycle GHG emission factor is 250.54 g/MJ, much higher than other forms of final energy because of the high proportion of coal-based power generation [30]. It should be mentioned that the results might be underestimated given that coke oven gas and refinery gas are not considered in the calculation.

Table 4. Calculation results of energy consumption and GHG emissions

Categories of final energy	Fossil energy consumption (MJ/MJ)				GHG emissions ($gCO_{2,e}$/MJ, N_2O: mg $CO_{2,e}$/MJ)			
	Coal	NG	Oil	Total	CO_2	CH_4	N_2O	Total
Raw Coal	1.036	0.001	0.002	1.039	82.54	0.43	1.07	93.51
Crude Gas	0.034	1.037	0.036	1.107	62.96	0.10	1.36	65.95
Crude Oil	0.034	0.037	1.036	1.107	79.29	0.04	0.36	80.43
Coal	1.040	0.001	0.008	1.049	85.52	0.43	1.18	96.61
Natural Gas	0.044	1.037	0.041	1.122	64.25	0.11	1.38	67.44
Diesel	0.090	0.044	1.111	1.245	90.42	0.08	28.56	100.98
Gasoline	0.094	0.044	1.117	1.256	86.54	0.16	2.57	91.33
Fuel Oil	0.074	0.042	1.089	1.205	90.61	0.07	0.52	92.48
Electricity	2.379	0.052	0.047	2.478	200.42	1.97	3.11	250.54

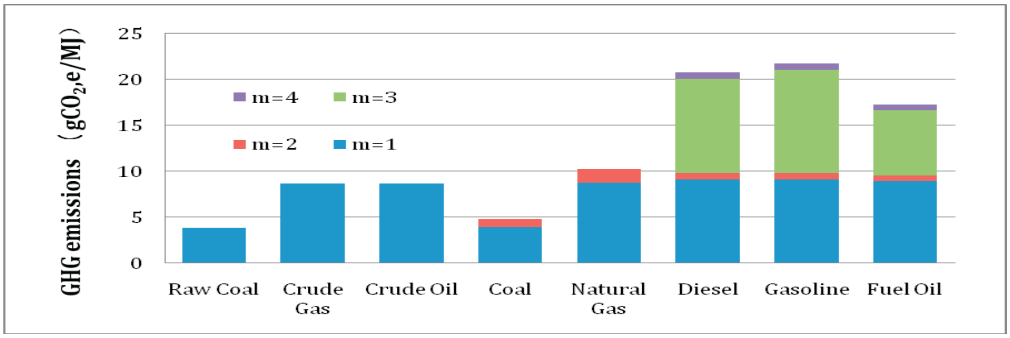

Figure 2. GHG emission in each section

The life-cycle GHG emission factors of different types of final energy all show a remarkable increase comparing with direct emissions, ranging from 12% to 31%, as shown in Figure 3.

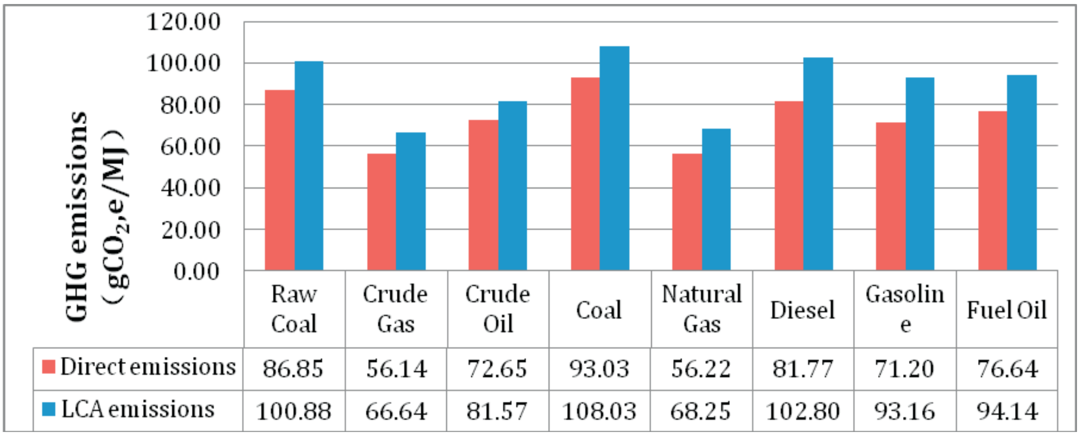

Figure 3. Comparison of direct emissions and LCA emissions

Compared with previous study in 2007[20](Figure 4), both the GHG emissions and fossil energy consumption of final energy slightly decreased in 2009, due to the improvement of energy efficiency and optimization of energy structure. Especially for electricity, rising ratio of non-fossil fuel power propels the GHG emission of electricity falling from 297.7 g/MJ in 2007 to 250.5 g/MJ in 2007.

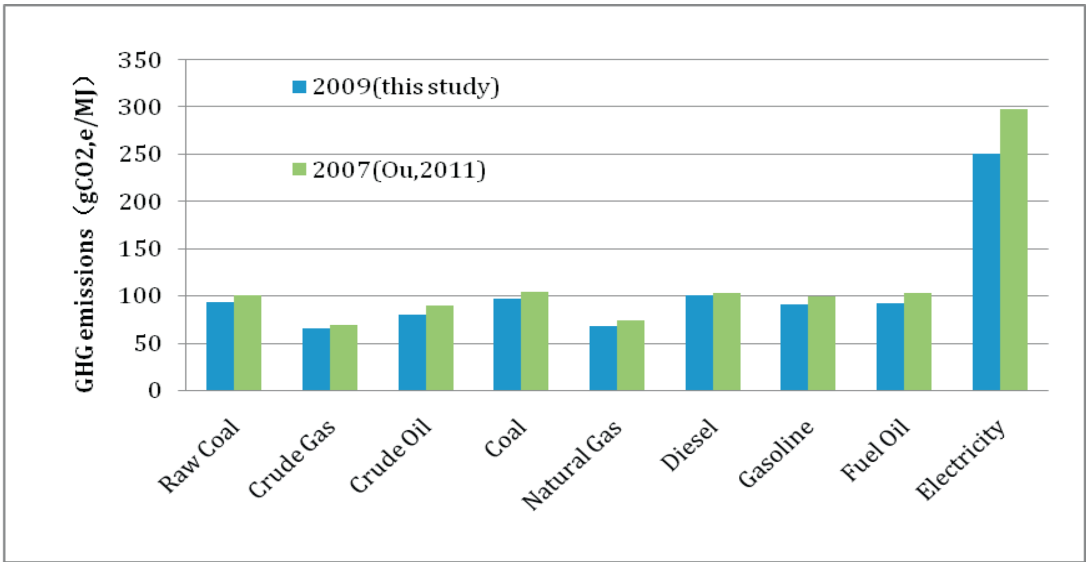

Figure 4. The comparison between GHG emissions in 2007 and 2009

5. Conclusions

This work presents life cycle fossil energy consumption and GHG emissions analysis of nine types of final energy in China based on a linear programming estimating model. With the above discussions, we may draw following conclusions:

- The indirect emissions caused by the extraction, production, and transportation of fossil fuels contribute a remarkable portion to the life-cycle GHG emissions of fossil fuels, ranging from 12%~ 31% of the direct emissions by end-use combustions, especially for the feedstock extractions of crude oil and natural gas, and fuel productions of product oil like diesel, gasoline, and fuel oil.
- Due to the improvement of energy efficiency and optimization of energy structure, the fossil energy consumption and GHG emission factors of final energy in China decrease lightly in 2009 compared to the results in 2007.

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