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ORIGINAL RESEARCH

Life-cycle greenhouse gas emissions in power generation using palm kernel shell

Issei Sato[1] | **Takanobu Aikawa**[2] | **Chun Sheng Goh**[3] | **Chihiro Kayo**[1]

[1]Institute of Agriculture, Tokyo University of Agriculture and Technology, Tokyo, Japan

[2]Renewable Energy Institute, Minato-ku, Tokyo, Japan

[3]Jeffrey Sachs Center on Sustainable Development, Sunway University, Selangor, Malaysia

Correspondence
Issei Sato, Institute of Agriculture, Tokyo University of Agriculture and Technology, 3-5-8 Saiwaicho, Fuchu, Tokyo 183-8509 Japan.
Email: s210576z@st.go.tuat.ac.jp

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Abstract

Palm kernel shell (PKS) utilization for power generation has greatly increased in Japan since the introduction of the feed-in tariff (FIT) in 2012. However, the FIT fails to consider the entire palm industry while evaluating the environmental impacts of using PKS. Therefore, this study aimed to elucidate the life-cycle greenhouse gas (GHG) emissions of power generation using PKS. We targeted two PKS-firing power plants as these are the first two instances of the use of PKS in power plants in Japan. A system boundary was established to cover palm plantation management in Indonesia and Malaysia, as both power plants import PKS from these countries. The GHG emissions were derived from land-use change, palm plantation, oil extraction, PKS transportation, and power plants. Six scenarios were examined for the emissions based on the type of land-use change and the existence of biogas capture in oil extraction. CO_2 emissions from PKS combustion were also calculated by assuming that carbon neutrality was lost because of cultivation abandonment. The GHG emissions in one scenario, where the plantations were replanted and continuously managed and no biogas capture implemented in oil extraction, exhibited an average of 0.134 kg-CO_2eq/kWh reduction in a plant in Kyushu District, and 0.043 kg-CO_2eq/kWh reduction in a plant in Shikoku District for liquid natural gas-fired steam power generation, respectively. More than 65% of life-cycle GHG emissions originate from biogas generated during oil extraction; thus, biogas capture is an effective strategy to reduce current emissions. In contrast, in the case of accompanying land-use change or collapse of carbon neutrality, the emissions considerably exceeded those of fossil fuels. These findings indicated that the FIT fails to consider the risk of increased emissions or further substantial emission reductions. Therefore, the feasibility of FIT application to PKS needs to be re-established by evaluating the entire PKS life cycle.

KEYWORDS
biogas capture, greenhouse gas emission, land-use change, oil extraction, palm kernel shell, palm plantation

1 | INTRODUCTION

At the 21st session of the Conference of the Parties (COP21) in 2015, the Paris Agreement was adopted as a post-2020 legal framework to combat climate change, with the participation of several developed and developing countries. In the Nationally Determined Contribution of the Paris Agreement, the Japanese government announced that the life-cycle greenhouse gas (GHG) reduction target for 2030 is 26.0%, which is higher than that for the FY2013 level (Ministry of the Environment, 2019). The "Long-Term Strategy under the Paris Agreement," which was approved by the Cabinet in 2019, stated that a "decarbonized society" should be realized as early as possible in the second half of this century and an 80% reduction in GHG emissions should be achieved by 2050 (Ministry of the Environment, 2019). In this situation, as the international community strives to reduce GHG emissions, there is a growing trend in the field of energy use to replace fossil fuels such as coal and oil with renewable energy sources. In Japan, feed-in tariff (FIT) was introduced to expand electricity from renewable energy sources in 2012 (Ministry of Economy, Trade and Industry Agency for Natural Resources and Energy, 2020). The validity of the application of the FIT and the sustainability of fuel use have been examined considering the increasing use of renewable energy in Japan since the introduction of FIT. Palm kernel shell (PKS) is an imported biomass fuel currently used as a fuel for power generation in Japan. Japan's import volume has increased from 74,871 t in 2011 to 3,481,194 t in 2020 since the introduction of the FIT (Japan Ministry of Finance, 2021). The country's total import value of PKS ranked first worldwide in 2018, making it a major importer of PKS internationally (Tridge, 2021). Currently, the total power generation of PKS can be assumed less than 1% based on the imported amount mentioned above to whole Japanese power generation, which was 845 TWh in 2020 (Ministry of Economy, Trade and Industry Agency for Natural Resources and Energy, 2021b). However, the amount of PKS imports is expected to further increase in the future as the government is expected to expand the amount of power generation from "woody biomass," which includes PKS, more than two times by FY2030 (Ministry of Economy, Trade and Industry Agency for Natural Resources and Energy, 2021c).

PKS is the shell of palm seeds, being generated as a co-product of crude palm oil (CPO) in oil extraction. Most PKS used in Japan originates from palm plantations in Indonesia and Malaysia (Tridge, 2021). However, palm plantations are established by converting other land types, including tropical forests and peatlands, and are significant contributors to GHG emissions (Hassan et al., 2011; Wicke et al., 2008). Thus, the use of palm plantation-derived biomass as a fuel for power generation requires a life-cycle assessment (LCA) approach to determine the sustainability of its use and the actual GHG emission reductions. In Japan, palm oil, PKS, and oil palm trunk, which are currently subject to the FIT, are required to obtain third-party certifications after the PKS generation point, such as the Roundtable of Sustainable Palm Oil (RSPO), Green Gold Label (GGL), and Roundtable on Sustainable Biomaterials (RSB) for the sustainability of their procurement by the end of March 2023; meanwhile, the Ministry of Economy, Trade, and Industry is considering the criteria of the life-cycle GHG emissions for these fuels (Ministry of Economy, Trade and Industry Agency for Natural Resources and Energy, 2021d). Because the current FIT fails to consider a full LCA, quantifying the life-cycle GHG emissions of PKS based on possible scenarios can contribute to an improved evaluation of the environmental performance of using PKS as a power generation fuel.

With regard to palm oil, various studies have been conducted to calculate the life-cycle GHG emissions of palm oil using LCA (Arshad et al., 2017; Choo et al., 2011; Hassan et al., 2011; Muhammad et al., 2010; Subramaniam et al., 2010; Tan et al., 2010; Zulkifli et al., 2010); in particular, Kamahara et al. (2009) revealed the life-cycle GHG emissions of biodiesel derived from palm oil that was consumed in Japan. As for the LCA of PKS utilization, several studies have shown its life-cycle GHG emissions and the reduction potential. Beaudry et al. (2017) and You et al. (2017) examined the optimal use of palm biomass from the perspective of GHG emissions, considering processes after the palm biomass generating point. Chan et al. (2015, 2018) focused on the hydrothermal liquefaction of PKS and elucidated its life-cycle GHG emission in the processing of PKS. However, all of these studies set a limited system boundary, which fail to consider the palm plantation management and consumption processes.

Bałazińska (2017) revealed the life-cycle GHG emissions of PKS torrefaction in Poland but evaluated data just after the PKS generating point. Mitsubishi UFJ Research and Consulting (2019) described the life-cycle GHG emissions of using PKS for power generation in their report; however, the report primarily discusses life-cycle GHG emissions of palm oil and that of PKS as only supplemental information.

In the FIT in Japan, processes after the generation point of the PKS are defined as the life cycle of the PKS (Ministry of Economy, Trade and Industry Agency for Natural Resources and Energy, 2021a), corresponding to EU standards (EU, 2018). On the contrary, the International Organization for Standard (ISO) recommends including co-products in the allocation of LCA while ignoring wastes (ISO 14067, 2018). PKS was previously regarded as a waste of palm oil production; however, today, it is traded as a commodity, and was priced from USD 20 to 50 at mills in 2019 (Biomass Power Association, 2019) and at approximately JPY 13,000/t in the Japanese market at the end of 2020 (Japan Woody Bioenergy Association, 2020). Thus, it can be now recognized as a co-product of palm oil production rather than waste.

Finnan et al. (2012) conducted a holistic LCA analysis of co-firing power generation using PKS in Ireland by setting the system boundary from the land-use change to ash disposal. However, even though Japan is the greatest importer of PKS in the world, there have been no studies to discuss the feasibility of PKS use in Japan considering emissions from the entire life cycle of PKS. Therefore, the objective of this study was to elucidate the life-cycle GHG emissions of PKS power generation in Japan by considering land-use change and palm plantation management in the life cycle of PKS and verifying whether PKS can reduce GHG emissions compared to fossil fuel power generation and power generation using domestic biomass by establishing several scenarios.

2 | MATERIALS AND METHODS

2.1 | Objective area

This study focused on power plants using only PKS, rather than co-firing with other biomass fuels, to elucidate the life-cycle GHG emissions of PKS power generation. The target power plants are located in: (1) Tosa City, Kochi Prefecture, Shikoku District, which is the first PKS-burning power plant (hereafter, Shikoku Power Plant) in Japan (since June 2013) with an installed capacity of 20 MW; and (2) Saiki City, Oita Prefecture, Kyushu District, which is the second PKS-burning power plant (hereafter, Kyushu Power Plant) in Japan (since November 2016) with an installed capacity of 50 MW. These were the only power plants available for LCA as they had collected data over several years; most PKS-firing power plants were either launched a few years ago or are still under construction. Both of the target power plants in this study are owned by erex Co., Ltd., and the total amount of PKS used in both power plants is 350,000 t, accounting for 10% of PKS imported to Japan. erex Co., Ltd. was the first company to acquire GGL certification in its supply chain of PKS. Since both power plants only use PKS imported from Malaysia and Indonesia as of 2020, we evaluated the life-cycle GHG emissions of four routes: (1) Malaysian PKS used in Kyushu Power Plant; (2) Indonesian PKS used in Kyushu Power Plant; (3) Malaysian PKS used in Shikoku Power Plant; and (4) Indonesian PKS used in Shikoku Power Plant.

2.2 | System boundary and functional units

The system boundary is divided into five sectors: land-use change, palm plantation, oil extraction, PKS transportation, and power plants, each of which includes processes (Figure 1). Data used in the land-use change, palm plantation, and oil extraction sector were obtained from the literature, and those used in the PKS transportation and power plant sector were mainly obtained from erex Co., Ltd. by conducting surveys and by interviewing the general manager, head of corporate planning (Table 1). The global warming potential of CH_4 and N_2O to CO_2 was 25 [kg-CO_2/kg-CH_4] and 298 [kg-CO_2/kg-N_2O], respectively, as indicated by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2007).

The functional unit was defined as 1 kWh of electricity produced. The amount of PKS required to generate 1 kWh (U_{PKS} [kg-PKS/kWh]) was calculated from the low heating value of PKS (LHV_{PKS} [MJ/kg]), moisture content of PKS (u), power generation end efficiency (η) provided by erex Co., Ltd., and kWh conversion factor (3.6 MJ/kWh) (Formula 1). Each value was 0.839 kg-PKS/kWh in Kyushu Power Plant and 1000 kg-PKS/kWh in Shikoku Power Plant because the power generation end efficiency was different between power plants and was 31% in Kyushu Power Plant and 26% in Shikoku Power Plant.

$$U_{PKS} = 1 / LHV_{PKS} \times 1 / \eta \times 1 / (1 - u) \times 3.6\ (1) \tag{1}$$

Since fresh fruit bunches (FFB), fruits of oil palm, and CPO are used in the calculation of GHG emissions before the oil extraction sector, the amount of FFB (U_{FFB} [kg/kWh]) and CPO (U_{CPO} [kg/kWh]) to produce U_{PKS} were calculated (Formulas 2 and 3). The value was quoted on the weight ratio of PKS to FFB (W_{PKS}) (Komata, 2018; Vijaya & Choo, 2010) and that of CPO to FFB (W_{CPO}) (Woittiez et al., 2017).

$$U_{FFB} = U_{PKS} / W_{PKS} \tag{2}$$

$$U_{CPO} = U_{PKS} \times W_{CPO} / W_{PKS} \tag{3}$$

2.3 | Calculation of life-cycle GHG emissions

Formula 4 shows the life-cycle GHG emissions of the PKS power generation. The GHG emissions from land-use change to oil extraction were allocated into CPO and palm kernel oil (PKO), which is one of the main products, in addition to the calorific value ratio of PKS. In the allocation of GHG emissions, other biomass products that

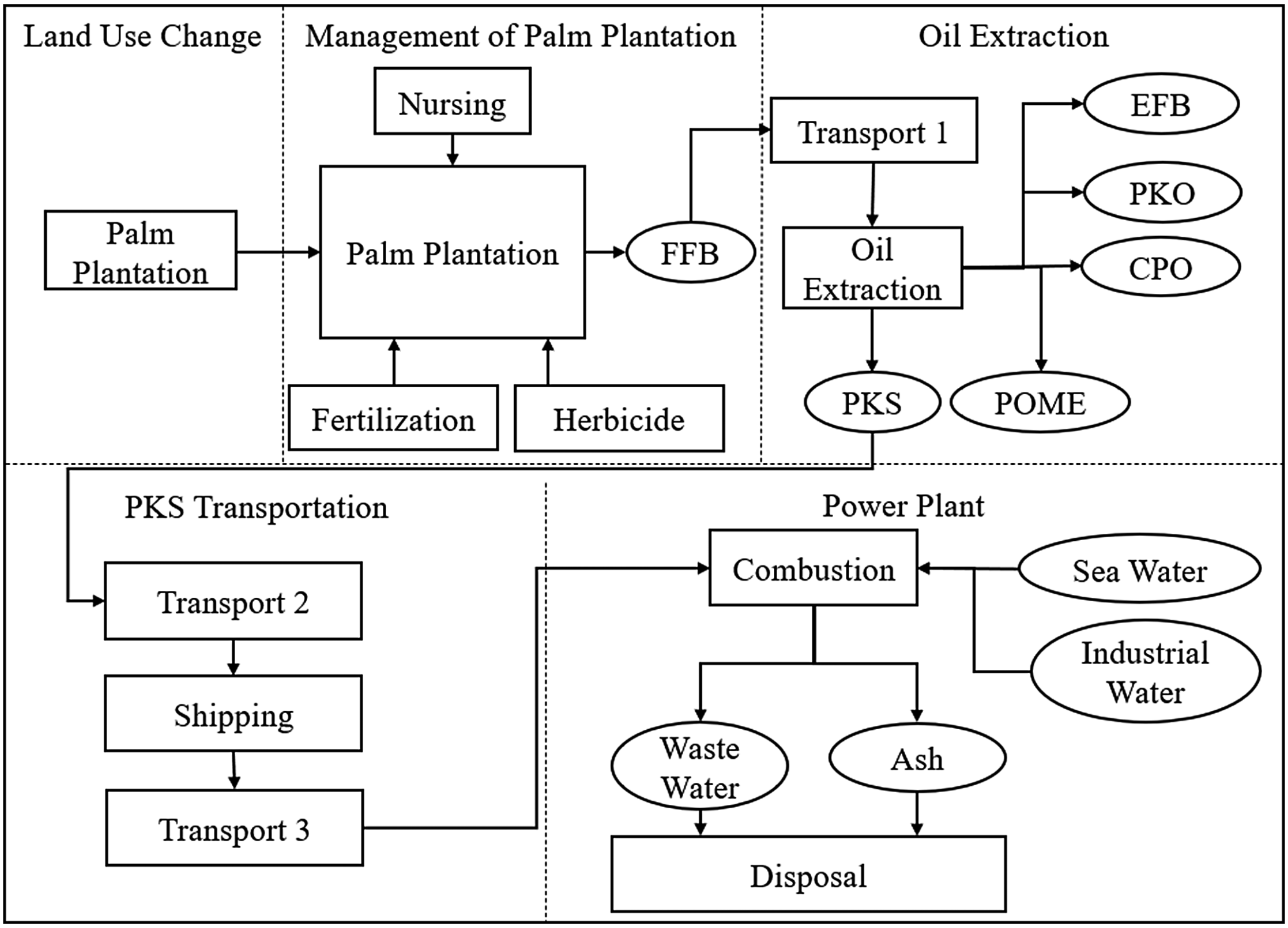

FIGURE 1 System boundary. Note: Each process is shown in rectangles and input–output products are shown in ellipses. The full form of each abbreviation is indicated as follows: CPO, crude palm oil; EFB, empty fruits bunches; FFB, fresh fruits bunches; PKO, palm kernel oil; PKS, palm kernel Shell; POME, palm oil mill effluent.

have less commodity value, such as EFB, were not considered. The calorific value ratio of PKS (Cal_{PKS}) was calculated from the LHV ($_{\text{PKS, CPO, PKO}}$) and weight ratio to FFB ($W_{\text{PKS, CPO, PKO}}$) (Formula 5). The values are cited from Phyllis 2 (TNO, 2021b), which is managed by TNO Biobased and Circular Technologies regarding the LHV of CPO (LHV_{CPO} [MJ/kg]), and from food database of Ministry of Education, Culture, Sports, Science and Technology (2020) regarding LHV of PKO (LHV_{PKO} [MJ/kg]). The weight ratio of PKO to FFB (W_{PKO}) was obtained from the annual amount of PKO and FFB in Indonesia and Malaysia as reported in the Database of the Food and Agriculture Organization of the United Nations (FAOSTAT) (FAO, 2021a, 2021b).

$$\begin{aligned}\text{CO}_{2\text{-PKS}} = (&\text{CO}_{2\text{-LUC}} + \text{CO}_{2\text{-nursing}} + \text{CO}_{2\text{-fertilization}} \\ &+ \text{CO}_{2\text{-herbicide}} + \text{CO}_{2\text{-transport 1}} + \text{CO}_{2\text{-extract}}) \times \text{Cal}_{\text{PKS}} + \text{CO}_{2\text{-transport 2}} \\ &+ \text{CO}_{2\text{-shipping}} + \text{CO}_{2\text{-transport 3}} + \text{CO}_{2\text{-combustion1,2}} + \text{CO}_{2\text{-disposal}}\end{aligned} \tag{4}$$

where $\text{CO}_{2\text{-PKS}}$: Life-cycle GHG emissions of PKS power generation [kg-CO_2eq]; $\text{CO}_{2\text{-LUC}}$: GHG emissions in land-use change [kg-CO_2]; $\text{CO}_{2\text{-nursing}}$: GHG emissions in nursing [kg-CO_2eq]; $\text{CO}_{2\text{-fertilization}}$: GHG emissions in fertilization [kg-CO_2eq]; $\text{CO}_{2\text{-herbicide}}$: GHG emissions in herbicide application [kg-CO_2eq]; $\text{CO}_{2\text{-transport 1}}$: GHG emissions in transportation of FFB [kg-CO_2eq]; $\text{CO}_{2\text{-extract}}$: GHG emissions in oil extraction [kg-CO_2eq]; $\text{CO}_{2\text{-transport 2}}$: GHG emissions in transportation of PKS in Malaysia or Indonesia [kg-CO_2eq]; $\text{CO}_{2\text{-shipping}}$: GHG emissions in shipping [kg-CO_2eq]; $\text{CO}_{2\text{-transport 3}}$: GHG emissions in transportation of PKS in Japan [kg-CO_2eq]; $\text{CO}_{2\text{-combustion1,2}}$: GHG emissions in PKS combustion [kg-CO_2eq]; $\text{CO}_{2\text{-disposal}}$: GHG emissions in disposal treatment [kg-CO_2eq]; Cal_{PKS}: Ratio of lower heating value of PKS.

$$\text{Cal}_{\text{PKS}} = \frac{W_{\text{PKS}} \times \text{LHV}_{\text{PKS}}}{W_{\text{PKS}} \times \text{LHV}_{\text{PKS}} + W_{\text{CPO}} \times \text{LHV}_{\text{CPO}} + W_{\text{PKO}} \times \text{LHV}_{\text{PKO}}} \tag{5}$$

TABLE 1 All the parameters used in this research

Parameter	Character	Value	Unit	Source
Power generation end efficiency in Kyushu Power Plant	η	31.0%	—	A survey with erex Co., Ltd.
Power generation end efficiency in Shikoku Power Plant	H	26.0%	—	A survey with erex Co., Ltd.
Moisture content of PKS	U	20.0%	—	A survey with erex Co., Ltd.
Carbon content of oven-dried PKS	C_{PKS}	46.7%	—	TNO (2021b)
Weight ratio of PKS to FFB	W_{PKS}	5.0%	—	Komata (2018); Vijaya and Choo (2010)
Lower heating value of PKS (dry)	LHV_{PKS}	17.3	MJ/kg	A survey with erex Co., Ltd.
Weight ratio of CPO to FFB	W_{CPO}	20.0%	—	Woittiez et al. (2017)
Lower heating value of CPO	LHV_{CPO}	39.7	MJ/kg	TNO (2021a)
Weight ratio of PKO to FFB	W_{PKO}	2.0%	—	FAO (2021a, 2021b)
Lower heating value of PKO	LHV_{PKO}	38.5	MJ/kg	Ministry of Education, Culture, Sports, Science and Technology (2020)
Average yield of CPO for 25 years	Y_{CPO}	87.5	t/ha	Woittiez et al. (2017)
Aboveground biomass in tropical primary forest	B_{rain}	413.1	t d.m./ha	IPCC (2019b)
Ratio of belowground biomass to aboveground biomass	R	21.2%	—	IPCC, (2019b)
Carbon fraction of tropical primary forest wood	CF	0.47	t-C/(t d.m.)	IPCC (2006a)
Above- and belowground carbon stock in peat	$C_{b\text{-}peat}$	250	t-C/ha	RSPO (2016)
Soil carbon stock in peat	$C_{s\text{-}peat}$	570	t-C/ha	Hooijer et al. (2010)
Above- and belowground biomass carbon stock in palm plantation at 25 years	$C_{b\text{-}palm}$	60	t-C/ha	IPCC (2019)
Soil carbon stock in palm plantation/tropical forest	$C_{s\text{-}palm,\ rain}$	72	t-C/ha	Hassan et al. (2011)
Emission factor of nursing	$EF_{nursing}$	0.0165	Kg-CO_2eq/t-FFB	Choo et al. (2011)
Total amount of fertilizer input for 25 years	F_{25}	2000.25	kg-N/ha	Choo et al. (2011)
Emission factor of N_2O in fertilizing	EF_1	0.0062	kg-N_2O-N/kg-N	Research Center for Global Environmental National Institute for Environmental Studies (2020)
Nitrogen volatilization ratio	$Frac_{GAS}$	0.11	kg-NH_3-N + NO_x-N/kg-N	IPCC, (2019a)
Emission factor of N_2O in atmospheric sedimentation	EF_2	0.010	kg-N_2O-N/ kg-NH_3-N + NO_x-N	IPCC (2006b)
Nitrogen leaching ratio	$Frac_{LEACH}$	0.240	kg-N/kg-N	IPCC (2019a)
Emission factor of N_2O in dissolution	EF_3	0.0075	kg-N_2O-N/kg-N	IPCC (2006b)
Annual input amount of Herbicide	H	491.885	g/(ha·year)	Kamahara et al. (2009); Moulin et al. (2017)
Emission factor in herbicide input	$EF_{herbicide}$	16.904	kg-CO_2eq/kg-herbicide	Kamahara et al. (2009)
Distant of Transport 1 (Indonesia/Malaysia)	D_1	8.5/33	km	Arshad et al. (2017); Kamahara et al. (2009)

(Continues)

TABLE 1 (Continued)

Parameter	Character	Value	Unit	Source
Emission factor of 20 t truck in Malaysia and Indonesia	EF_{20t_1}	0.169	kg-CO_2eq/tkm	Giuntoli et al. (2014); Lastauto Omnibus (2010)
Emission factor in oil extraction	$EF_{Extract}$	90.913	kg-CO_2eq/t-CPO	Hosseini and Wahid (2015); Vijaya and Choo (2010)
Emission Factor from Palm Oil Mill Effluent (POME)	EF_{POME1}	953.84	kg-CO_2eq/t-CPO	Hosseini and Wahid (2015); Vijaya and Choo (2010)
Emission Factor from POME with 85% capture of biogas	EF_{POME2}	143.076	kg-CO_2eq/t-CPO	Hosseini and Wahid (2015); Vijaya and Choo (2010)
Distance of Transport 2 (Malaysia/Indonesia)	D_2	103/200	km	A survey with erex Co., Ltd.
Emission factor of 40 t truck	EF_{40t}	0.07892	kg-CO_2eq/tkm	Giuntoli et al. (2014)
Distance of shipping (Malaysia—Kyushu/Malaysia—Shikoku/Indonesia—Kyushu/Indonesia—Shikoku)	D_{ship}	5011.5/5117.1/6265.3/6369	km	A survey with erex Co., Ltd and associated company
Emission Factor of Shipping	EF_{ship}	0.0177	kg-CO_2eq/tkm	Giuntoli et al. (2014); Lastauto Omnibus (2010)
Distance of Transport 3 (Kyushu/Shikoku)	D_3	6.3/2.7	km	A survey with erex Co., Ltd.
Emission factor of 20 t truck in Japan	EF_{20t_2}	0.0692	kg-CO_2eq/tkm	Japan Environmental Association for Industry (2020)
N_2O emission from combustion of U_{PKS}	EF_{N2O}	0.0000048	kg-N_2O/MJ-PKS	Edwards et al. (2017)
CH_4 emission from combustion of U_{PKS}	EF_{CH4}	0.0000036	kg-CH_4/MJ-PKS	Edwards et al. (2017)
Conversion factor from N_2O into CO_2	—	298	kg-CO_2/kg-N_2O	IPCC (2007)
Conversion factor from CH_4 into CO_2	—	25	kg-CO_2/kg-CH_4	IPCC (2007)
Weight ration of ash to PKS	W_{ash}	5.0%	—	A survey with erex Co., Ltd.
Ratio of boiler supply water (fresh water) to PKS	$W_{f\ water}$	0.00008	m^3/kg-PKS	A survey with erex Co., Ltd.
Ratio of boiler supply water (sea water) to PKS	$W_{s\ water}$	0.00032	m^3/kg-PKS	A survey with erex Co., Ltd.
Emission factor of ash treatment	EF_{ash}	0.001858	kg-CO_2eq/kg	Japan Environmental Association for Industry (2020)
Emission factor of waste water treatment	$EF_{water\ dis}$	1.83	kg-CO_2eq/m^3	Japan Environmental Association for Industry (2020)

2.3.1 | Land-use change

GHG emissions from the conversion of tropical primary forest and peatland into palm plantations were considered as the GHG emissions from land-use change in this study. GHG emissions from land-use change were calculated from the gap of carbon stock in each land type ($C_{peat,\ rain,\ palm}$ [t/ha]) (Formula 6) under the assumption that carbon stock in land is defined as the sum of soil carbon stock ($C_{s\text{-peat},\ rain,\ palm}$ [t-C/ha]) and aboveground and belowground biomass carbon stock ($C_{b\text{-peat},\ rain,\ palm}$ [t-C/ha]) (Formula 7). Additionally, it was assumed that there would be no GHG emissions from palm replantation since no substantial land-use change would occur. As shown in Formula 8, the area required to produce U_{PKS} (A_{PKS} [ha]) was calculated based on the quoted value of CPO yield per area over 25 years, one palm plantation cycle (Y_{CPO} [t/ha]) (Woittiez et al., 2017).

$$CO_{2-LUC} = \left(C_{peat,rain} - C_{palm}\right) \times 1000 \times A_{PKS} \times 44/12 \qquad (6)$$

$$C_{peat,rain,palm} = C_{s-peat,rain,palm} + C_{b-peat,rain,palm} \qquad (7)$$

$$A_{PKS} = \frac{U_{PKS}}{Y_{CPO} \times 1000 \times W_{PKS} / W_{CPO}} \qquad (8)$$

The aboveground and belowground biomass carbon stocks in tropical rainforests were calculated using the values of aboveground biomass in tropical rainforests (B_{rain} [t d.m./ha]) (IPCC, 2019b), the ratio of belowground biomass to aboveground biomass in tropical rainforests (R) (IPCC, 2019b), and the carbon content of biomass in tropical rainforests (CF) (IPCC, 2006a) from the IPCC Guidelines (Formula 9). The aboveground and belowground biomass carbon stocks in palm plantations at 25 years were also quoted from the IPCC Guidelines because there was no difference between the values specified by the RSPO (2016) and those of the IPCC Guidelines (IPCC, 2019). As for the aboveground and belowground biomass carbon stocks in peatlands, the values given by RSPO (2016) as undisturbed swamp forest were quoted as there was no description in the IPCC Guidelines. As for soil carbon stock, while one study reports that soil carbon stock decreases with the conversion from rainforest to palm plantation (Guillaume et al., 2015), other studies show that soil carbon stock increases (Goodrick et al., 2015) or remains unchanged (Khasanah et al., 2015). Thus, there is high uncertainty in comparing soil carbon stocks in tropical forests and palm plantations. In contrast, soil carbon stocks in peatlands are known to be much larger than those in palm plantations, and the RSPO GHG Assessment Procedure (RSPO, 2016) stipulates that only soil carbon stocks in peatlands should be considered when assessing land-use change. Therefore, it was assumed that there is no difference in soil carbon stock between tropical rainforests and palm plantations, and the gap in soil carbon stock between peat and palm plantations was assessed in this study. Soil carbon stock in palm plantations was considered based on the value used by Hassan et al. (2011) in their LCA; soil carbon stock in peatland varies with soil depth (Hooijer et al., 2006, 2010; Melling et al., 2008). It is reported that the average soil depth of peatland which was converted into palm plantation is 0.95 m (Hooijer et al., 2010); thus, this depth value was adopted in our assessment.

$$C_{b-rain} = B_{rain} \times (1 + R) \times CF \tag{9}$$

2.3.2 | Palm plantation

After planting, palms are ready for FFB harvesting in 2–3 years, with peak yields in 7–8 years, and are then managed until the 25th year (Choo et al., 2015; Din et al., 2018). The sources of GHG emissions in the management of palm plantations are nursing, fertilization, and herbicides, and the equations for calculating the respective emissions are shown in Formulas 10–12. The emission factor (EF) from nursing ($EF_{nursing}$ [kg-CO_2eq/t-FFB]) was quoted from Choo et al. (2011). Although numerous studies have reported the annual input amount of fertilizer (Choo et al., 2011; Egeskog & Scheer, 2016; Kamahara et al., 2009; Moulin et al., 2017; Woittiez et al., 2019), the value was adopted from Choo et al. (2011), wherein the total input amount of fertilizer for 25 years (F_{25} [kg/ha]) was reported, while the EFs of fertilization were adopted from a report by the National Institute for Environmental Studies in Japan (EF_1 [kg-N_2O-N/kg-N]) (Research Center for Global Environmental National Institute for Environmental Studies, 2020) and IPCC Guidelines (EF_2 [kg-N_2O-N/kg-NH_3-N + NO_x-N], EF_3 [kg-N_2O-N/kg-N]) (IPCC, 2006b). Both the volatile ratio ($Frac_{GAS}$ [kg-NH_3-N + NO_x-N/kg-N]) and dissolution ratio ($Frac_{LEACH}$ [kg-N/kg-N]) to each EF was quoted from IPCC Guidelines (IPCC, 2019a). The annual input amount of herbicide used in this assessment (H [g/(ha year)]) is the average score of the values reported by Moulin et al. (2017) and Kamahara et al. (2009); the EF of herbicide ($EF_{herbicide}$ [kg-CO_2eq/kg-herbicide]) was quoted from Kamahara et al. (2009).

$$CO_{2-nursing} = EF_{nursing} \times U_{FFB} \times 1/1000 \tag{10}$$

$$\begin{aligned} CO_{2-fertilization} = {} & \left(EF_1 + EF_2 \times Frac_{GAS} + EF_3 \times Frac_{LEACH}\right) \\ & \times F_{25} \times A_{PKS} \times 44/28 \times 298 \end{aligned} \tag{11}$$

$$CO_{2-herbicide} = H \times EF_{herbicide} \times A_{PKS} \times 1/1000 \times 25 \tag{12}$$

2.3.3 | Oil extraction

FFB harvested from palm plantations are transported to oil extraction mills. Formula 13 shows the GHG emissions in the transportation of FFB. It was assumed that 20 t trucks transport FFB to oil extraction mills, and the EF of the 20 t truck (EF_{20t_1} [kg-CO_2eq/tkm]) is quoted from the literature (Giuntoli et al., 2014; Lastauto Omnibus, 2010). Transportation distance (D_1 [km]) was distinguished between Malaysia (Arshad et al., 2017) and Indonesia (Kamahara et al., 2009).

$$CO_{2-transport1} = D_1 \times EF_{20t\_1} \times U_{FFB} \times 1/1000 \tag{13}$$

In addition to CPO and PKS from FFB, PKO and EFB occur during oil extraction. The water generated through this process is discharged from the mill as a palm oil mill effluent (POME), subsequently generating biogas, such as CO_2 and methane gas. The GHG emissions during this process were calculated using Formula 14. The EFs of oil extraction ($EF_{extract}$ [kg-CO_2eq/t-CPO]) and POME ($EF_{POME1,}$

EF_{POME2} [kg-CO_2eq/t-CPO]) were obtained from the average values of Vijaya and Choo (2010) and Hosseini and Wahid (2015).

$$CO_{2-\mathrm{extraction}} = \left(EF_{\mathrm{extract}} + EF_{\mathrm{POME1,2}}\right) \times U_{CPO} \times 1/1000 \quad (14)$$

2.3.4 | PKS transportation

The PKS generated at the oil extraction mills is transported to the stockpile adjacent to the port and then arrives in Japan via shipping. After arriving in Japan, the PKS is transported to the power plant and stored in a stockpile inside the power plant. The distances for each transportation route (D_2, D_{ship}, D_3 [km]) were obtained from a survey by erex Co., Ltd., and associated companies that ship PKS. The EFs were quoted for transportation 2 (EF_{40t} [kg-CO_2eq/tkm]) (Giuntoli et al., 2014), shipping (EF_{ship} [kg-CO_2eq/tkm]) (Giuntoli et al., 2014; Lastauto Omnibus, 2010), and transportation 3 (EF_{20t_2} [kg-CO_2eq/tkm]) (Japan Environmental Association for Industry, 2020). The calculations of each emission are shown in Formulas 15–17.

$$CO_{2-\mathrm{transport2}} = D_2 \times EF_{40t} \times U_{PKS} \times 1/1000 \quad (15)$$

$$CO_{2-\mathrm{shipping}} = D_{\mathrm{ship}} \times EF_{\mathrm{ship}} \times U_{PKS} \times 1/1000 \quad (16)$$

$$CO_{2-\mathrm{transport3}} = D_3 \times EF_{20t\_2} \times U_{PKS} \times 1/1000 \quad (17)$$

2.3.5 | Power plant

Kyushu and Shikoku power plants are steam-turbine power generation plants with circulating fluidized bed boilers. Combustion and waste treatment are considered the main sources of GHG emissions because of the limited reliable data from surveys with power plants. The GHG emissions generated during PKS combustion were calculated assuming that CO_2 emissions from combustion were not included ($CO_{2\text{-combustion1}}$ [kg-CO_2eq]) and that CO_2 emissions were included ($CO_{2\text{-combustion2}}$ [kg-CO_2eq]), each of which is shown in Formulas 18 and 19. The EFs of CH_4 and N_2O (EF_{CH4} [kg-CO_2eq/MJ] and EF_{N2O} [kg-CO_{2}/MJ]) were provided by erex Co., Ltd., based on EU legislation (Edwards et al., 2017), and the carbon content of PKS (C_{PKS}) was quoted from Phyllis 2 (TNO, 2021c).

$$CO_{2-\mathrm{combustion1}} = \left(EF_{CH_4} \times 25 + EF_{N_2O} \times 298\right) \times 3.6/\eta \quad (18)$$

$$CO_{2-\mathrm{combustion2}} = CO_{2-\mathrm{combustion1}} + \left(U_{PKS} \times C_{PKS} \times (1-u) - EF_{CH_4} \times \frac{1}{\eta} \times \frac{12}{16}\right) \times \frac{44}{12} \quad (19)$$

Formula 20 shows the calculation of GHG emissions from disposal treatment. The weight ratio of ash to PKS (W_{ash}) and the amount of wastewater from power plants ($W_{f\text{-water}}$, $W_{s\text{-water}}$ [m^3/kg-PKS]) were obtained from erex Co. Ltd. The EFs of disposal (EF_{ash}, EF_{water_dis}) were quoted from the Life-Cycle Inventory (LCI) database Inventory Database for Environmental Analysis v2.1.3 (Japan Environmental Association for Industry, 2020).

$$CO_{2-\mathrm{disposal}} = U_{PKS} \times W_{ash} \times EF_{ash} + U_{PKS} \times EF_{\mathrm{water-dis}} \times \left(W_{\mathrm{f-water}} + W_{\mathrm{s-water}}\right) \quad (20)$$

2.4 | Scenario setting

Six scenarios, as shown in Table 2, were established to calculate the life-cycle GHG emissions of PKS power generation. Since it has been reported that the GHG emissions from land-use change (Hassan et al., 2011; Wicke et al., 2008) and biogas generated during oil extraction (Hosseini & Wahid, 2015; Vijaya & Choo, 2010) have a large impact on the results of LCA in palm oil production, each scenario was determined based on the type of land-use change and the existence of biogas capture, which reduced the biogas emission to 85% (Choo et al., 2011; Vijaya & Choo, 2010). According to the survey by erex Co. Ltd., the majority of mills which export PKS to Japan ignore biogas capture from POME which is generated during oil extraction process and the certifications including GGL is adopted for the supply chain after PKS generation point regardless of the existence of biogas capture. Moreover, the impact of land-use change is out of the scope of the FIT application to PKS (Ministry of Economy, Trade and Industry Agency for Natural Resources and Energy, 2021a) even though erex Co., Ltd. endeavor to confirm the low impact land-use change. Therefore, large proportion of PKS is imported through Scenario 1, 3, and 5 in Japan; meanwhile PKS can be consumed through all scenarios, currently.

TABLE 2 Scenario settings

Scenarios	Land-use change	85% biogas capture
S1	From Peatland	×
S2	From Peatland	○
S3	From Tropical Forest	×
S4	From Tropical Forest	○
S5	Replanting	×
S6	Replanting	○

2.5 | CO_2 derived from PKS combustion

While the ISO (ISO 14067, 2018) encourages the separate inclusion of CO_2 generated from biomass combustion in carbon footprints, it has been demonstrated that considering biomass fuels as carbon neutral is problematic in terms of the time lag in reabsorbing CO_2 (Norton et al., 2019). Thus, as shown in Formulas 18 and 19, the results of life-cycle GHG emissions with and without CO_2 emissions from combustion were examined in this assessment. The former refers to a situation in which the palm plantation is continuously managed to produce fruit every year, while the latter referred to a situation where carbon neutrality was not maintained, such as when a palm plantation cannot be maintained continuously due to abandonment of cultivation.

3 | RESULTS

Figure 2a,b and Table 3 present the results for individual scenarios. Datasets of the calculation processes and the results of assessments are shown in Material S1. The life-cycle GHG emissions (from fuel mining to power generation and waste treatment) of coal-fired power generation and liquid natural gas (LNG) steam power generation were quoted from a report published by the Central Research Institute of Electric Power Industry in Japan, which is 0.943 and 0.599 kg-CO_2eq/kWh, respectively (Imamura et al., 2016). The lower heating value of coal and LNG in this report is 24.4–26.0 and 50.6–54.9 MJ/kg, respectively, depending on the region of import, and the generation end efficiency is 38.3% and 44.6%, respectively. The difference in emissions between Kyushu Power Plant and Shikoku Power Plant mostly depends on the difference in power generation end efficiency. The CO_2 derived from PKS combustion is 1.149 kg-CO_2/kWh in Kyushu Power Plant and 1.370 kg-CO_2eq/kWh in Shikoku Power Plant, meaning that the life-cycle GHG emission in PKS power generation is higher than that of fossil fuels in all scenarios, when CO_2 emissions from PKS combustion are included. This difference in emissions is because the LHV_{PKS} is 17.3 MJ/kg and the power generation end efficiency is 31% and 26%, both of which are lower than those of fossil fuels; moreover, the amount of CO_2 generated during the combustion of PKS is larger than that generated during the combustion of fossil fuels. In contrast, in the absence of CO_2 derived from the combustion of PKS, it was confirmed that the life-cycle GHG emissions in scenarios that include emissions from land-use change exceed that of fossil fuels. In particular, GHG emissions from peatland depend on the soil depth, and GHG emissions from peatland conservation can be 24.37 kg-CO_2eq/kWh in Kyushu Power Plant and 29.06 kg-CO_2eq/kWh when the soil depth is 3 m, which is the dimension of RSPO (2016). On the other hand, it is considered that some palm plantations have been established from other land types. Gaveau et al. (2016) reported that approximately 76% of the total

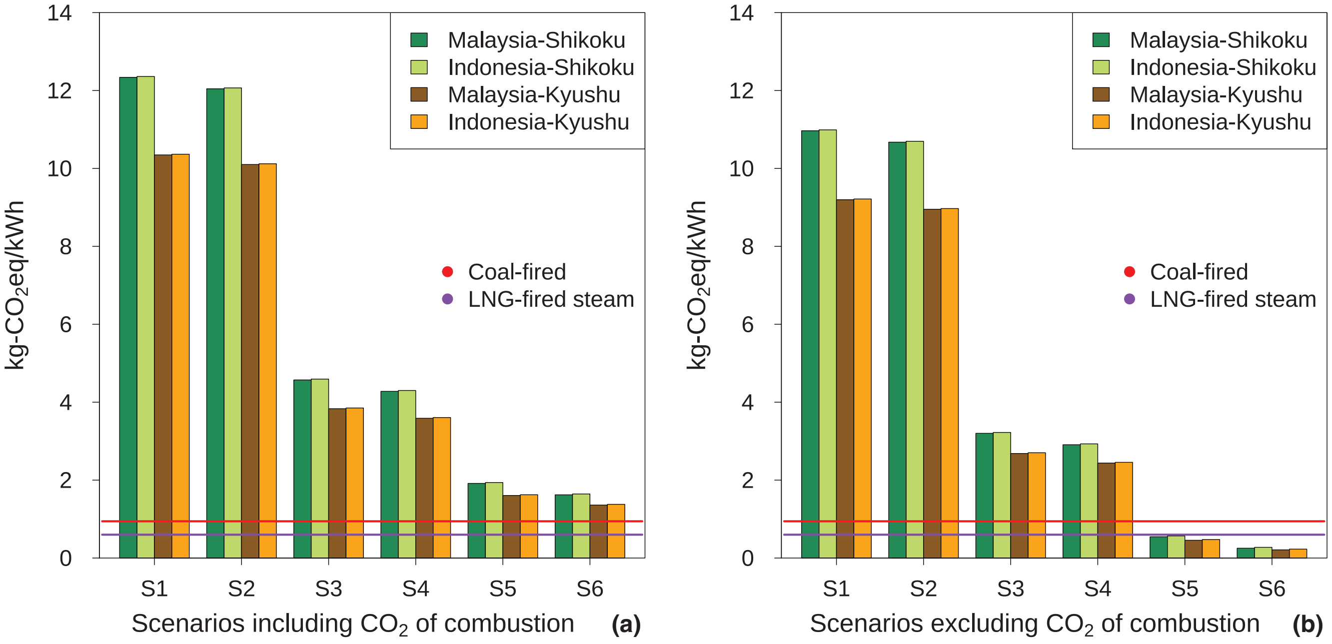

FIGURE 2 Life-cycle GHG emission in each scenario. Note 1: CO_2 derived from combustion of PKS is included in fraction (a) whereas it is excluded in fraction (b). Note 2: Each line represents the life-cycle greenhouse gas emissions from coal-fired power generation and LNG steam power generation presented by the Central Research Institute of Electric Power Industry in Japan (Imamura et al., 2016). The emissions from coal-fired and LNG-fired power generation are 0.943 kg-CO_2eq/kWh and 0.599 kg-CO_2eq/kWh, respectively.

TABLE 3 Life-cycle GHG emission in each scenario

	Malaysia-Kyushu	Malaysia-Shikoku	Indonesia-Kyushu	Indonesia-Shikoku	Malaysia-Kyushu	Malaysia-Shikoku	Indonesia-Kyushu	Indonesia-Shikoku
	Scenario 1				Scenario 2			
LUC	8.7		10.4		8.7		10.4	
Nursing	0.000025		0.000030		0.000025		0.000030	
Fertilization	0.030		0.035		0.030		0.035	
Herbicide	0.00072		0.00086		0.00072		0.00086	
Transport1	0.0085	0.0022	0.0101	0.0026	0.0085	0.0022	0.0101	0.0026
Oil Extraction	0.32		0.38		0.07		0.08	
Trasport2	0.007	0.013	0.008	0.016	0.007	0.013	0.008	0.016
Shipping	0.07	0.09	0.09	0.11	0.07	0.09	0.09	0.11
Transport 3	0.00037		0.00019		0.00037		0.00019	
Combustion	0.018/1.2		0.021/1.4		0.018/1.2		0.021/1.4	
Disposal	0.00069		0.00083		0.00069		0.00083	
SUM	9.2/10.3	9.2/10.6	11.0/12.1	11.0/12.4	9.0/10.1	9.0/10.3	10.7/11.8	10.7/12.1
	Scenario 3				Scenario 4			
LUC	2.2		2.7		2.2		2.7	
Nursing	0.000025		0.000030		0.000025		0.000030	
Fertilization	0.030		0.035		0.030		0.035	
Herbicide	0.00072		0.00086		0.00072		0.00086	
Transport1	0.008	0.002	0.010	0.003	0.008	0.002	0.010	0.003
Oil Extraction	0.32		0.38		0.07		0.08	
Trasport2	0.007	0.013	0.008	0.016	0.007	0.013	0.008	0.016
Shipping	0.07	0.09	0.09	0.11	0.07	0.09	0.09	0.11
Transport 3	0.00037		0.00019		0.00037		0.00019	
Combustion	0.018/1.2		0.021/1.4		0.018/1.2		0.021/1.4	
Disposal	0.00069		0.00083		0.00069		0.00083	
SUM	2.7/3.8	2.7/4.1	3.2/4.3	3.2/4.6	2.4/3.6	2.5/3.8	2.9/4.1	2.9/4.3
	Scenario 5				Scenario 6			
LUC	—							
Nursing	0.000025		0.000030		0.000025		0.000030	
Fertilization	0.030		0.035		0.030		0.035	

TABLE 3 (Continued)

	Malaysia-Kyushu	Malaysia-Shikoku	Indonesia-Kyushu	Indonesia-Shikoku	Malaysia-Kyushu	Malaysia-Shikoku	Indonesia-Kyushu	Indonesia-Shikoku
Herbicide	0.00072		0.00086		0.00072		0.00086	
Transport1	0.008	0.002	0.010	0.003	0.008	0.002	0.010	0.003
Oil Extraction	0.32		0.38		0.07		0.08	
Trasport2	0.007	0.013	0.008	0.016	0.007	0.013	0.008	0.016
Shipping	0.07	0.09	0.09	0.11	0.07	0.09	0.09	0.11
Transport 3	0.00037		0.00019		0.00037		0.00019	
Combustion	0.018/1.2		0.021/1.4		0.018/1.2		0.021/1.4	
Disposal	0.00069		0.00083		0.00069		0.00083	
SUM	0.46/1.6	0.48/1.8	0.54/1.7	0.57/1.9	0.21/1.4	0.23/1.6	0.25/1.4	0.27/1.6

The unit of every value corresponds to kg-CO_2eq/kWh.

The values without and with CO_2 generated from the combustion of PKS are separated by slashes (without/with).

area of industrial plantations (oil palm and pulpwood) in Borneo Island in 2015 were old-growth forests in 1973 and the rest were the secondary forests or other land types. Aboveground biomass in the secondary forests depends on forest age and its value is 131 t-d.m./ha as its age is more than 20 years per the IPCC report (IPCC, 2019b). With Formula 9, the carbon stock in the secondary forests (>20 years) was 74.3 t-C/ha, which is higher than that of palm plantation. Considering that carbon stock in palm plantations at 25 years is 60 t-C/ha, the secondary forests grown for 25 years would have more carbon stock and net GHG emissions will be generated when the secondary forests are converted in other land types. Assuming secondary forest conversion, the emissions in land-use change were 0.186 kg-CO_2eq/kWh in Kyushu Power Plant and 0.222 kg-CO_2eq/kWh in Shikoku Power Plant, which are smaller than those from the conversion of tropical primary forests or peatlands.

In contrast, scenarios without land-use change exhibited lower life-cycle GHG emissions than those by fossil fuels; meanwhile, the emissions from transportation 2 to disposal treatment accounted for 26.6% of the total emissions even at the longest shipping distance (from Indonesia to Shikoku Power Plant), which means that the FIT evaluates the life-cycle GHG emissions of PKS as much smaller. The results of each process in Scenario 5 without CO_2 emissions from combustion are shown in Figure 3. The difference in life-cycle GHG emissions of each route depends on the difference in transportation distance; emissions from Indonesia are 0.022 kg-CO_2eq/kWh and 0.019 kg-CO_2eq/kWh, which are larger than those from Malaysia in the case of Shikoku Power Plant and Kyushu Power Plant, respectively. In case of averaging the emissions from Malaysia and Indonesia, the reduction in GHG emissions to coal-fired power generation and LNG-fired steam power generation was 0.478 kg-CO_2eq/kWh and 0.134 kg-CO_2eq/kWh in Kyushu Power Plant ($\eta = 31\%$) and 0.387 kg-CO_2eq/kWh and 0.043 kg-CO_2eq/kWh in Shikoku Power Plant ($\eta = 26\%$).

According to these results, to maintain the life-cycle GHG emissions of PKS power generation at a lower level than that of fossil fuels, it is necessary to import PKS selectively from replanted palm plantations and to guarantee the sinks for CO_2 emitted during combustion through continuous management afterward.

4 | DISCUSSION

4.1 | Sensitivity analysis

The results are uncertain because the data were quoted from the literature and gathered based on a survey of the

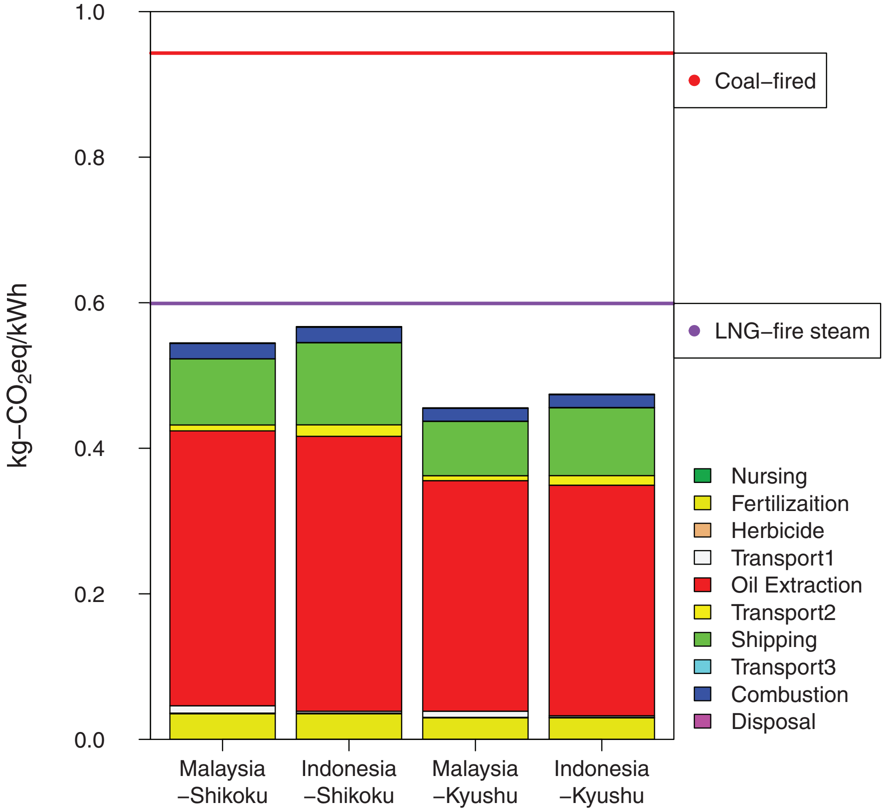

FIGURE 3 Life-cycle GHG emission in Scenario 5. Note: Each line represents the life-cycle greenhouse gas emissions from coal-fired power generation and LNG steam power generation presented by the Central Research Institute of Electric Power Industry in Japan (Imamura et al., 2016). The emissions from coal-fired and LNG-fired power generation plant are 0.943 kg-CO_2eq/kWh and 0.599 kg-CO_2eq/kWh, respectively.

company. Therefore, sensitivity analysis was conducted for Scenario 5, which is the one of high probable scenarios, and exhibited the reduction effect to fossil fuels, to examine the extent to which the results would be affected if the parameters were varied. Datasets of the calculation processes and the results of the sensitivity analysis are shown in Material S1.

4.1.1 | Sensitivity analysis for each process

Regarding data provided by companies, the distance of Transport 2 is the maximum value known by erex Co. Ltd., and thus its emission is the largest case. Assuming that the distance of shipping, also provided by the company, is the transportation distance from Indonesia to Hokkaido, which is 1500 km longer than that from Indonesia to Kyushu (SEA-DISTANCES.ORG, 2021) and estimated to be 7765 km, the emissions from shipping would be 0.1155 kg-CO_2eq/kWh ($\eta = 31\%$) and 0.1377 kg-CO_2eq/kWh ($\eta = 26\%$). Thus, the life-cycle GHG emissions from PKS power generation would be less than that of fossil fuels regardless of where the power plants are located in Japan. As for the data quoted from the literature, the emissions from nursing, fertilization, herbicide, and oil extraction vary in each palm plantation or oil extraction mill. However, nursing and herbicide have little effect on the whole result, and thus the difference in the amount of input is inconsequential in this assessment. The input amount of fertilization varies for palm plantations, but the average amount of annual input is reported to be under 100 kg/ha/year (Woittiez et al., 2019). Under these conditions, the emission from fertilization would be 0.0369 kg-CO_2eq/kWh ($\eta = 31\%$) and 0.0440 kg-CO_2eq/kWh ($\eta = 26\%$), and whose difference to the provisional result is only 0.0074 kg-CO_2eq/kWh ($\eta = 31\%$) and 0.0088 kg-CO_2eq/kWh ($\eta = 26\%$). Regarding oil extraction, which is the largest source of GHG emission in all routes, biogas from POME occupies the main part of emissions from this process, and the EF of the POME, 953.84 kg-CO_2eq/t-CPO, was the average score of 896.5 kg-CO_2eq/t-CPO (Vijaya & Choo, 2010) and 1011.2 kg-CO_2eq/t-CPO (Hosseini & Wahid 2015) due to the difference in the POME amount. However, the emission from oil extraction would be 0.3342 kg-CO_2eq/kWh ($\eta = 31\%$) and 0.3984 kg-CO_2eq/kWh ($\eta = 26\%$) when adopting 1011.2 kg-CO_2eq/t-CPO as the EF of the POME, and the difference to provisional emissions would be only 0.0174 kg-CO_2eq/kWh (η = 31%) and 0.0207 kg-CO_2eq/kWh (η = 26%). Thus, the life-cycle GHG emissions would not be more than that of fossil fuels due to the uncertainty of emissions from the POME. Therefore, the life-cycle GHG emission in PKS generation would be lower than that of fossil fuels, considering the uncertainty of data in each process. In contrast, the emissions from the POME would be 0.2994 kg-CO_2eq/kWh (η = 31%) and 0.3570 kg-CO_2eq/kWh (η = 26%) when 896.5 kg-CO_2eq/t-CPO was adopted as the EF of the POME, indicating that oil extraction would be the largest part of emissions, and biogas capture would be the best strategy to further reduce life-cycle GHG emissions. However, considering that the reduction in Shikoku Power Plant emissions with 26% efficiency was 0.043 kg-CO_2eq/kWh compared with the life-cycle emissions of LNG steam power generation, the Shikoku Power Plant emissions would exceed the emission of LNG steam power generation under the condition of duplicate increase in the amount of fertilization input, POME, and transport distance. Additionally, in the case of LNG-fired combined cycle power generation, which is currently used in Japan, the power generation efficiency is 49.2%, which is more than 10% higher than that of steam power generation, and its life-cycle GHG emissions are 0.474 kg-CO_2eq/kWh (Imamura et al., 2016). This power generation value is comparable with the PKS power generation value in Kyushu Power Plant with an efficiency of 31%, indicating that the emissions from PKS power generation are higher than those from LNG power generation in Shikoku Power Plant.

4.1.2 | Sensitivity analysis in power generation efficiency

The power generation end efficiency of the power plants was different because of their installed capacity. Erex Co., Ltd., recently has been operating power plants with greater installed capacity, and the end efficiency of these plants is reported to be 40%. Figure 4 shows the results of life-cycle GHG emissions under 40% power generation end efficiency in addition to the current results of both power plants. As shown in the Figure 4, under end power efficiency of 40%, the difference of emissions between power plants is negligible. By considering the average emissions in every route, the emissions of 40% power efficiency were 0.361 kg-CO_2eq/kWh, reducing emissions by 0.238 kg-CO_2eq/kWh compared with LNG steam power generation and 0.113 kg-CO_2eq/kWh compared with LNG combined cycle power generation. In addition, under the assumption of transportation to Hokkaido, 100 kg/year fertilizer input, and 1011.2 kg-CO_2/t-CPO EF for POME, as mentioned previously, the emissions of 40% efficiency were 0.4040 kg-CO_2eq/kWh, which are lower than those of LNG combined cycle power generation. Thus, emissions from fossil fuel-fired power generation would be reduced under 40% efficiency.

4.1.3 | Sensitivity analysis in allocation

EFB is primarily used as a fuel for boilers of oil extraction mills or mulches in palm plantations (Phang &

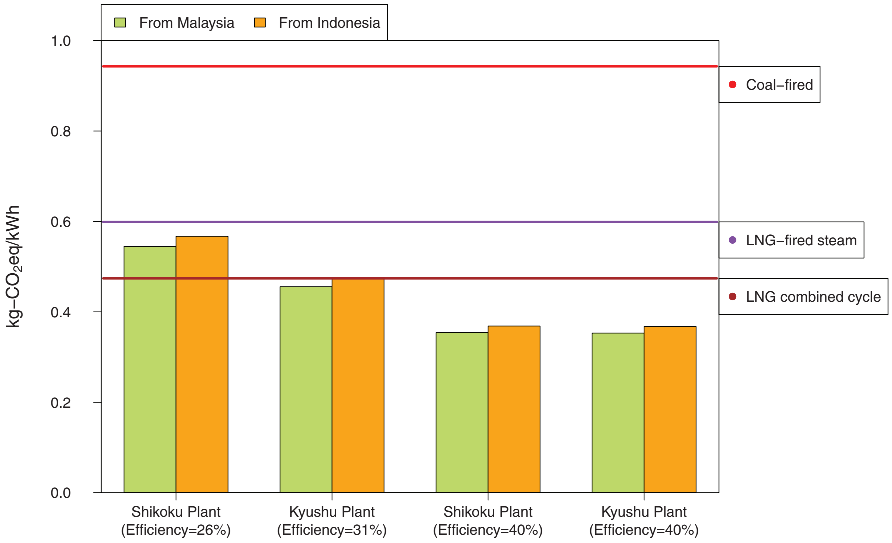

FIGURE 4 Sensitivity analysis of Scenario 5. Note 1: Each line represents the life-cycle greenhouse gas emissions from coal-fired power generation, LNG steam power generation and LNG combined cycle power generation presented by the Central Research Institute of Electric Power Industry in Japan (Imamura et al., 2016). The emissions from coal-fired and LNG-fired steam, and LNG combined cycle power generation are 0.943 kg-CO_2eq/kWh, 0.599 kg-CO_2eq/kWh, and 0.474 kg-CO_2eq/kWh, respectively. Note 2: "η" represents power generation end efficiency in the targeted power plants.

Lau, 2017). Since they are rarely traded as a commodity and treated as waste, EFB was not included in the allocation of GHG emissions. However, Japanese companies that import PKS, including erex Co., Ltd., are currently attempting to use EFB as a biomass fuel; thus, EFB may need to be regarded as a commodity and not as waste in the future. Figure 5 shows the life-cycle GHG emissions of PKS power generation in Scenario 5, including EFB, into the allocation, which was calculated by adding EFB to Formula 5. The values were quoted as the LHV of EFB (TNO, 2021a) and the weight ratio of EFB to FFB (Vijaya & Choo, 2010). The life-cycle GHG emissions of domestic forest residues used in power generation in Japan are shown in Figure 5. Forest residues were divided into two parts based on thinning and harvesting, both of whose life-cycle GHG emissions were quoted from Komata et al. (2013) with 20% power generation efficiency, which has been reported in several woody biomass power plants in Japan (Yanagida et al., 2015). The life-cycle GHG emissions of each forest residue from thinning and harvesting are reported as 0.361 and 0.177 kg-CO_2eq/kWh, respectively.

The life-cycle GHG emissions from PKS power generation are comparable with those from forest residue thinning in Kyushu Power Plant if EFB is included in the allocation, whereas the emissions from Shikoku Power Plant exceed. On the other hand, under 40% efficiency, emissions from both power plants are less than that from forest residue thinning. However, this allocation is based on the calorific value, and the results are changed in the allocation based on commodity value. Additionally, the potential increase in the use of EFB can give rise to different processes such as pelletizing, making it necessary to elucidate the life-cycle emissions of EFB. The life-cycle GHG emissions in PKS did decrease when EFB was considered, but it does not indicate the reduction of GHG emissions from the whole process. Therefore, the application of biogas capture for the reduction of the total GHG emissions in the industry needs to be studied further.

4.2 | Potential of biogas capture

The potential of biogas capture was examined in the case with 100% capture in addition to the current situation (Scenario 5) and the case with 85% capture (Scenario 6), all of which were confirmed to have lower emissions compared to LNG power generation. Since the difference in distances between transportation routes had a negligible effect on the results of different scenarios, the average value of each route is shown in Figure 6. The life-cycle GHG emissions of PKS power generation with biogas capture were lower than that of forest residue from thinning and lower than that of harvesting at 40% power generation efficiency. With 100% capture of biogas and 40% efficiency, the average emission reduction of PKS power generation in every route to coal-fired power generation and LNG steam power generation was 0.806 and 0.462 kg-CO_2eq/kWh in

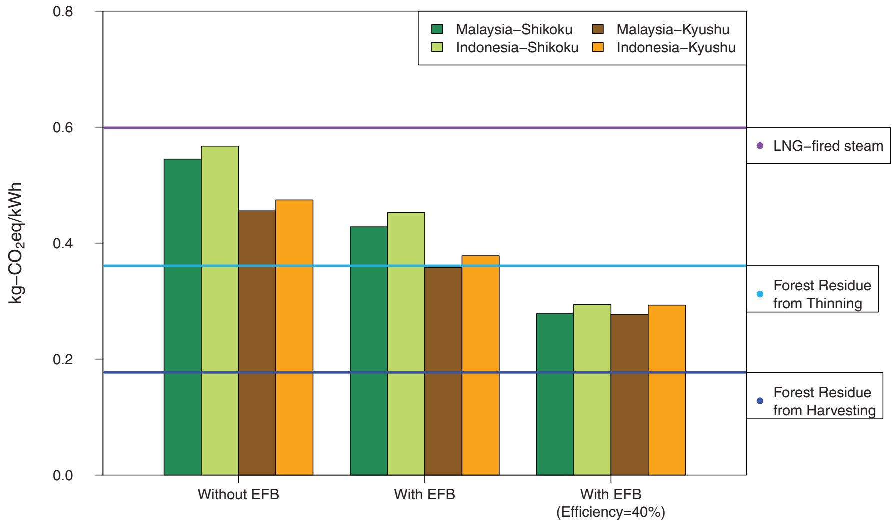

FIGURE 5 Sensitivity analysis of Scenario 5 with allocation to empty fruits bunches (EFB). Note 1: "Without EFB" and "with EFB" represent excluding EFB in allocation and including in allocation, respectively. Note 2: Each line represents the life-cycle greenhouse gas emission from LNG steam power generation presented by the Central Research Institute of Electric Power Industry in Japan (Imamura et al., 2016) and from power generation using forest residue at a power generation end efficiency of 20% presented by Komata et al. (2013). The emission from LNG-fired steam power generation plant is 0.599 kg-CO_2eq/kWh, and respective forest residues represent those occurring during thinning (0.361 kg-CO_2eq/kWh) and during harvesting (0.177 kg-CO_2eq/kWh). Note 3: "η" represents the power generation end efficiency of the targeted power plant.

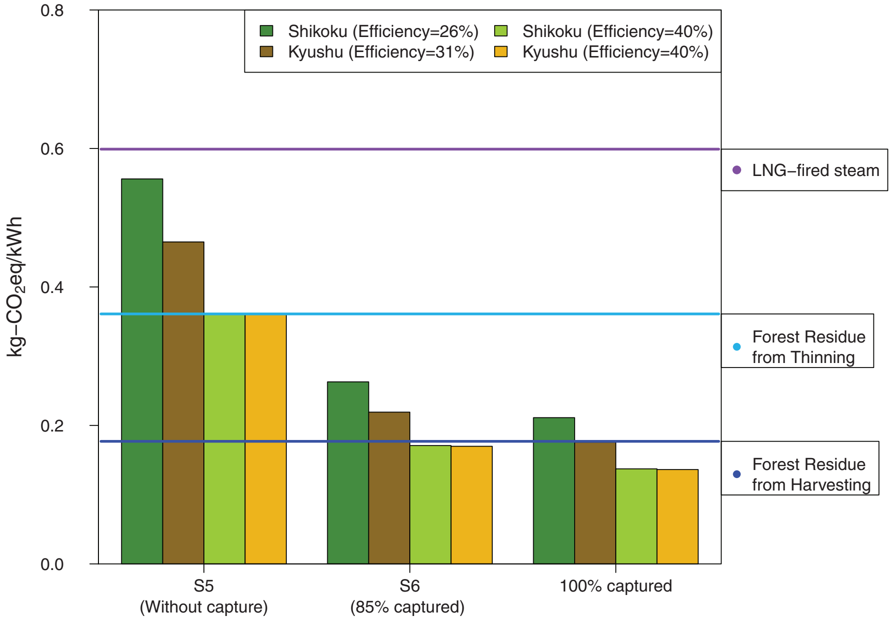

FIGURE 6 GHG emission reduction potential of biogas capture. Note 1: Each column represents the average score of every route. Note 2: Each line represents the life-cycle greenhouse gas emission from the life-cycle greenhouse gas emissions from LNG steam power generation presented by the Central Research Institute of Electric Power Industry in Japan and power generation using forest residue at a power generation end efficiency of 20% presented by Komata et al. (2013). The emission from LNG-fired power generation is 0.599 kg-CO_2eq/kWh, and respective forest residues represent those occurring during thinning (0.361 kg-CO_2eq/kWh) and harvesting (0.177 kg-CO_2eq/kWh). Note 3: "η" represents the power generation end efficiency of the targeted plants.

both power plants. In contrast, for Scenario 4, with tropical forest land conversion and biogas capture, the average life-cycle emissions in both power plants were 1.897 kg-CO_2eq/kWh at 40% power efficiency, which is higher than those from fossil fuels. Thus, life-cycle GHG emissions from PKS power generation will remain larger than those of fossil fuels as long as land conversion exists, and biogas capture has no potential to offset emissions from land-use change. Therefore, to reduce the GHG emissions of the entire industry and achieve the same level of life-cycle GHG emissions as forest residues when using PKS as a fuel for power generation, it is crucial to implement necessary measures not only in Japan but also in countries of origin of source materials. If biogas capture is implemented in the countries from where the source material is obtained without land-use change and the efficiency of power plants in Japan can be improved, then PKS power generation can reduce the emissions and achieve the same or lower emissions as domestic forest residue utilization. However, currently, biogas power plants are less likely to be installed because of high investment and low returns in Malaysia and Indonesia (Chin et al., 2013; Rajani et al., 2019). In addition, the palm oil mills located in remote areas require more financial investment for connection of grid, and thus, the installation of these are not recommended (Hamzah et al., 2019). Considering the current situation, only domestic efforts to capture biogas may not be successful and international actions will be needed. One of the successful cases was the clean development mechanism (CDM) program under the Kyoto protocol. In fact, several CDM projects contributed to developing biogas capturing technology in Malaysia and Indonesia before 2012 (UNFCCC, 2021), which was the last year of the commitment period of the Kyoto protocol (United Nations, 1998). Therefore, to generate awareness about oil mills in origin countries to capture and utilize biogas, the corporation of Japanese company is needed.

5 | CONCLUSION

This study elucidated the life-cycle GHG emissions of PKS power generation imported from Malaysia and Indonesia to Japan. In the Japanese FIT, the life-cycle GHG emissions of PKS power generation are currently only considered after the point of generation of PKS; however, in this assessment, the life cycle of PKS power generation is evaluated for the entire palm industry and clarified for each scenario of land-use change and biogas capture. As a result, while the emissions from the processes after the PKS generation point were far below the life-cycle GHG emissions of fossil fuels power generation, we obtained different results in each scenario.

In the case that PKS is imported from the replanted palm plantation and the biogas capture in the oil extraction mills fails to be implemented (corresponding to

Scenario 5), the life-cycle GHG emissions of PKS were smaller than those of coal- and LNG-fired power generation. However, these were approximately four times larger than the boundary emissions from FIT. The emission of Scenario 5 is primarily dominated by biogas generated during the oil extraction process, which can be reduced to the same level or less than that of power generation of forest residues by complete capture of biogas and improved power generation end efficiency of 40%.

In contrast, the life-cycle GHG emissions of the scenario with land-use change greatly exceeded those of fossil fuels, even if the biogas capture was implemented. In addition, the life-cycle GHG emissions of PKS power generation were higher than those of fossil fuels in all scenarios when the CO_2 emissions from PKS combustion were considered. These results indicate that any emission reduction efforts implemented through the supply chain of PKS will be rendered ineffective by the factors of land use, such as the conversion of land with high carbon stock or the loss of carbon sinks due to the abandonment of palm plantations. Therefore, as land use has the greatest impact on the life-cycle GHG emissions of PKS, it is necessary not only to expand the emission reduction efforts in the supply chain, but also to consider the optimal way of land use in order to maintain the life-cycle GHG emissions of PKS at a level below that of fossil fuels.

The current FIT repetitively evaluates the GHG emissions reduction effect of PKS power generation derived from various scenarios. This is because it focuses on the processes after PKS generation points. However, there is a large difference in the life-cycle GHG emissions of PKS power generation on considering the land-use change and biogas capture. Thus, it is necessary to review the feasibility of PKS use while differentiating the PKS utilization system from the fossil fuel utilization system or other alternatives. Therefore, the FIT application to PKS needs to be based on the LCA whose objectives include land use and palm oil production processes in order to guarantee the substantial GHG reduction of PKS use.

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DATA AVAILABILITY STATEMENT

All data used in this study are shown in Supplementary Materials. In addition, it is available from Dryad, an open access repository. The link is shown below. (https://doi.org/10.5061/dryad.9ghx3ffk6).

ORCID

Issei Sato https://orcid.org/0000-0001-6584-0973

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