Estimated CO_2 Emissions and Analysis of Solid Recovered Fuel (SRF) as an Alternative Fuel

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ABSTRACT

The purpose of this study was to develop a CO_2 emission factor for refuse plastic fuel (RPF) combustion facilities, and calculate the CO_2 emissions from these facilities. The CO_2 reduction from using these facilities was analyzed by comparing CO_2 emission to facilities using fossil fuels. The average CO_2 emission factor from RPF combustion facilities was 59.7 Mg CO_2/TJ. In addition, fossil fuel and RPF use were compared using net calorific value (NCV). Domestic RPF consumption in 2011 was 240,000 Mg/yr, which was compared to fossil fuels using NCV. B-C oil use, which has the same NCV, was equal to RPF use. In contrast, bituminous and anthracite were estimated at 369,231 Mg/yr and 355,556 Mg/yr, respectively. In addition, the reduction in CO_2 emissions due to the alternative fuel was analyzed. CO_2 emissions were reduced by more than 350 Mg CO_2/yr compared to bituminous and anthracite. We confirmed that using RPF, an alternative fuel, can reduce CO_2 emissions.

Key words: Solid recovered fuel (SRF), Refuse plastic fuel (RPF), Alternative fuel, CO_2 emission, CO_2 reduction

1. INTRODUCTION

In the Republic of Korea, industrial waste and municipal solid waste are increasing quickly due to the nation's industrial and economic growth (Yoon *et al*., 2008). As a result, much attention has been paid to techniques that turn waste into renewable energy sources because of their ability to address waste treatment and rising air pollution (Stasta *et al*., 2006). Waste-to-energy techniques are effective for waste management because they can resolve various issues, such as increasing waste production, soaring oil prices, and increasing greenhouse gas (GHG) production. Therefore,

the Ministry of Environment (MOE) established "comprehensive measures for waste" and "waste and biomass energy measures for green growth and climate change response" in 2008, to develop various techniques for renewable energy. According to this plan, 3.78 percent of domestic energy will come from renewable sources by 2013. More than 80 percent of renewable energy comes from waste energy, and typical waste-to-energy facilities include combustible waste (refuse derived fuel [RDF], refuse plastic fuel [RPF], wood chip fuel [WCF], and tire derived fuel [TDF]) facilities (NIER, 2011).

The emission of GHG and air pollutants from the facilities is a serious issue and is expected to get worse. In particular, CO_2 was the 7th largest pollutant in the nation and the 3rd largest pollutant in the world (ECJRC & NEAA, 2011). Therefore, reducing GHG emissions from waste-to-energy facilities is important.

To determine GHG emissions, the Intergovernmental Panel on Climate Change (IPCC) Guideline (IPCC, 2006) recommended using country-specific emission factors when available. The gap between emissions from pollutants and the measured emission factor can be large if the international emission factor is used (Jang *et al*., 2009). Therefore, developed countries are trying to determine their emission factors (Jeon, 2007; AGO, 2001; EPA, 2000), and Korea should determine its emission factor for GHG emission sources as well. Solid recovered fuel (SRF) facilities were studied to develop the CO_2 emission factor. By applying this emission factor, the CO_2 emissions from targeted SRF facilities were estimated, and decreased CO_2 emissions were determined by comparing alternative fuels. This study was conducted to produce basic data for national emissions calculations of waste-to-energy facilities.

2. METHODOLOGY

2.1 Process of Study
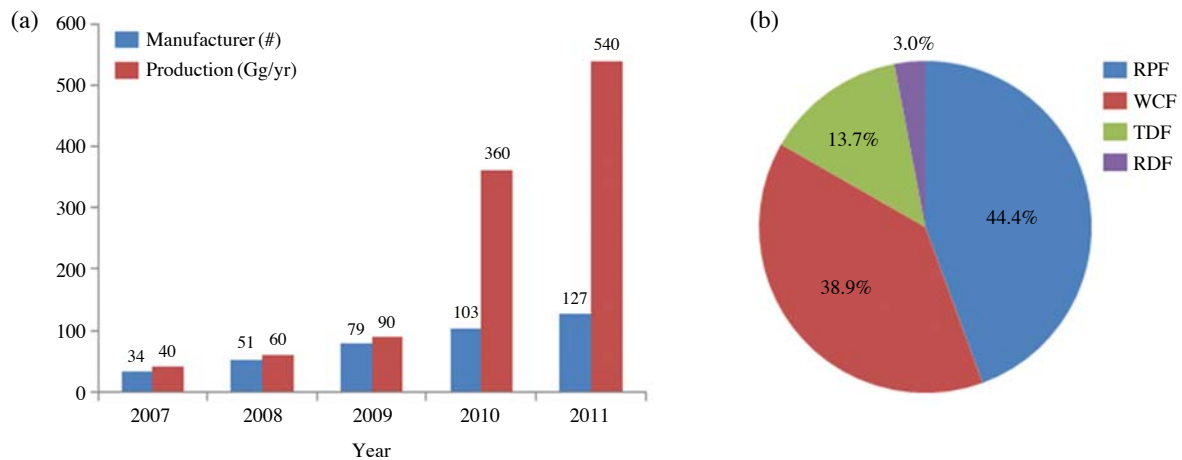
SRF reduces GHG emission, serves as an alterna-

Fig. 1. (a) Yearly status of Solid Recovery Fuel output and producing facility (b) 2011's ratio of Solid Recovery Fuel usage.

Table 1. General information on the investigated industry.

Facilities	Industry type	Capacity (Mg/day)	Boiler type	Control device
A	Dyeing and Finishing of Fiber and Yams	17.9	Stoker	Cyclon, SDR[a], B/F[b]
B	Manufacture of Shaped Wood Products and Wood for Special Purpose	20.3	Stoker	SNCR[c], Cyclon, SDR, B/F
C	Dyeing and Finishing of Fiber and Yams	9.5	Circulating fludized bed	Cyclon, SDR[a], B/F[b]

[a]: Semi-Dry Reactor, [b]: Bag-Filter, [c]: Selective Non Catalytic Reduction

tive to fossil fuels, and increases energy self-sufficiency (Hiromi *et al.*, 2012). This study was conducted at 3 solid-waste fuel facilities that use the most RPF.

The theoretical calorific value was calculated by collecting the fuels used at each facility and an industrial analysis was conducted. Using the theoretical calorific value and worksheets provided by the IPCC, a CO_2 emission factor was developed and the CO_2 emissions were calculated. Several emission characteristics, such as the facility types (stoker/fluidized bed), fuel injection (semi-automatic/automatic), and combustion type (exclusive use/mixed fuel), differed from facilities using RPF. Therefore, the best possible method to calculate CO_2 emissions was to use the Tier 3 emission factor. However, Tier 3 emission factors were not available, so Tier 1 emission factors were used.

To compare the estimated CO_2 emissions from RPF and fossil fuel (B-C oil, bituminous, and anthracite) combustion, the yearly total use of heat production value of RPF was calculated using the estimated CO_2 emission. This yearly total use of heat production value and the coefficient of heat and CO_2 emission factor for fossil fuels, provided by the IPCC, were used con-

vert estimated CO_2 emissions from RPF to fossil fuel use and CO_2 emissions. Converted fossil fuel use and CO_2 emissions and RPF use and CO_2 emissions were cross analyzed. The decrease in fossil fuel use and CO_2 emissions due to alternative fuel (RPF) use was determined.

2.2 Selection of Target Facility

Through 2011, 540,000 Mg/yr of SRF was produced in 127 manufacturing facilities, as shown in Fig. 1. The most common SRF was RPF (240,000 Mg/yr). A total of 34 RPF facilities were in operation, 20 of which were dedicated facilities (NIER, 2011). The facilities targeted in this study were selected using maintenance information from the Korea Environment Corporation (KECO) for SRF facilities that use RPF.

The facilities were selected from the National Institute of Environmental Research (NIER)'s Stack Emission Management System (SEMS) database, and basic information for the selected facilities was secured. Both small-scale and regular-sized facilities used 400-900 kg RPF per hour as a fuel to produce steam, as shown in Table 1.

2. 3 Ultimate Analysis and Proximate Analysis

Of the fuels used to develop a CO_2 emission factor on the IPCC worksheet, carbon content was a major factor in CO_2 emissions from combustion facilities. Water and moisture content are necessary to convert gross calorific value (GCV) to NCV and are essential for elemental and industrial analysis (Quick and Glick, 2000). The sample, needed for elemental and industrial analysis, shows fuel composition and heterogeneity. According to waste processing test methods, a waste sample of more than 1 kg was collected at random, screened, and smashed for analysis. An elemental analysis, including carbon, hydrogen, nitrogen, and sulfur, was carried out using a PerkinElmer Series II Analyzer. The remainder of the sample was considered to be oxygen.

The sample was weighed in an area with oxygen, combusted to ionize the elements (C, H, N, S), and oxidized or reduced in an oxygen reactor or reduction reactor. CO_2, H_2O, N_2, and SO_2, generated through this process were separated into Gas Chromatography columns. Each element was quantified using a thermal conductivity detector (TCD). The standards used for analysis were cystine organic analytical standards (C=29.99, H=5.03, N=11.67, S=26.69).

The moisture content was determined after heating about 1 g of smashed sample for 1 hour, placing it in a dry tray, and cooling in a desiccator. The sample was weighed (to 0.1 mg precision) before and after drying. To determine the ash content, about 1 g of smashed sample was placed in an incineration tray and heated to 500°C for 60 minutes. Heating continued for 30-60 minutes at 815°C, and the temperature was maintained at 815 ± 10°C for 1 hour. After incineration, the incineration tray was cooled on a metal plate for 10 minutes in a desiccator, and weighed (to 0.1 mg precision). The combustible solids were determined using the difference in the mass of dry solid samples and ash samples.

Table 2. Step by step calculation work-sheet for CO_2 emission factor.

Step 1 (Fuel data)					
Item	Carbon of fuel (as received basis)	Carbon of fuel (as dried basis)	Total moisture	Inherent moisture	Hydrogen
Sub-Item	A	①	②	③	④
Unit	(%)	(%)	(%)	(%)	(%)
Calculation	①×(100÷(100+②))	−	−	−	−

Step 2 (Raw data)					
Item	Gross heating value	Net heating value		Fuel consumption	Electric power generation	Heating generation
Sub-Item	B	C		D	E	F
Unit	(kcal/kg)	TJ/Mg		Mg/hr	MWh	TJ/hr
Calculation		$([B-\{6\times(9\times④+③)\}]\times 4.18) \times 10-6$		−	−	C×D

Step 3 (Emission)			
Item	C emission factor	C emission	Oxidation rate	Real carbon emission
Sub-Item	G	H	I	J
Unit	Mg C/TJ	Mg/hr	−	Mg/hr
Calculation	(A÷100)÷C	F×G	−	H×I

Step 4 (Carbon emission factor)		
Item	C emission factor		
Sub-Item	K	L	M
Unit	Mg/TJ	Mg/Mg	Mg/MWh
Calculation	(J÷F)	(J÷D)	(J÷E)

Step 5 (Carbon dioxide emission factor)		
Item	CO_2 emission factor		
Sub-Item	N	O	P
Unit	Mg CO_2/TJ	Mg CO_2/Mg	Mg CO_2/MWh
Calculation	K×(44÷12)	L×(44÷12)	M×(44÷12)

2.4 Calorific Value Analysis

Calorific value, the calories emitted when a unit mass of fuel is fully combusted, is a key factor in expressing various energy statistics and performance. Developing a CO_2 emission factor uses molecular weight and a fuel's calorific value per carbon content. Therefore, we determined calorific value using two methods. After elemental and industrial analysis, the theoretical calorific value was calculated by using the Dulong formula. The calorific value was divided into gross calorific value (GCV) and net calorific value (NCV). GCV includes the heat of water condensation, which is produced through combustion, and NCV is all other heat. Because the water in combustion gases is released as a vapor, the heat of condensation is not included in combustion. The Dulong formula that was used to calculate GCV and NCV is identical to (1) and (2).

$$GCV\,(kcal/kg) = 8,100C + 34,000\,(H - O/8) + 2,500S \quad (1)$$

$$NCV\,(kcal/kg) = GCV\,(kcal/kg) - 600\,(9H + W) \quad (2)$$

The NCV was converted from kcal/kg to TJ/kg by using the conversion factor $4.184 \times 10(-3)$. For our calculations we used the NCV. As an alternative method to determine calorific value, in fuel manufacturing facilities, a qualification test for quality assurance is conducted at the Korea Institutes of Machinery & Material (KIMM). The certificate of analysis 『Quality and rating of solid waste fuels, certificate』 includes the fuel's calorific value and proximate analysis.

2.5 Estimation of Emission Factor and Emission

According to the IPCC Guidelines (2006), carbon content is a main factor in the CO_2 emission factor of fuel combustion due to carbon combustion being less sensitive than other fuels. The CO_2 emission factor was developed by using ultimate and proximate analyses and a 5-step worksheet (Table 2). The 1st step investigated carbon content, hydrogen content, and water needed to convert GCV to NCV. The 2nd step used the values from step 1 to convert the calculated GCV to NCV. Also, calories were converted from kcal/kg to TJ/kg. A fuel's NCV (TJ/kg) and use (Mg/hr) were multiplied to determine the total heat production (TJ/hr). The 3rd step calculated the emission factor by deducting the carbon emission factor (Mg C/TJ) by using carbon content (%) and NCV. The carbon emission factor and the total heat production were multiplied to determine the carbon emission (Mg C/day). The IPCC suggested that the CO_2 oxidation rate be used to calculate the actual carbon emission factor; we used oxidation rate 1. In the 4th step, the carbon emission factor was determined by dividing the actual carbon emission factor by the heat production and fuel use. Step 5 deducted the CO_2 emission factor by using the molecular weights of CO_2 and carbon. The RPF facilities' total CO_2 emission factor was calculated using the deducted CO_2 emission factor, fuel use (Mg/yr), and NCV from equation (3).

CO₂ Emission (Mg/yr)
  =CO₂ Emission Factor (Mg/TJ)
    × Fuel Consumption (Mg/yr) × NCV (TJ/kg) × 10³

$$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad (3)$$

2.6 Alternative Fuel Effect and CO₂ Emission Reduction

SRF includes recycled combustibles from household wastes that were reclaimed or incinerated. Among SRF, RPF, a fuel made of more than 60% of plastic waste, attracted particular public attention as alternative to fossil fuels, because it is cheap with a high calorific value. Alternative fuel use varies in 2 ways. Some facilities use fossil fuels and mixed combustion and are usually larger, such as electric power plants and cement manufacturing companies (Bonnie and Yiannis, 1998). Other facilities, such as those targeted in this study, use only alternative fuels, such as RPF. Equations (4) and (5) can be used to calculate the emissions for each type are facility. We used these equations to analyze the reduction in emissions. The unit cost of fossil fuels and RPFs, however, were not considered.

Alternative Fuel (Mg/yr)
$$= \frac{RPF\ Consumption\,(Mg/yr) \times RPF\ NCA\,(TJ/kg)}{Alternative\ Fuel\ NCA\,(TJ/kg)} \quad (4)$$

Alternative Fuel CO₂ Emission (Mg CO₂/yr)
  =RPF Consumption (Mg/yr) × RPF NCA (TJ/kg)
    × Alternative Fuel Emission Factor (Mg CO₂/yr)   (5)

3. RESULTS AND STUDY

3.1 Calories Calculations

Elemental and industrial analyses were performed to calculate the calories in the fuel. Each sample was analyzed 3 times, and the results are shown in Tables 3 and 4. The elemental analysis showed that 66.8-70.39% of the samples was carbon, 16.81-18.81% was hydrogen, 11.19-15.47% was oxygen, and only 1% or was nitrogen and sulfur. The industrial analysis and certificate results showed that domestic SRF had less than 10% water and less than 20% ash. Furthermore, our experiment had lower values in each column than those on the certificate. The calories calculated from the test values from elemental and industrial

Table 3. Ultimate analysis of samples by this study.

Facilities	Test No.	Carbon (%)	Hydrogen (%)	Nitrogen (%)	Sulfur (%)	Oxygen (%)
A	1	64.43	17.83	0.18	0.74	16.82
	2	68.55	15.46	0.24	0.71	15.04
	3	67.46	17.14	0.22	0.65	14.53
	Sub-avg.	66.81	16.81	0.21	0.70	15.47
B	1	72.46	17.95	0.30	0.72	8.57
	2	68.84	17.67	0.36	0.75	12.39
	3	69.86	16.51	0.37	0.67	12.59
	Sub-avg.	70.39	17.38	0.34	0.71	11.19
C	1	69.52	18.23	0.08	0.74	11.43
	2	69.36	17.30	0.10	0.71	12.53
	3	66.73	20.89	0.12	0.85	11.41
	Sub-avg.	68.54	18.81	0.10	0.77	11.79

Table 4. Proximate analysis of RPF samples by this study.

Facilities	Test No.	Test result (% wt.)			Certification (% wt.)		
		Moisture	Ash	Combustible	Moisture	Ash	Combustible
A	1	6.67	4.82	88.51	–	–	–
	2	8.21	4.53	87.26	–	–	–
	3	6.52	3.92	89.56	–	–	–
	Sub-avg.	7.13	4.42	88.45	6.53	1.28	92.19
B	1	3.66	9.82	86.52	–	–	–
	2	3.94	9.11	86.95	–	–	–
	3	3.52	9.43	87.05	–	–	–
	Sub-avg.	3.71	9.45	86.84	1.49	2.86	95.65
C	1	3.03	4.96	92.01	–	–	–
	2	2.89	5.41	91.70	–	–	–
	3	2.49	5.55	91.96	–	–	–
	Sub-avg.	2.80	5.31	91.89	0.22	2.05	97.73

Table 5. Net Calorific Value analysis of RPF samples by this study.

Fuel type	Facilities	Test result		Certification results		Source
		(kcal/kg)	(TJ/Mg)	(kcal/kg)	(TJ/Mg)	
RPF	A	9,555	0.040	9,063	0.038	This study
	B	10,230	0.043	9,712	0.041	
	C	10,473	0.044	9,922	0.042	
	Avg.	10,086	0.042	9,565	0.040	
B-C Oil	–	–	–	–	0.040	(IPCC, 2006)
Bituminous	–	–	–	–	0.026	
Anthracite	–	–	–	–	0.027	
RDF	–	–	–	–	0.021	(Hiromi et al., 2012)
RPF (GCV)	–	–	–	–	0.039	(Hibber et al., 2007)

analyses and the calories suggested by the certificate are presented in Table 5. The calculated calorific value was 9,555-10,437 kcal/kg, higher than the RPF standard of 6,500 kcal/kg, while the calorific value on the certificate was 9,063-9,922 kcal/kg. The calculated calories in RPF were about 500 kcal/kg higher than reported on the certificate. After converting to TJ/kg, the calorific value on the certificate was similar to calorific values of B-C oil and 1.5 times higher than the values bituminous and anthracite suggested by the

IPCC. RPF had more calories than bituminous and anthracite because RPF had a higher hydrogen content. Even in Dulong's calorie equation, hydrogen had the biggest influence on calorific value. According to the elemental analysis of bituminous and anthracite conducted by the American Society for Testing Materials (ASTM), bituminous and anthracite were about 5% hydrogen, whereas RPF was more than 15% hydrogen in this study.

3.2 RPF Emission Factor Development

The following study used the IPCC-suggested, 5-step worksheet to determine the CO$_2$ emission factor for alternative fuel. The calculated RPF emission factor and the IPCC-suggested fossil fuel emission factor are described in Table 6. An RPF emission factor was calculated for each facility, and facility C, with 57.4 Mg CO$_2$/TJ, had the lowest. Facility A, with 61.3 ton Mg CO$_2$/TJ, had the highest and the average RPF was 59.7 Mg CO$_2$/TJ. The IPCC-suggested emission factors for B-C oil, bituminous, and anthracite are 77.4, 94.6, and 98.3 Mg CO$_2$/TJ, respectively.

3.3 The Calculated Decrease in CO$_2$ Emission Due to Alternative Fuels

CO$_2$ emissions were calculated by applying the calculated emission factor reported above. The average RPF emission factor was 59.7 Mg CO$_2$/TJ. Because RDF facilities emit much CO$_2$ and because there is

little literature on this issue, further studies should verify this emission factor. In this study, the decrease in CO$_2$ emissions due to alternative fuel was calculated in multiple steps. First, alternative fuel use was determined by replacing fossil fuel use with RPF. The amount RPF used was proportional to NCV. RPF use is shown in Table 7. The amount of fossil fuel replaced by RPF was inversely proportionate to the NCV. For B-C oil,
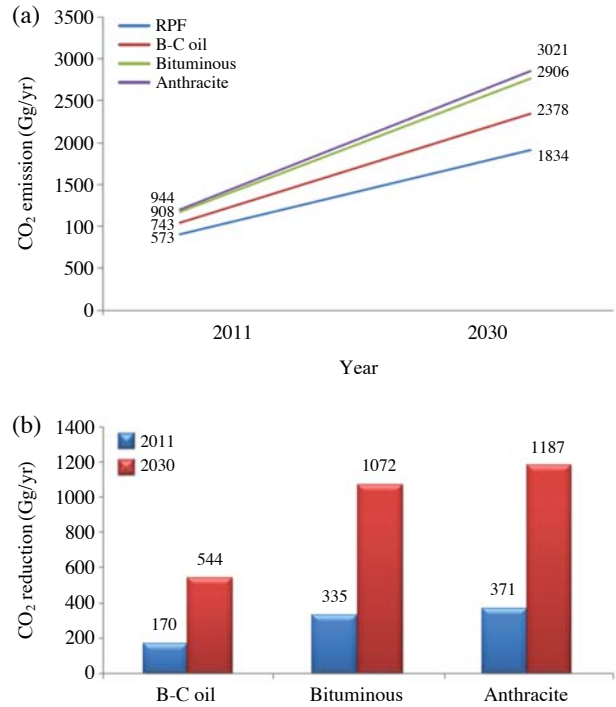

Fig. 2. (a) Estimated CO$_2$ emission by fuel, respectively, in 2011-2030 (b) CO$_2$ emission reduction by fuel, respectively, replacing fossil fuel by RPF in 2011-2030.

Table 6. CO$_2$ emission factors of RPF and fossil fuels.

Fuel type	Facilities	CO$_2$ emission factor Mg CO$_2$/TJ	Source
RPF	A	61.3	This study
	B	60.3	
	C	57.4	
	Avg.	59.7	
B-C Oil		77.4, 76.3	(IPCC, 2006), (Hong et al., 2010)
Bituminous		94.6, 91.5	(IPCC, 2006), (Hong et al., 2010)
Anthracite		98.3, 97.5, 111.7	(IPCC, 2006), (EPA, 2002), (Jeon et al., 2007)

Table 7. Converted amounts of alternative fuels.

Fuel type	Fuel consumption (Mg/yr)	Net calorific value (TJ/Mg)	Alternative fuel (Mg/yr)
RPF	240,000	0.040	–
B-C Oil	–	0.040	240,000
Bituminous	–	0.026	369,231
Anthracite	–	0.027	355,556

Table 8. Comparison of CO$_2$ emission factors and reduced amounts for different fuels.

Fuel type	Total heat production (TJ/yr)	Emission factor (Mg CO$_2$/TJ)	Emission (Mg CO$_2$/yr)	CO$_2$ reduction (Mg CO$_2$/yr)
RPF	9,600	59.7	573,120	–
B-C Oil		77.4	743,040	169,920
Bituminous		94.6	908,160	335,040
Anthracite		98.3	943,680	370,560

the fuel replaced did not changed since the NCVs for both fuels were equal. For bituminous, RPF replaced 369 Gg/yr, and for anthracite, RPF replaced 356 Gg/yr.

As shown in Table 8, CO_2 emissions from each fuel were calculated by multiplying the replaced fuel by its emission factor. RPF emitted the least CO_2, followed by B-C oil, bituminous, and anthracite. This process allowed us to analyze the decrease in CO_2 emissions due to replacing each fuel with RPF. Replacing B-C oil decreased emissions by 170 Gg CO_2/yr. The difference was more pronounced with coal fuel. Using RPF rather than bituminous or anthracite decreased emissions by 350 Gg CO_2/yr.

Renewable energy will account for 11% of all total energy by 2030, up from 2.3% in 2007, under the plan for distributing renewable energy sources. We used 2011 as a base year since statistics on total solid fuel use were compiled then. Using the interpolation method, we estimated the solid fuel penetration ratio to be roughly 3.5% in 2011 on the basis of the 2007 and 2030 values. The use and effects of alternative fuel were analyzed as the RPF distribution increases and CO_2 reduction was estimated. By 2030, 768 Gg/yr of RPF will be used, 3.2 times more than the current ratio, and it will replace 768 Gg/yr B-C oil, 1,181 Gg/yr bituminous, and 1,136 Gg/yr anthracite. By replacing fossil fuels with RPF, CO_2 emission will decrease significantly as shown in Fig. 2. As of 2011, 44% of the total solid fuel in the nation is RPF, so CO_2 emissions from solid fuel will be much lower. Similar studies should be performed for other types of solid fuel.

4. CONCLUSIONS

RPF is one of the most widely produced SRF fuels and is a renewable energy source. Furthermore, RPF use is likely to replace fossil fuels. Therefore, in this study, adjusting to the change in global fuel use, the emission characteristics of SRF facilities were surveyed, and a greenhouse gas (CO_2) emission factor was developed.

By calculating the greenhouse gas emission factors of targeted facilities and comparing greenhouse gas emissions, we reached the following conclusions. RPF emission factors were 61.3, 60.3, and 57.4 Mg CO_2/TJ in facilities A, B, and C, respectively. The average emission factor of the 3 facilities was 59.7 Mg CO_2/TJ. Additional experiments are needed to verify this result. The calorific value of each fuel calories was used to compare fossil fuel use with RPF use. In 2011, the domestic RPF use was 240,000 Mg/yr. By using the NCV, RPF use was converted to B-C oil, bituminous, and anthracite use. B-C oil had the same NCV as RPF.

Bituminous and anthracite had relatively low NCVs: 369,231 Mg/yr and 355,556 Mg/yr, respectively. By incorporating alternative fuel use, the decrease in CO_2 emissions for each fuel were analyzed. When RPF replaced B-C oil, emissions decreased by 169,920 Mg CO_2/yr. When RPF replaced bituminous or anthracite, emissions decreased by 350,000 Mg CO_2/yr. The results of this study are limited to RPF because no other alternative fuels were considered. However, considering that the emission factor for RPF facilities was nonexistent, the decrease in CO_2 emissions is significant. Furthermore, using RPF can reduce CO_2 emissions. If RPF facilities satisfy air pollutant quality standards, it can be expected to provide further momentum for environmental policy.

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