Development of a CO₂ emission factor in Korea from sub-bituminous coal by the classification method

Seungjin Kim · Jeongwoo Lee · Seehyung Lee ·
Chang-Sang Cho · Jae-Hwan Sa · Eui-Chan Jeon

Received: 15 April 2013 / Accepted: 11 February 2014 / Published online: 14 March 2014
© The Author(s) 2014. This article is published with open access at Springerlink.com

Abstract While the Intergovernmental Panel on Climate Change classifies coal as anthracite, bituminous coal, and sub-bituminous coal, Korea only distinguishes coal as anthracite and bituminous coal while sub-bituminous coal is considered bituminous coal. As a result, Korea conducted research in the CO₂ emission factors of anthracite and bituminous coal, but largely ignored sub-bituminous coal. Therefore, the purpose of this research is to develop the CO₂ emission factor of sub-bituminous coal by classifying sub-bituminous coal from resources of bituminous coal activities collected in Korea between 2007 and 2011. The 2007–2011 average carbon content of sub-bituminous coal was analyzed to be 69.63 ± 3.11 %, the average hydrogen content 4.97 ± 0.37 %, the inherent moisture 12.60 ± 4.33 %, the total moisture 21.91 ± 5.45 %, and the dry-based gross calorific value was analyzed to be $5,914 \pm 391$ kcal/kg; using these analyzed values, the as-received net calorific value was found to be 20.75 ± 7.59 TJ/Gg and the CO₂ emission factor was found to be $96,241 \pm 4,064$ kg/TJ. In addition, the 62.7

million ton amount for the 2009 greenhouse gas emission from sub-bituminous coal as estimated with the analyzed value of this study is an amount that is equivalent to 11.1 % of the 2009 total greenhouse gas emission amount of 564.7 million tons, and this amount is larger than the 9.3 % for the industrial processes sector, 3.3 % for the agricultural sector and 2.5 % for the waste sector. Therefore, it is important to reflect the realities of Korea when estimating the greenhouse gas emission from such sub-bituminous coals.

Keywords Climate change · Sub-bituminous coal · Classification method · Emission factor

Introduction

In order to effect significant greenhouse gas reduction and evaluate the reduction potential, greenhouse gas emissions must be identified per source. Constructing a greenhouse inventory requires clear classification and standardization per category, and greenhouse gas emission factors and activity data are necessary. The 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines specifically classified the categories of greenhouse gas inventory, but when constructing the National Inventory Report, most countries follow the category that fits the emission traits of their country, and put in efforts into securing activity resources and emission factors. The IPCC Good Practice Guidance and the 2006 IPCC Guideline recommend the application of country-specific emission factors before the basic emission factors in cases in which the country holds specific emission factors (IPCC 2006); even developed countries are conducting research to develop these specific emission factors (Dios et al. 2013; Sheng and Li 2008;

S. Kim · C.-S. Cho
Cooperate Course for Climate Change, Sejong University,
98 Gunja-dong Gwangjin-gu, Seoul 143-747, Korea

J. Lee · S. Lee
Department of Earth and Environmental Sciences, Sejong
University, 98 Gunja-dong Gwangjin-gu, Seoul 143-747, Korea

J.-H. Sa
Environment and Energy Institute, Sejong University,
98 Gunja-dong Gwangjin-gu, Seoul 143-747, Korea

E.-C. Jeon (✉)
Department of Environment and Energy, Sejong University,
98 Gunja-dong Gwangjin-gu, Seoul 143-747, Korea
e-mail: ecjeon@sejong.ac.kr

AGO 2001; US EPA 2000; Quick and Glick 2000). Korea is also in urgent need of provision in country-specific emission factor regarding greenhouse gas emissions.

The total greenhouse gas net emissions in Korea during 2009 were counted as 564.7 million ton of CO₂ eq. This numerical value increased by 0.6 % compared to 2008. In addition, when compared to 1990, the greenhouse net emissions have greatly increased recently, as it increased by 106.6 %. Domestic greenhouse emissions predominantly originate, in the energy sector. When observed per sector, 84.9 % is emitted by energy, 9.3 % by industrial, and 3.3 and 2.5 % each for agricultural and waste sectors, respectively. When the consumption forms of 2009 are observed per energy source, the ratio consisted of oil was the highest with 42.1 %, and coal 28.2 %, LNG 13.9 %, nuclear energy 13.1 %, and water power 0.5 % (The Republic of Korea 2011).

For its abundant reserve quantities and low cost among fossil fuels (Galeovic and Munoz 2013; Lorenz and Grudzinski 2003), coal is being recognized as an important energy source and has induced a number of research on how to apply CCS technology at coal-fired power plants, in response to the rapid increases in energy consumption (Kotowicz and Bartela 2012; Pettinau et al. 2012). In terms of the 1st energy consumption per source of energy in Korea during 2009, it consisted of 68,604 Ton of Oil Equivalent (TOE) for coal, 102,336 TOE for petroleum, 33,908 TOE of natural gas, 1,213 TOE for water power, 31,771 TOE for nuclear power, and 5,480 TOE for renewable energy. Among these, coal is an important source of energy, taking up for about 28.2 % of the total energy consumption. The amount of fuel consumption during 2009 was about 108,378 thousand tons, and it increased by about 4,180 thousand tons (KEEI 2011). Global energy consumption also is expected to increase annually at about 1.6 % from 132 quadrillion British thermal units (Btu) in 2007 to 206 quadrillion Btu in 2035 (US EIA 2010). In the same way, coal discharges CO₂, greenhouse gas, and therefore, research on emission factor are imperative (Ozdogan 1998).

Even though the IPCC classifies coal as anthracite, bituminous coal, and sub-bituminous coal (IPCC 2006), Korea only distinguishes coal as anthracite and bituminous coal, while sub-bituminous coal is considered bituminous coal. As a result, Korea conducted research on the CO₂ emission factors of anthracite and bituminous coal (Lee et al. 2011, 2012, 2013; Jeon et al. 2006), but largely ignored sub-bituminous coal.

The national greenhouse gas emissions were calculated by applying national statistics such as the energy statistical year book. Differences may be displayed in the greenhouse emissions and emission estimations due to the different statistical methods used for coal by Korea and the IPCC.

Therefore, the purpose of this research is to develop a CO₂ emission factor of sub-bituminous coal by classifying sub-bituminous coal from resources of bituminous coal activities collected between 2007 and 2011 in Korea.

Methods

Evaluation on reliability of activity data for coal

This research made progress by collecting the activity data of the workplace which applied mass amount of bituminous coal. The activity data of the workplace include the analysis of the received amount and calorific value per each item, elemental analysis, and proximate analysis value from 2007 to 2011, and it is the amount that counts for about 69 % of the bituminous coal supply and demand data from the Korea Energy Statistical Year Book (KEEI 2011). In terms of the evaluation of reliability for the coal activity data, a comparative method was applied in which the coal samples actually used in the workplace were distinguished evenly and followed by conducting the calorific value analysis, elemental analysis, and proximate analysis in the laboratory of the workplace and Sejong University (Lee et al. 2012).

Calculation method of as-received net calorific value

When calculating the greenhouse gas emissions, it is the same as formula (1) as the calorie occurring from fuel combustion is applied instead of the weight of the fuel for the fuel consumption, and it is necessary to calculate the calorific value per fuel accordingly.

$$\text{GHG emissions} = \text{Fuel consumption} \times \text{Emission factor} \quad (1)$$

Here, Green House Gas (GHG) emissions is the greenhouse gas emission by fuel type (kg GHG). In terms of the fuel consumption, the calorific value depends on fuel combustion (TJ), and emission factor is the greenhouse gas emission factor by fuel type (ton/TJ).

Since coal differs from other fuels in that it contains much moisture and ash, the result of analysis conducted in coal is classified between as-received base, air dried base, and dried basis according to the inclusion of moisture and ash. As coal differs in its calorific value according to the indicated standard of analysis, a standard appropriate to the purpose of use should be applied (Jeon et al. 2006).

This research applied the ‘as-received base’ suggested by the IPCC. In order to calculate the ‘as-received base’ calorific value of the coal, the air-dry-based calorific value must be analyzed first, and the inherent moisture of the coal

must be applied as shown in formula (2) to convert it into the dried basis calorific value. In terms of the dried basis calorific value, the total moisture of the coal is applied to convert it into the as-received calorific value as shown in formula (3) (ASTM 2012a; IPCC 2006).

$$\text{GCV (dried basis)} = \text{GCV (air dried basis)} / \{(100 - \text{IM})/100\} \quad (2)$$

$$\text{GCV (as received Basis)} = \text{GCV (dried basis)} \times \{(100 - \text{TM})/100\} \quad (3)$$

GCV is the gross calorific value (kcal/kg), and IM the inherent moisture (%), and TM is the total moisture (%). The calorific value of coal is classified as the gross calorific value and net calorific value according to whether the condensation heat of water vapor occurring during the combustion process is included, and generally, the calorific value calculated by the calorific value analyzer is displayed as a gross calorific value which includes the condensation heat of the water vapor (Yoon et al. 2008). Since IPCC applies the net calorific value while calculating the emission factor, formula (4) was applied to convert the gross calorific value into net calorific value. The as-received hydrogen content applied here is the value converted by applying formula (5) to the dry-based hydrogen content and the total moisture (ASTM 2012c; IPCC 2006).

$$\text{NCV (as received basis)} = \{\text{GCV (as received basis)} - 5.72 \times (\text{H (as received basis)} \times 9)\} \quad (4)$$

$$\begin{aligned} \text{H (as received basis)} &= \{\text{H (dried basis)} \times (100 - \text{TM})/100\} \\ &+ (0.1119 \times \text{TM}) \end{aligned} \quad (5)$$

NCV is the net calorific value (kcal/kg), and H refers to the hydrogen content (%).

Elemental analysis method

In this research, the automatic elemental analyzer (Thermo Finnigan-Flash EA 1112, USA) was applied to measure the hydrogen and carbon contents of the coal, and a ParaQX column with the length of 2 m was applied. In terms of the analysis, the compound was oxidized through a dynamic flash combustion method and separated into columns, and the TCD detector was applied for analysis (ASTM 2008).

Calorific value analysis method

In this research, auto calorie analyzer of IKA (IKA-C2000, Germany) was applied to measure the calorific value. For the sample used for analysis, a highly sensitive electronic scale (Mettler Toledo-AB204S, Switzerland) was applied to quantify to 0.0001 g. For the coolant, distilled water was

applied, and the water temperature was set as 20 °C and analyzed the isoperibolic at 25 °C (ASTM 2012c; ISO 2009; KS 2006).

Proximate analysis method

Proximate analysis was conducted by applying the thermogravimetry to quantify the moisture and ash and volatile matter. Nitrogen was injected when the moisture was at 105 °C and volatile matter at 940 °C to measure the reduced amount, and during the measurement of samples, analysis was conducted until the fluctuation deviation became <0.5 mg after three rounds of measurement in the temperature for each item (ASTM 2012d).

QA/QC

In order to conduct elemental analysis, calorific value analysis, and a proximate analysis of coal, experiments on the reproducibility and degree of precision for elements, calorific value, and proximate analysis machinery as a part of analysis QA/QC were carried out. For the degree of precision evaluation of elemental analysis, 2, 5-bis(5-tert-butyl-benzoxazolyl)thiophene (BBOT), standard sample was applied for conduct. The reproducibility evaluation was repeated three times by setting the sample volume used during analysis within the range of 1.5–2.0 mg, and the results are displayed in Table 1. The carbon and hydrogen contents were each analyzed as 72.53 and 6.09 %, and during elemental analysis, density of standard material is not inserted, and even when the analyzed sample is put into analysis, analysis results most equal with the BBOT analysis result were displayed. When BBOT was fixed as the sample, the difference in the absolute value of carbon was

Table 1 Results of reproducibility test for elemental analysis

Times	Sample type	Injection weight (mg)	Element content (%)	
			C	H
1	BBOT	1.883	72.53	6.09
	Unknown	1.857	72.74	6.14
	Absolute difference (%)		0.21	0.05
2	BBOT	1.881	72.53	6.09
	Unknown	1.862	72.83	6.17
	Absolute difference (%)		0.30	0.08
3	BBOT	1.778	72.53	6.09
	Unknown	1.711	72.88	6.16
	Absolute difference (%)		0.35	0.07

shown as 0.21–0.35 % and between 0.05 and 0.08 % for hydrogen.

For the calorific value analyzer, benzoic acid (calorific value: $6,320 \pm 0.63$ kcal/kg, Germany), a standard sample, was applied to conduct repeat analysis for five rounds, and the results were displayed in Table 2. The average calorific value was $6,310 \pm 3.67$ kcal/kg. The tolerance with the standard sample calorific value resulted in 6,305–6,314 kcal/kg, which is less in 15 kcal/kg, and the relative standard deviation was found to be 0.06 % and displayed outstanding reproducibility.

The standard sample analysis result of proximate analysis is shown in Table 3. In terms of the standard deviation

per analysis factor, moisture resulted in 0.01–0.02 %, volatile matter 0.02–0.20 % ash 0.01–0.09 %, and fixed carbon 0.02–0.20 %. Accordingly, outstanding reproducibility was displayed.

Calculation method of greenhouse gas emissions

In this research, the fuel analysis method suggested by the IPCC was applied to calculate the CO₂ emission factor of coal (Quick and Brill 2002; IPCC 1996). The major components of fuel are carbon, hydrogen, nitrogen, sulfur, moisture, and ash, and among these, carbon and hydrogen contents, and moisture are very important factors in calculating the emission factor (Jeon et al. 2006). The dry basis carbon content attained from the elemental analysis was converted into as-received basis carbon content through formula (6), and the oxidation rate suggested by the as-received basis carbon content, net calorific value, and IPCC was applied to calculate the carbon emission factor as shown in formula (7) (IPCC 1996).

$$C(\text{as received basis}) = C(\text{dried basis}) \times \{(100 - \text{TM})/100\} \quad (6)$$

$$C \text{ emission factor} = \{C(\text{as received basis})/100\}/\text{NCV}(\text{as received basis}) \quad (7)$$

Here C stands for the carbon content (%), and the C emission factor stands for the carbon emission factor

Table 2 Results of reproducibility test for calorific value

Time	Mass of standard (g)	Gross calorific (kcal/kg)
1	0.5325	6,305
2	0.5340	6,310
3	0.5335	6,308
4	0.5326	6,314
5	0.5325	6,313
	Mean	6,310
	SD	3.67
	RSD (%)	0.06
	Min	6,305
	Max	6,314

Table 3 Results of reproducibility test for proximate analysis

Sample type	Times	Weight (mg)	Contents (%)			
			Inherent moisture	Volatile matter	Ash	Fixed carbon
0.75 % Sulfur coal PROX-X	1	962.9	2.03	33.68	6.86	57.43
	2	954.3	2.02	33.69	6.89	57.40
	3	972.7	2.06	33.66	6.88	57.39
		Mean	2.03	33.68	6.88	57.41
		SD	0.02	0.02	0.02	0.02
		RSD (%)	1.02	0.04	0.22	0.04
3 % Sulfur coal PROX-X	1	1,012.6	1.05	35.42	8.55	54.98
	2	964.3	1.08	35.33	8.56	55.02
	3	953.2	1.08	35.72	8.55	54.65
		Mean	1.07	35.49	8.55	54.88
		SD	0.02	0.20	0.01	0.20
		RSD (%)	1.62	0.58	0.07	0.37
5 % Sulfur coal PROX-X	1	951.1	1.33	30.33	21.16	47.18
	2	966.3	1.35	30.11	21.09	47.45
	3	959.6	1.33	30.27	20.98	47.42
		Mean	1.34	30.24	21.08	47.35
		SD	0.01	0.11	0.09	0.15
		RSD (%)	0.86	0.38	0.43	0.31

(kg C/GJ). For the CO₂ emission factor, it was calculated in the same way as formula (8) by applying the carbon weight, among the CO₂, onto the emission factor.

$$\text{CO}_2 \text{ emission factor} = C \text{ emission factor} \times (44/12) \quad (8)$$

Result and discussion

Comparative analysis by laboratories

In this research, samples of coal were collected in workspaces where coal is found in mass amounts in order to acquire reliability of the overall statistical data of the workplace. The businesses in Korea that use large amounts of bituminous coal are coal-fired power plants, and there are a total of 10 such power plants. For this study, coal samples from all 10 of these power plants were collected. These power plants are located in Boryeong, Seochon, Sacheon, Yeongdong, Yeongheung, Dangjin, Honam, Donghae, Taean and Hadong. Through the method shown in Fig. 1, samples of coal imported from Russia were collected at the Boryeong and Donghae plants, samples of coal imported from South Africa at the Seochon plant, samples of coal imported from Indonesia at the Sacheon, Yeongdong, Yeongheung and Honam plants, samples of coal imported from Canada at the Dangjin plant, and samples of coal imported from Australia were collected at the Taean and Hadong plants (ASTM 2013). Korea currently imports all of its bituminous coal quantities from seven countries—Russia, South Africa, Indonesia, Canada, Australia, the United States and Colombia—and, except for Colombia and the United States of these seven countries, coals from five countries were analyzed in this study. Coals imported from these two countries, Colombia and the United States, which were not analyzed in this study, were found to account for 2.8 and 2.3 %, respectively, of the total 2011 domestic coal consumption.

The collected samples were distributed evenly, and calorific value analysis, elemental analysis, and proximate analysis were conducted in the laboratory of the workplace and Sejong University. Then, the result values were compared to check for reliability (ASTM 2012d; KS 2009; ASTM 2008). The results of analysis conducted in each laboratory must satisfy the analysis of tolerance between laboratories as given in Table 4. As it is displayed in Table 5, the difference of calorific value is 14–69 kcal/kg, 0.06–0.98 % for carbon, 0.02–0.22 % for hydrogen, and 0.11–0.46 % for inherent moisture. Accordingly, the results satisfy the analysis of tolerance between the laboratories.

Fig. 1 Sample Preparation Flowchart

Table 4 Tolerance of analysis in laboratory

Category	Calorific value (kcal/kg)	C (%)	H (%)	Inherent moisture (%)
Tolerance of interior	40	0.45	0.10	0.25
Tolerance of interloculus	80	1.00	0.25	0.79

Workplace activity data

In this research, the received amount and the C and H contents of coal per coal type, total moisture, inherent

Table 5 Result of coal analysis

Power plant/ producing area	Institution	Calorific value (kcal/kg)	C (%)	H (%)	Inherent moisture (%)
Boryeong/ Russia	Laboratory	6,383	70.23	4.87	7.77
	Workplace	6,360	69.43	5.01	7.49
	Error	23	0.80	0.14	0.28
Seocheon/ South Africa	Laboratory	6,629	67.87	4.63	2.91
	Workplace	6,666	67.40	4.81	3.24
	Error	37	0.47	0.18	0.33
Sacheon/ Indonesia	Laboratory	5,665	67.90	4.95	12.95
	Workplace	5,651	67.84	4.97	12.77
	Error	14	0.06	0.02	0.18
Yeongdong/ Indonesia	Laboratory	6,920	75.30	4.68	4.34
	Workplace	6,979	74.98	4.86	4.50
	Error	59	0.32	0.18	0.16
Yeongheung/ Indonesia	Laboratory	5,526	70.20	5.41	17.37
	Workplace	5,510	69.22	5.53	18.07
	Error	16	0.98	0.12	0.7
Dangjin/ Canada	Laboratory	6,243	69.93	4.73	2.18
	Workplace	6,215	69.21	4.80	2.64
	Error	28	0.72	0.07	0.46
Honam/ Indonesia	Laboratory	5,965	70.89	4.91	12.64
	Workplace	5,987	70.04	5.05	12.75
	Error	22	0.85	0.14	0.11
Donghae/ Russia	Laboratory	6,608	73.88	4.35	6.18
	Workplace	6,583	73.20	4.55	5.77
	Error	25	0.68	0.20	0.41
Taean/ Australia	Laboratory	6,467	72.39	5.04	8.28
	Workplace	6,501	71.85	4.82	8.78
	Error	34	0.54	0.22	0.5
Hadong/ Australia	Laboratory	6,724	72.19	4.34	4.69
	Workplace	6,655	71.87	4.52	4.54
	Error	69	0.32	0.18	0.15

moisture, and dry-based gross calorific value among the workplace activity data needed for the calculation of greenhouse emissions were taken and as-received net calorific value and greenhouse gas emission factor were calculated. In case of sub-bituminous coal in Korea, ASTM was applied for classification since it is included in the bituminous coal. Classification based on ASTM refers to the 4,610–6,390 kcal/kg of coal from the calorific value (moist, mineral-matter-free basis) as sub-bituminous coal

(ASTM 2012b). Among the total 3,561 workplace activity data, bituminous coal was classified as 1,727 quantities and sub-bituminous coal as 1,834. This is organized in Table 6.

The average carbon and hydrogen contents of bituminous coal were each displayed at 71.29 ± 3.85 and 4.49 ± 0.50 %, and sub-bituminous coal was displayed at 69.63 ± 3.11 and 4.97 ± 0.37 %. The carbon and hydrogen content data are important source for converting dry-based gross calorific value into as-received net calorific value as well as when calculating the CO₂ emission factor. And since the carbon and hydrogen contents are based on the dry basis, the total moisture is needed to convert it into the as-received standard. The average inherent moisture and total moisture of bituminous coal were identified as 4.39 ± 2.74 and 11.35 ± 3.52 %, and in the case of sub-bituminous coal, it resulted in 12.60 ± 4.33 and 21.91 ± 5.45 %. In the same way as the data of carbon and hydrogen contents, data of inherent and total moisture are important base that is applied when converting dry-based gross calorific value into the as-received net calorific value as well as when calculating the CO₂ emission factor.

The average dry-based gross calorific value of bituminous coal is $6,553 \pm 302$ kcal/kg, and $5,914 \pm 391$ kcal/kg for the sub-bituminous coal. The caloric value provided by the IPCC is the as-received net calorific value. Accordingly, in order to compare the collected sub-bituminous coal calorific value with the sub-bituminous coal calorific value provided by the IPCC, inherent and total moisture are to be applied on the sub-bituminous coal dry-based gross calorific value of this research to convert it into as-received gross calorific value, and apply the hydrogen content to convert it into the as-received net calorific value. As shown in Table 6, the bituminous coal and sub-bituminous coal show differences in the moisture content and calorific value. Therefore, it is considered that Korea should not include sub-bituminous coal as bituminous coal, but should classify it separately to calculate the CO₂ emission factor.

Calculation of as-received net calorific value of sub-bituminous coal and development of emission factor

In this research, the dry-based gross calorific value of sub-bituminous coal was converted into as-received net calorific value to compare it with the as-received net calorific value of sub-bituminous coal suggested by the IPCC. As a result, the as-received net calorific value of sub-bituminous

Table 6 Statistical data of workplace

Category	Consumption (ton)	C (%)	H (%)	IM (%)	TM (%)	Calorific value (kcal/kg)
Other bituminous coal	193,519,465	71.29 ± 3.85	4.49 ± 0.50	4.39 ± 2.74	11.35 ± 3.52	$6,553 \pm 302$
Sub-bituminous coal	153,553,329	69.63 ± 3.11	4.97 ± 0.37	12.60 ± 4.33	21.91 ± 5.45	$5,914 \pm 391$

Table 7 Comparison of net calorific value and CO₂ emission factor

Category	This study	IPCC		
		Default value	Lower	Upper
Net calorific value (as-received basis) (TJ/Gg)	20.75 ± 7.59	18.09	11.5	26.0
CO ₂ emission factor (kg/TJ)	96,241 ± 4,064	96,100	89,500	99,700

Fig. 2 Compare CO₂ emissions in this study

coal used domestically, as seen in Table 7, resulted in 20.75 ± 7.59 TJ/Gg, and it was recognized how it was included in the range of as-received net calorific value of sub-bituminous coal suggested by the IPCC. Moreover, in this research, the dry basis carbon content was converted in the as-received basis to calculate the C emission factor and CO₂ emission factor. The calculated CO₂ emission factor of sub-bituminous coal was $96,241 \pm 4,064$ kg/TJ, and almost no difference was displayed with 96,100 kg/TJ, the default value suggested by the IPCC.

In this study, Korea's 2009 greenhouse gas emission from sub-bituminous coals was estimated and then compared, using the analyzed figure of this study and the IPCC's default value. In 2009, Korea's sub-bituminous coal usage was approximately 31.4 million tons; the greenhouse gas emission of such sub-bituminous coal usage was, as shown in Fig. 2, estimated to be approximately 62.7 million tons when using the analyzed figure of this study, and approximately 54.6 million tons when using the IPCC's default value.

Conclusion

The coal statistics in Korea include sub-bituminous coal in bituminous coal.

As such, centered around the sub-bituminous coals used in the energy sector of Korea, the CO₂ emission factor of sub-bituminous coal was estimated in this study. The 2007–2011 average carbon content of sub-bituminous coal was analyzed to be 69.63 ± 3.11 %, the average hydrogen content 4.97 ± 0.37 %, the inherent moisture 12.60 ± 4.33 %, the total moisture 21.91 ± 5.45 %, and the dry-based gross calorific value was analyzed to be $5,914 \pm 391$ kcal/kg; using these analyzed values, the as-received net calorific value was found to be 20.75 ± 7.59 TJ/Gg and the CO₂ emission factor was found to be $96,241 \pm 4,064$ kg/TJ.

The CO₂ emission factor for sub-bituminous coal estimated in this study is similar to the 96,100 kg/TJ CO₂ emission factor for sub-bituminous coal suggested by the IPCC; however, when compared to the CO₂ emission factor for sub-bituminous coal, it shows a value that is 1.73 % higher. The inclusion of such sub-bituminous coal into bituminous coal may become a factor that degrades the confidence level when Korea establishes its greenhouse gas inventory.

In addition, the 62.7 million ton amount for the 2009 greenhouse gas emission from sub-bituminous coal as estimated with the analyzed value of this study is an amount that is equivalent to 11.1 % of the 2009 total greenhouse gas emission amount of 564.7 million tons, and this amount is larger than the 9.3 % for the industrial processes sector, 3.3 % for the agricultural sector and 2.5 % for the waste sector. Therefore, it is important to reflect the realities of Korea when estimating the greenhouse gas emission from such sub-bituminous coals. Even though the greenhouse gas emission is 14.9 % higher than the value estimated using the IPCC's default value, the greenhouse gas emission amount that reflects the realities of Korea can be a factor that increases the confidence level of Korea's greenhouse gas inventory.

As such, for Korea, it is necessary to conduct research on classification systems for coals to ensure the confidence level of greenhouse gas inventory; after establishing such classification systems, development research for CO₂ emission factor that is adjusted for classification systems would need to be undertaken.

Acknowledgments This work was supported by the Human Resources Development program (No. 20094010200030) of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Trade, Industry and Energy. This subject is supported by Korea Ministry of Environment as "Climate Change Correspondence R&D Program".

Open Access This article is distributed under the terms of the Creative Commons Attribution License which permits any use, distribution, and reproduction in any medium, provided the original author(s) and the source are credited.

References

- ASTM (2008) Standard test methods for instrumental determination of carbon, hydrogen, and nitrogen in laboratory samples of coal and coke. ASTM D 5373
- ASTM (2011) Standard practice for preparing coal samples for analysis. ASTM D 2013/D2013M-11
- ASTM (2012) Standard practice for calculating coal and coke analyses from as-determined to different bases. ASTM D 3180
- ASTM (2012) Standard classification of coal by rank. ASTM D 388
- ASTM (2012) Standard test method for gross calorific value of coal and coke. ASTM D 5865
- ASTM (2012) Proximate analysis of coal and coke by micro thermogravimetric analysis. ASTM D 7582
- Australian Greenhouse Office (AGO) (2001) Technical guidelines (Generator efficiency standards) version 1.2
- Dios M, Souto JA, Casares JJ (2013) Experimental development of CO₂, SO₂ and NO_x emission factors for mixed lignite and subbituminous coal-fired power plant. *Energy* 53:40–51
- Galetovic A, Munoz CM (2013) Wind, coal, and the cost of environmental externalities. *Energy Policy* 62:1385–1391
- Intergovernmental Panel on Climate Change (IPCC) (1996) Revised 1996 IPCC guidelines for national greenhouse gas inventories
- Intergovernmental Panel on Climate Change (IPCC) (2006) 2006 IPCC guidelines for national greenhouse gas inventories
- ISO 1928 (2009) Solid mineral fuels—determination of gross calorific value by the bomb calorimetric method and calculation of net calorific value
- Jeon EC, Sa JW, Lee SH, Jeong JH, Kim KH, Bea WS (2006) Development of emission factors for greenhouse gas from bituminous coal fired power plants. *J KOSAE* 22:107–116
- Korea Energy Economics Institute (KEEI) (2011) Yearbook of energy statistics
- Kotowicz J, Bartela L (2012) Optimisation of the connection of membrane CCS installation with a supercritical coal-fired power plant. *Energy* 38:118–127
- KS (2006) Determination of calorific value of coal and coke. KS E 3707
- KS (2009) Coal and coke-general rules for sampling, analysis and testing. KS E 3709
- Lee S, Kim J, Lee J, Lee SH, Jeon EC (2011) A study of the bituminous coal oxidation factor in large scale boilers, A for estimating GHG emissions. *Asian J Atmos Environ* 5(3): 189–195
- Lee J, Kim J, Kim S, Im G, Lee S, Jeon EC (2012) Development of a country-specific CO₂ emission factor for domestic anthracite in Korea, 2007–2009. *Environ Sci Pollut Res* 19:2722–2727
- Lee J, Cho CS, Hong KH, Jeong JH, Kim S, Jeon EC (2013) A study on carbon dioxide emissions from bituminous coal in Korea. *Environ Earth Sci*. doi:10.1007/s12665-013-2258-6
- Lorenz U, Grudzinski Z (2003) Hard coal for energetic purposes: price–quality relationships; international coal market observations and Polish practice. *Appl Energy* 74:271–279
- Ozdogan S (1998) Estimation of CO₂ emission factors of coals. *Fuel* 77(14):1605–1609
- Pettinau A, Ferrara F, Amorino C (2012) Techno-economic comparison between different technologies for a CCS power generation plant integrated with a sub-bituminous coal mine in Italy. *Appl Energy* 99:32–39
- Quick JC, Brill T (2002) Provincial variation of carbon emissions from bituminous coal: influence of inertinite and other factors. *Int J Coal Geol* 49:263–275
- Quick JC, Glick DC (2000) Carbon dioxide from coal combustion: variation with rank of US coal. *Fuel* 79:803–812
- Sheng C, Li Y (2008) Experimental study of ash formation during pulverized coal combustion in O₂/CO₂ mixtures. *Fuel* 87:1297–1305
- The Republic of Korea (2011) Korea's third national communication under the United Nations framework convention on climate change
- US Energy Information Administration (EIA) (2010) International energy outlook 2010
- US Environmental Protection Agency (EPA) (2000) Carbon dioxide emissions from the generation of electric power in the United States
- Yoon SK, Myeong SJ, Jang TH, Kim JS, Lee SH, Kim KH, Jeon EC (2008) Development of CO₂ emission factors for alternative fuels with assessment of emission reduction in cement industry. *J KOSAE* 24(2):189–195