Calculation of Greenhouse Gas Emissions : A Case Study of Crude Palm Oil Production in Thailand

Roihatai Kaewmai

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Author	Miss Roihatai Kaewmai
Major Program	Environmental Engineering

Major Advisor :	**Examining Committee :**
………………………………………….	……………………………Chairperson
(Asst. Prof. Dr. Charongpun Musikavong)	(Assoc. Prof. Dr. Sumate Chaiprapat)
	………………………………………….
Co-advisors :	(Assoc. Prof. Dr. Aran H-Kittikun)
………………………………………….	………………………………………….
(Assoc. Prof. Dr. Aran H-Kittikun)	(Asst. Prof. Dr. Charongpun Musikavong)
………………………………………….	………………………………………….
(Asst. Prof. Dr. Chaisri Suksaroj)	(Dr. Warit Jawjit)
	………………………………………….
	(Dr. Kuaanan Techato)

The Graduate School, Prince of Songkla University, has approved this thesis as partial fulfillment of the requirements for the Master of Engineering Degree in Environmental Engineering

……………………………………

(Prof. Dr. Amornrat Phongdara)

Dean of Graduate School

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สาขาวิชา วิศวกรรมสิ่งแวดล้อม
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บทคัดย่อ

งานวิจัยนี้มีวัตถุประสงค์เพื่อพัฒนาวิธีการคำนวณการปล่อยก๊าซเรือนกระจกและประเมินแนวทางการลดก๊าซเรือนกระจกสำหรับอุตสาหกรรมสกัดน้ำมันปาล์มดิบในประเทศไทย ขอบเขตของการศึกษาครอบคลุมโรงงานสกัดน้ำมันปาล์มดิบแบบเปียก โดยได้ประเมินแหล่งปล่อยก๊าซเรือนกระจกตามหลักการประเมินวัฏจักรชีวิต ในการศึกษาได้ทบทวนวิธีการคำนวณการปล่อยก๊าซเรือนกระจกที่มีอยู่ในปัจจุบัน เพื่อพัฒนาให้เหมาะสมกับอุตสาหกรรมสกัดน้ำมันปาล์มดิบของประเทศไทย โรงงานสกัดน้ำมันปาล์มดิบจำนวน 6 โรงงานเข้าร่วมในการศึกษานี้ ซึ่งมีกำลังการผลิตคิดเป็นร้อยละ 11.9 ของศักยภาพการผลิตน้ำมันปาล์มดิบทั้งหมดในประเทศไทย ผลการศึกษาพบว่าการปล่อยก๊าซเรือนกระจกจากโรงงานสกัดน้ำมันปาล์มดิบแบบเปียก เกิดจากการได้มาของวัตถุดิบ การใช้สารเคมี การใช้พลังงาน การขนส่ง และการจัดการของเสียที่เกิดขึ้น การปล่อยก๊าซเรือนกระจกจากโรงงานที่มีระบบรวบรวมก๊าซชีวภาพ โรงงานที่ไม่มีระบบรวบรวมก๊าซชีวภาพ ค่าเฉลี่ยของโรงงานทั้งสองประเภท และโรงงานที่มีการปล่อยก๊าซเรือนกระจกน้อยที่สุดในการศึกษาครั้งนี้ คิดเป็น 883, 1,164, 935 และ 548 กิโลกรัมคาร์บอนไดออกไซด์เทียบเท่าต่อตันน้ำมันปาล์มดิบ โดยในปีพ.ศ. 2553 การผลิตน้ำมันปาล์มดิบทั้งหมดในประเทศไทยปล่อยก๊าซเรือนกระจกทั้งสิ้นประมาณ 1.20 ล้านตันคาร์บอนไดออกไซด์เทียบเท่า แหล่งปล่อยก๊าซเรือนกระจกหลักของการสกัดน้ำมันปาล์มดิบแบบเปียกเกิดจากการเพาะปลูกและเก็บเกี่ยวทะลายปาล์มสดและระบบการบำบัดน้ำเสีย ในทางปฏิบัติการลดก๊าซเรือนกระจกจากการได้มาของทะลายปาล์มสดสามารถทำได้โดยการปรับปรุงประสิทธิภาพการใช้ปุ๋ยไนโตรเจนของปาล์มน้ำมัน โดยลดการสูญเสียของปุ๋ยที่เกิดขึ้นจากการระเหยไปในอากาศ การเกิดกระบวนการดีไนตริฟิเคชัน การถูกชะล้าง และการพัดพาไปจากหน้าดิน สำหรับการลดก๊าซเรือนกระจกจากการจัดการระบบบำบัดน้ำเสีย สามารถปฏิบัติได้โดยการติดตั้งระบบรวบรวมก๊าซชีวภาพในระบบบำบัดน้ำเสียที่ไม่มีการรวบรวมก๊าซชีวภาพ วิธีการนี้สามารถลดการปล่อยก๊าซเรือนกระจกได้ถึงร้อยละ50 ของการปล่อยก๊าซเรือนกระจกทั้งหมดจากระบบบำบัดน้ำเสียที่ไม่มีการรวบรวมก๊าซชีวภาพ สำหรับระบบบำบัดน้ำเสียที่มีการรวบรวมก๊าซชีวภาพอยู่แล้วสามารถเพิ่มประสิทธิภาพการลดการปล่อยก๊าซเรือนกระจกได้โดย (1) การใช้หอคอยไล่อากาศสำหรับลดอุณหภูมิน้ำเสียแทนบ่อเปิดไร้อากาศ (2) การปิดคลุมบ่อเปิดไร้อากาศเพื่อรวบรวมก๊าซชีวภาพ (3) การปรับปรุงประสิทธิภาพของระบบรวบรวมก๊าซชีวภาพจากร้อยละ 80 ไปสู่ค่าสูงสุดที่ร้อยละ 93 และ (4) การเปลี่ยนจากระบบบ่อปรับเสถียรแบบไร้อากาศเป็นระบบบ่อเติมอากาศ โดยแนวทางดังกล่าวสามารถลดการปล่อยก๊าซเรือนกระจกได้ 216, 208, 92.2 และ 83.5 กิโลกรัมคาร์บอนไดออกไซด์เทียบเท่าต่อตันน้ำมันปาล์มดิบ ตามลำดับ

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ABSTRACT

This research aimed at developing a methodology for the calculation of greenhouse gas (GHG) and estimating GHG reduction for palm oil mills in Thailand. It was prepared by setting up a system boundary to cover palm oil mills with the wet extraction process for the evaluation of the cradle to gate process. The existing methodologies for calculation were reviewed to develop a Thai GHG calculation methodology. There were 6 palm oil mills that participated in this study. They accounted for 11.9% of total crude palm oil (CPO) production capacity in Thailand. The GHG emissions of the wet extraction process arose from the acquisition of raw material, the chemicals used, the energy used, transportation and wastewater management. The GHG emissions from 1 metric ton of CPO production from the mills with biogas capture, without biogas capture, both with and without biogas capture, and the best cases observed were 883, 1,164, 935 and 548 kgCO_2eq, respectively. The total CPO production in Thailand in the year 2010 by the wet extraction process emitted approximately 1.20 million GHG metric tons of CO_2eq. The major sources emitting GHG were from the cultivation and harvesting of fresh fruit bunches (FFB) and the wastewater treatment system. In practical, mitigation for GHG emission from oil palm plantation could be achieved by improving nitrogen use efficiency of oil palm. Losses from volatilization, de-nitrification, leaching and surface run-off of nitrogen fertilizer should be minimal. For GHG reduction through management of the wastewater treatment plants can be accomplished by establishing the methane capture system in wastewater treatment plant. This could reduce GHG emission by 50% of the total GHG emission from plants without the methane capture. In case of the existing plants with methane capture, option I: using air striping tower replaces open ponds for cooling down the temperature, option II: the cover pond practice, option III: improving the efficiency of the biogas system from the base value of 80% to the highest value of 93%, and option IV: by changing the stabilization pond to aerated lagoon system could reduce GHG emission by 216, 208, 92.2 and 83.5 kg CO_2eq per metric ton CPO respectively.

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Roihatai Kaewmai

CONTENTS

Page

Appendices

LIST OF TABLES

LIST OF FIGURES

ABBREVATIONS AND SYMBOLS

BioGrace	Biofuel greenhouse gas emissions in europe
BOD	Biochemical oxygen demand
C2G	Cradle to gate
CDM	Clean development mechanism
CH_4	Methane
CH_4	Methane
CO_2	Carbon dioxide
COD	Chemical oxygen demand
CPO	Crude palm oil
DIT	Department of internal trade
DIW	Department of industrial works
DOAE	Department of agricultural extension
DQI	Data quality index
EF	Emission factors
EFB	Empty fruit bunches
EU	European union
EU RED	European renewable energy directive
FAO	United nations food and agriculture organization
FFB	Fresh fruit bunches
FU	Functional unit
GHG	Greenhouse gas
GIZ	Deutsche gesellschaft für internationale zusammenarbeit
GMO	Genetically modified organisms
GREET	Greenhouse gases, regulated emissions, and energy use in transportation
GWP	Global warming potential
HFCs	Hydrofluorocarbons
IEA	International energy agency

IFOAM	International federation of organic agriculture movements
IPCC	Intergovernmental panel on climate change
ISCC	International sustainability & carbon certification
ISO	International organization for standardization
JI	Joint Implementation
LCA	Life cycle assessment
LCI	Life cycle inventory
MCF	Methane correction factor
Mt	Metric tons
N_2O	Nitrous oxide
OAE	Office of agricultural economics
OER	Oil extraction rate
PEA	Provincial electricity authority
PFCs	Perfluorocarbons
PK	Palm kernel
PKM	Palm kernel meal
PKO	Palm kernel oil
POME	Palm oil mill effluent
RBD oil	Refined, bleached and deodorized oil
SF_6	Sulfurhexafluoride
TFA	Trans-fatty acids
TGO	Thailand greenhouse gas management organization (public organization)
UNFCCC	United nation framework convention on climate change
USDA	United states department of agriculture

CHAPTER 1

INTRODUCTION

1.1 Motivation

The expansion of palm oil industry in Thailand is continuously increased for direct consumptions as edible oil and biodiesel production. During the years 2006-2010, palm oil production quantity in the world increased by average rate of 6.41% per year. In year 2010, palm oil of 1.35 million metric tons (Mt) or 3.0% of the total world palm oil production was produced in Thailand. (Office of Agricultural Economics, OAE 2010a). The palm oil industry in Thailand is developed rapidly to support the demand for consumers in both domestic and export markets. Its production chain consists of the oil palm plantation, crude palm oil (CPO) extraction, refinery of edible oil, and/or biodiesel production. The whole oil palm plantation area in Thailand was expanded from approximately 0.46 million hectares in the year 2008 to 0.57 million hectares in the year 2010. Most of the plantation is located in the southern Thailand with the area of about 88.6% (OAE 2010b). The fresh fruit bunches (FFB) production yields averaged 16.9 Mt FFB per hectare (OAE 2010c).

The CPO production is divided into wet extraction and dry extraction processes. The wet extraction process is generally used in the conversion of FFB to CPO due to the high production capacity and self-sufficient regarding energy. However, solid wastes, wastewater, and air pollution are generated from this process and required the well management system. In order to promote the sustainable CPO production, this is necessary to reduce the environmental impacts including solid wastes, wastewater and greenhouse gas (GHG) emission. The increasing of GHG emissions such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfurhexafluoride (SF_6) has been considered worldwide as the major cause of global warming.

The well-known international organizations that proposed GHG emission calculations are the Intergovernmental Panel on Climate Change (IPCC) and the United Nation Framework

Convention on Climate Change (UNFCCC). These GHG emission calculations were developed for GHG emission of the nation (IPCC 2006a) and for the clean development mechanism (CDM) projects (UNFCCC 2010a). There are no specific methodologies for GHG emission calculation for palm oil mills. There are some researchers who studied and proposed the GHG emission values.

Reijnders and Huijbregts (2008) reported that losses of biogenic carbon from ecosystem, GHG emission due to the use of fossil fuels and the anaerobic conversion of wastewater from palm oil mill in the South Asia of about 2.8-19.7 kgCO_2 equivalent per kg of palm oil. The study in Malaysia showed that the GHG emission values for 1 Mt CPO from the mills without biogas capture systems were 987 kgCO_2eq whereas the mills with biogas capture systems emitted GHG of 225 kgCO_2eq (Vijaya *et al.* 2010). There are a few publications related to the GHG calculation and GHG emission of the wet extraction process in Thailand. The GHG emission from oil palm plantation to CPO production in Thailand was about 2,000 – 2,289 kgCO_2 equivalent per Mt CPO (H-Kittikun *et al.*2009). Chuchuoy *et al.* (2009) found that 1 Mt of CPO production in Thailand with and without biogas system could emit 698 and 1,009 kgCO_2 equivalent, respectively.

The main objective of this research, therefore, was to develop the GHG emission calculation methodology and provide options of the GHG emission reduction for the conversion of FFB to CPO by wet extraction process in Thailand. Six palm oil mills were participated in this study with the capacity of 11.9% of the total CPO production in Thailand in the year 2010. The emission factors (EFs) that related to CPO production are determined for further utilization in the calculation of GHG emission values of the next processing in the biodiesel supply chain or going through another supply chain. In addition, GHG emission hot spots of the wet extraction process could be investigated and the GHG emission optimization option could be recommended.

1.2 Objectives

The overall objective shall cover the following;

1. Development of a GHG calculation methodology for Thai palm oil industry;

2. Determining the factors of GHG emission for Thai palm oil industry with different actual practices and;

3. Developing GHG emission optimization options for Thai palm oil industry.

1.3 Scopes of This Work

1. The GHG emission calculation was developed according to the life cycle assessment (LCA) concept based on cradle to gate (C2G) evaluation. (International Organization for Standardization, ISO 2006a, 2006b).

2. All GHG emissions from production of inputs, transportation, processing, and waste disposal were counted in this study.

3. GHG addressed by the Kyoto protocol (UNFCCC 1998) including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) were accounted in this study.

4. The functional unit (FU) was defined as 1 Mt of CPO.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

2.1 Palm oil in the global oil and fat industry

The expansion of edible oil and fat market has rapidly increased with world population growth to respond on the demand of human. Overall vegetable oil production in the world has been increased by 241% since 1990 (Table 2.1). Amongst the major vegetable oils, the growth in palm oil production has been remarkable, with 4.36 times increase from 1990 to 2011 while its major competitor, soybean oil, slightly increases by 2.61 times during the same period. In the year 2011, palm oil production of 48.0 million metric tons (Mt) was equivalent to 32.8% of total vegetable oils, while the market share for soybean, rapeseed and sunflower seed oils were 28.8, 15.5 and 7.72% of total vegetable oils, respectively. The detail is presented in Table 2.1.

Table 2.1 World vegetable oil productions, 1990-2011 (Million Mt)

Type of Vegetable Oil	1990* (21 years ago)	2000* (11 years ago)	2005** (6 years ago)	2011** (Present)
Soybean Oil	16.1	25.6	32.2	42.1
Palm Oil	11.0	21.9	31.1	48.0
Rapeseed Oil	8.2	14.5	15.2	22.7
Sunflower seed Oil	7.9	9.7	8.86	11.3
Palm kernel Oil	1.5	2.7	3.79	5.65
Other Vegetable Oils	16.1	18.1	15.7	16.6
Total Vegetable Oils	**60.8**	**92.5**	**106.8**	**146.4**

Source: *Oil world (various years) Cited by Teoh (2010)

**United States Department of Agriculture, USDA (2012a)

The significant growth in production, consumption and market share of palm oil was due to its cost competitiveness compared with other vegetable oils and animal fats. Palm oil was found to be the cheapest oil among total vegetable oils. Palm oil is also very useful in many processing applications. The health hazards that associated with genetically modified organisms (GMO) and trans-fatty acids (TFA) have also raised the palm oil demand.

Another reason for the dominant of palm oil among other vegetable oils market was due to its inherent crop productivity compared with the oil seeds. The average oil yield of palm oil was 3.80 Mt per hectare which was 9.3, 7.6 and 5.8 times higher than soybean oil, rapeseed oil and sunflower seed oil, respectively (Oil World 2008 cite by Teoh 2010).

An approximately 80% of current palm oil produced was consumed for food uses, non-food uses, for instance, usage in soaps, detergents and surfactants, cosmetics, and pharmaceuticals. The global trend to substitute a portion of fossil fuel use with renewable fuels has given rose to increase demand for vegetable oils, one of the feedstock for bio-fuels. In addition to the concern for the environment, relatively high fossil fuel prices have created a demand for alternative cost-effective and clean fuels.

2.2 Developing of palm oil production in the world

The oil palm originated in West Africa. Over the last century, the oil palm, *Elaeis guineensis* Jacq., has been an increasingly important driver for the economies of producer countries in South-East Asia, Papua New Guinea, Central and West Africa, and to a lesser extent in tropical Latin America. Palm oil becomes the most important vegetable oil in the global oils and fats industry, in terms of trade and production. Formerly palm oil was used in crude form for cooking in its homeland. Palm oil has developed into the worldwide commodities with many food and non-food applications. More recently it has been utilized as a raw material for the biodiesel production.

Although commercial planting of oil palm started early in the 20th century, centered in Congo, Malaysia and Indonesia, extension on the large scale did not gain impulse until the 1960s. Oil palm was planted in about 43 countries around the world in the year 2006 (Figure 2.1). The development of the palm oil production in the last 4 decades is presented in Table 2.2. Global cultivation of oil palm increased 8 times in the past 4 decades to over 12 million hectares in 2009, the cultivation area in Malaysia grew by 5 times and in Indonesia by a remarkable 23 times over the same period (Teoh 2010). In Indonesia since 2000, an expansion of oil palm plantations has been rapidly grown. The area covered by oil palm increasing to 5.35 million hectares in 2009. For yearly growth of cultivated areas, in the 1980s an annual planting of about 100,000 hectares was planted which increased to about 200,000 hectares per year in the 1990s. The approximate cultivated areas of 500,000 hectares per year were estimated from 1999 to 2003. (Chandran 2010)

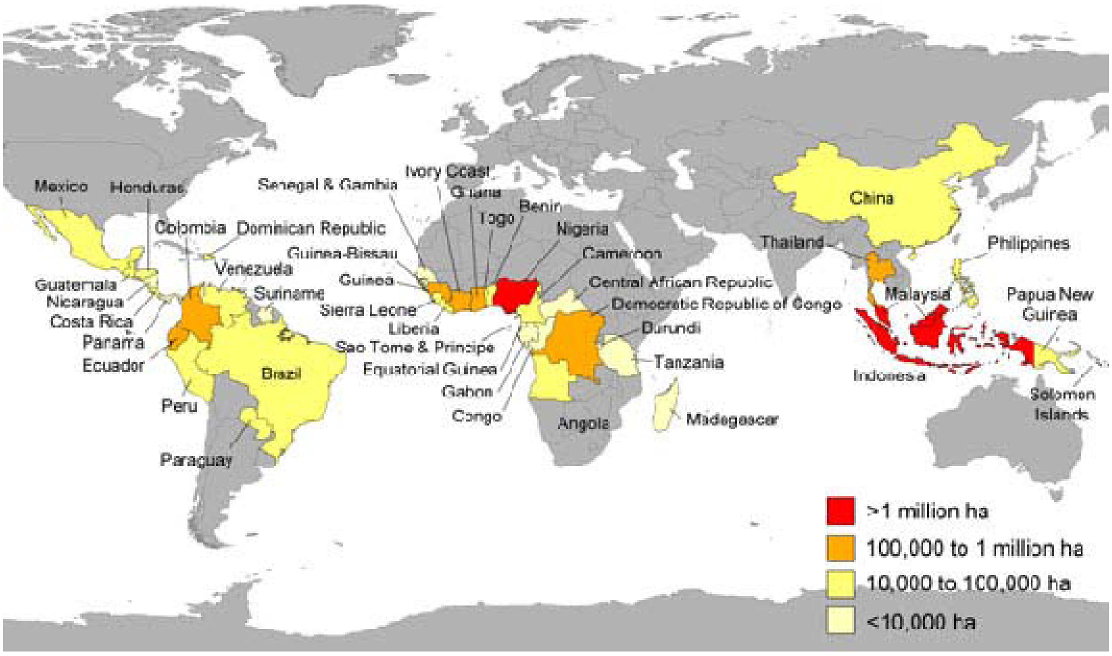

Figure 2.1 Map showing the extent of oil palm cultivation in 43 oil palm-producer countries in 2006 **Source**: FAO (2007) Cited by Koh and Wilcove (2008)

Since 1980, the palm oil production in the world increased more than 9.5 times to 45.9 million Mt in the year 2010 for supplying the major markets including the India, China, European Union-27, Pakistan, Malaysia, Egypt, United States, Bangladesh, Singapore, Vietnam and others (USDA 2012b). Indonesia overtook Malaysia as the world’s biggest palm oil producer in 2007. Indonesia and Malaysia accounted for 87% of the global palm oil production in the year 2011. In addition, the significant increases in production were from countries such as Thailand, Nigeria and Colombia, which accounted for 6.1% of the world’s production in the year 2011

Table 2.2 World's production of palm oil during 1980-2010 (x 1,000 Mt)

Country	**1980***	**1990***	**2000***	**2010****
Indonesia	691	2,413	6,900	22,000
Malaysia	2,576	6,095	10,800	17,763
Thailand	13	232	510	1,345
Nigeria	433	580	740	850
Colombia	74	226	516	770
Others	1,022	1,321	2,485	3,145
Total	4,809	10,867	21,951	45,873

Source: *Oil world (various years) Cited by Teoh (2010)

**USDA (2012b)

2.3 Future development of the palm oil industry

2.3.1 Needs for food, non-food and biofuel

The demand of palm oil for food is required to continue to rise with growing of population. During 2008 to 2009, the consumption of oils and fats in developed countries such as the European Union (EU)-27 and the United States were 59.3 and 51.7 kg per capita, respectively. For the consumption in developing countries such as India, Pakistan and Nigeria were 13.4 kg, 19.9 kg and 12.5 kg per capita, respectively. As the developing world desires for a better quality of life and consumption shifts towards the present world average of 23.8 kg per capita (Bek-Nielsen 2010). Assuming a 5% increase in consumption per capita and a population increase of 11.6% (based on World Bank's projection of 7.58 billion people in the year 2020), additional quantities of vegetable oils will have to be extracted approximately 27.7 million Mt by the year 2020. In the biofuel sector, many countries around the world have been setting national biodiesel blending targets varying from 1% in the Philippines to 10% in the EU by the year 2020.

2.3.2 Production of palm oil

Regard to the strong demand for palm oil, the Indonesian government set the objective of producing 40 million Mt of palm oil by the year 2020, which 50% would be for energy and 50% for food (Jiwan 2009). This means the national production would have to increase twice the amount in the next 10 years. Greenpeace (2009) estimated that to meet this demand, an additional 300,000 hectares of new soil would have to be cultivated with oil palm in each of the next 20 years.

Due to limited estate availability, the oil palm expansion in Malaysia was expected to slow, especially in Peninsular Malaysia and Sabah. Nevertheless, government of the Sarawak State has recently revealed that it is opening large estates for planting of oil palm. This will increase the national estate under oil palm cultivation from 4.67 million hectares to 5.4 million hectares (Wong 2010). For other countries, Thailand is expected to increase their planted areas of oil palm by 80,000 hectares per year until 2012. Moreover, there were reported that Chinese companies negotiated about very large estates in DR Congo and Zambia to expand their oil palm plantations to meet rising global demand (Economist 2009). Similarly, Malaysian companies have been surveying into the Amazon basin of Brazil. Malaysia and Brazil had set up a joint investment to open up approximately 100,000 hectares for oil palm cultivation in Brazil (Ismail and Abbas 2009).

2.4 Developing of palm oil in Thailand

The palm oil industry in Thailand has had a relatively late start in 1968, some 50 years after Malaysia and 57 years behind Indonesia. In 1974, palm oil production started to rapidly expand in Thailand, when the government permitted the private sector for producing palm oil to substitute for imports. Then, in the year 1977, the Board of investment conceded promotion to the establishment of the palm oil mill and refinery.

The oil palm cultivation area in Thailand continuously increased more than 15-fold since 1980 to 568,300 hectares in 2010 as shown in Table 2.3. The southern region of Thailand is important area in planting of oil palm (Table 2.4), particularly Krabi, Surat Thani, Chumphon, and Trang provinces. This accounted for 86.7% of the total planted area in Thailand in the year 2010. There were altogether 77 crude palm oil mills, 4 palm kernel oil extracted mills and 15 refining factories in Thailand in the year 2011 (DIT 2011). Most palm oil mills were located in Chumphon (21 mills), Krabi (18 mills), Surat Thani (15 mills), Satun (5 mills), Prachuap Khiri Khan (4 mills), and Trang (4 mills), because the majority of planted area for oil palm was in these area. The oil palm can be harvested throughout the year. The large amount of fresh fruit bunches

(FFB) is marketed in two periods; (1) beginning of the year period is around March – May, and (2) end of the year period is around September – November.

Table 2.3 Statistics of palm oil production in Thailand

Year	Harvested area* (x1,000 ha)	FFB yield* (Mt/ha)	CPO Production** (x1,000 Mt/ year)	CPO yield (Mt/ha)	Price of FFB* (Baht/kg)	Price of CPO** (Baht/kg)
1970	0.2	-	-	-	-	-
1975	5.6	-	-	-	-	-
1980	36.3	9.62	-	-	-	-
1985	82.2	11.43	205	1.88	-	-
1990	140.1	12.43	217	1.55	1.89	12.49
1995	168.1	15.34	403	2.39	2.05	15.87
2000	208.5	15.62	640	2.48	1.66	12.79
2005	324.2	15.43	784	2.42	2.76	16.82
2010	568.3	14.47	1,288	2.27	4.26	29.11

Source: *Office of Agricultural Economy, OAE (2012a)

**OAE (2012b)

Overall production of crude palm oil (CPO) in Thailand has been increased 628% since 1985, while CPO yields per hectare are relatively constant during 1995-2010. The last 8 years (2003-2010), the domestic demand for palm oil increased at a rate of 3.98% per year because the economy was improved. Moreover, in the year 2008, the commercial production of biodiesel was established in Thailand. The demand for raw materials used to produce biodiesel could affect the palm oil industry, an approximate CPO of 269,781 Mt were used in the year 2008 and up to 382,228 Mt in the year 2010 (DIT 2011). From Table 2.3, it can be seen that the prices of FFB trend is upward.

The purchase price of the FFB at a time depends on several factors including the CPO prices in Malaysia market, the FFB quality, the harvest season, and the domestic traded prices of CPO among refineries, palm oil mills, and biodiesel plants.

Table 2.4 Oil palm: Area, production and yield by region, 2010

Region	Planted area (x1,000 ha)	Harvested area (x1,000 ha)	Production (x1,000 Mt)	Yield per ha (Mt)
Northern	3.2	1.2	2.7	2.2
Northeastern	12.0	6.3	30.5	4.8
Central Plain	71.4	57.4	740.2	12.9
Southern	565.7	503.5	7,449.8	14.8
Whole Kingdom	652.3	568.4	8,223.1	14.5

Source: OAE (2011)

In Thailand, palm oil can be freely exported to the international market. The important export markets of CPO are Malaysia and India. However, CPO was exported in small amounts, representing 5.12% of its total production. This depends on the circumstances of production and prices in the domestic and overseas.

2.5 Palm oil mill process in Thailand

The palm oil mill process in Thailand consists of a wet extraction process (a standard process) and a dry extraction process. The wet process differs from the dry process with respect to the oil extraction stage: the wet process needs the large amount of hot water and steam to convert FFB into a homogeneous oily mass prior to feeding into the continuous screw press to extract the CPO. The wet extraction process is generally used in the conversion of FFB to CPO due to the high production capacity and self-sufficiency regarding energy. Considering the by-product from palm oil mill process, it composes of fibers, empty fruit bunches (EFB), and shells, For their utilization, fibers and shells have been utilized as the fuel in boiler where as the EFB has been used in many practices such as raw material for composting, biomass fuel for electricity generation, and mushroom cultivation.

The dry extraction process does not use water in palm oil production. The heat is employed to dry the palm fruit. Then, the screw press is applied to convert dry palm fruit to mixed palm oil (MPO), as the main product. The palm cake and fine palm residues are the co-products.

2.5.1 Wet extraction process

The wet extraction of palm oil from FFB involves five major sections: 1) primary production process 2) oil room 3) dry section 4) wastewater biogas system and 5) utility. In the production process, the large amounts of water and energy are needed to convert FFB into CPO. Figure 2.2 shows flow diagram of the CPO production. A standard wet processing mill produces a large amount of wastewater. The production process of palm oil mill is presented as follows:

1. Primary production process

1.1) Reception, transfer and storage of FFB; the FFB are harvested and transported to the palm oil mill by trucks for immediate processing. At the mill, FFB are unloaded on a ramp and put into containers with a standard capacity of 2.5 Mt each.

1.2) Sterilization; sterilization of the FFB is done batch wise in an autoclave with the application of steam at 120 –140 °C at 3.0-3.5 bar, for about 75-90 minutes. The objectives of the sterilization are: to prevent the formation of fatty acids, to facilitate stripping of palm fruits, and to prepare the fruit fiber for subsequent processing.

1.3) Bunch Stripping; the containers with the sterilized bunches are emptied into a rotary drum thresher where the palm fruits are separated from the bunch stalk. This processing step generates about 230 kg EFB/Mt FFB.

1.4) Digestion; the separated palm fruits are carried into digesters and mechanically converted into an extractable oily mash.

1.5) Extraction; the oily mash is fed into a continuous double screw press system where the oil is extracted. The extracted CPO is collected and flows to the oil room section. The remaining press cake is transported to a dry section.

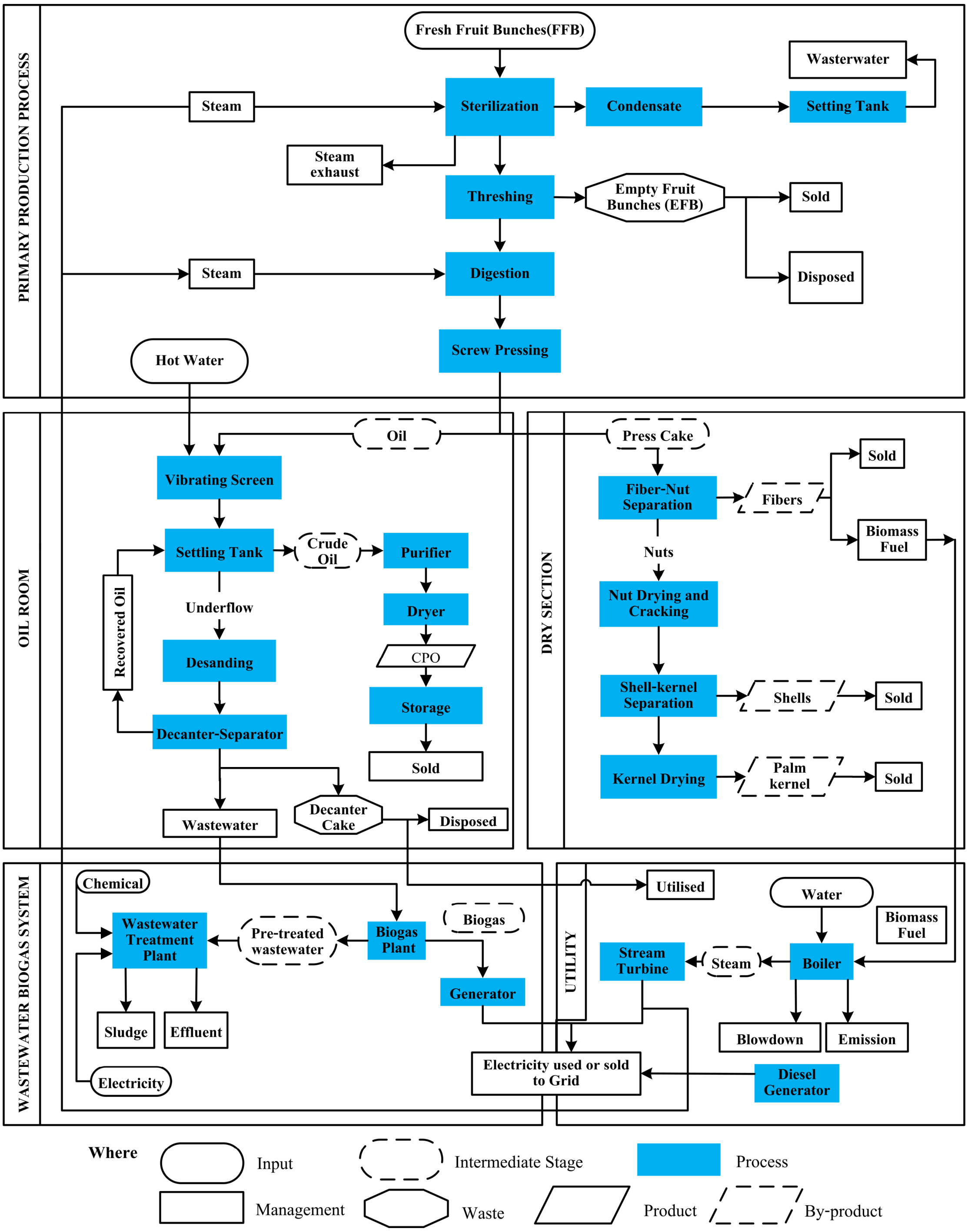

Figure 2.2 Schematic flow diagram of standard crude palm oil (CPO) production (Wet extraction process)

Source: Department of Industrial Works, DIW (2006)

2. Oil room

The CPO from the presses is a mixture of palm oil (25-35%), water (45-55%) and fibrous material varying in proportions.

2.1) Screening; a small amount of hot water is added to the raw palm oil and passed through a vibrating screen to separate fibrous particles. The palm oil after sieving still contains large amounts of suspended solids and water.

2.2) Sand removal; a sand cyclone is used to separate sand from the palm oil.

2.3) Suspended solid separating; the conventional procedure to separate palm oil from water is the settling tank method. Steam is used to heat the system and to maintain the temperature at 90^{o}C. Palm oil floats to the top of the tank and is collected by a funnel, and flows into the CPO tank.

2.4) Oil purification;

- Separation of fine suspended solids. The final purification step is done by centrifugation of the CPO from the settling tank to remove water and fine suspended solids.
- Drying and cooling. After centrifugation the CPO still contains water, which is removed by a vacuum evaporation system. The dried CPO is kept in storage tanks before selling to an oil refinery.

2.5) Treatment of sludge (oil/water mix) from settling tank; the sludge from the settling tank is collected in the sludge tank and subsequently treated to recover oil. To protect the equipment in the subsequent process steps against clogging, the sand is separated from sludge by a sand cyclone. The sand cyclone is cleaned by discharging the accumulated sand to the drain, followed by the injection of hot water.

2.6) Oil recovery; the sludge is collected in a sludge tank and then pumped to a decanter (three-phase centrifuge) or a separator (two-phase centrifuge) for palm oil recovery. To enhance the separator efficiency, it is common practice to add water during centrifugation. The separator will generate more wastewater than the decanter process. The recovered CPO is pumped to the settling tank.

3. Dry section

The remaining press cake is transported to a dry section. This section consists of fibers-nut separation, nut cracking, shells-kernel separation and kernel drying processes. A fibers-nut separation system consists of air clarifiers and cyclones for drying and separating the nuts and fibers. Fibers are removed from the nut in the air cyclone. The fibers are then blown through a cyclone to the boiler house where they are used as fuel. The nut is cracked by a ripple mill and the kernel and the shells are separated by a clay water bath. The produced kernel is dried to reduce its moisture to prevent molding, and subsequently stored in a silo. This kernel could be pressed inside the factory to produce palm kernel oil (PKO) or directly sold to other PKO mill.

4. Wastewater treatment system

Wastewater from the decanter/separator is discharged to a wastewater treatment plant. The traditional practice uses stabilization ponds consisting of anaerobic ponds, aerobic ponds and detention ponds for treating the wastewater. The treated wastewater is discharged into the oil palm fields or stored in the detention ponds. Currently, the wastewater treatment plants of several palm oil mills have been upgraded to biogas system. The biogas is used to generate the electricity by a gas engine. The electricity produced is used in the factory and the excess electricity is sold to Provincial Electricity Authority (PEA), Thailand by grid connection.

5. Utility

The utility section consisted of the water supply process and electricity generation. The raw water supply is commonly drawn from a river or reservoir. In general, the water supply was generally produced by coagulation, sedimentation, and filtration processes. The water supply produced was purified by the demineralization process prior to feeding the boiler. As mentioned earlier, fibers are used as the biofuel in the boiler to produce steam to generate electricity using in the mill and to sterilize FFB and to digest palm fruits in the digestion process.

6. Palm kernel oil (PKO) production

PKO is extracted from palm kernel by using single screw press and kernel meal is used as animal feed. PKO is fed to filter press or centrifuge in order to separate kernel sludge from PKO. The diagram of palm kernel oil mill process is shown in Figure 2.3.

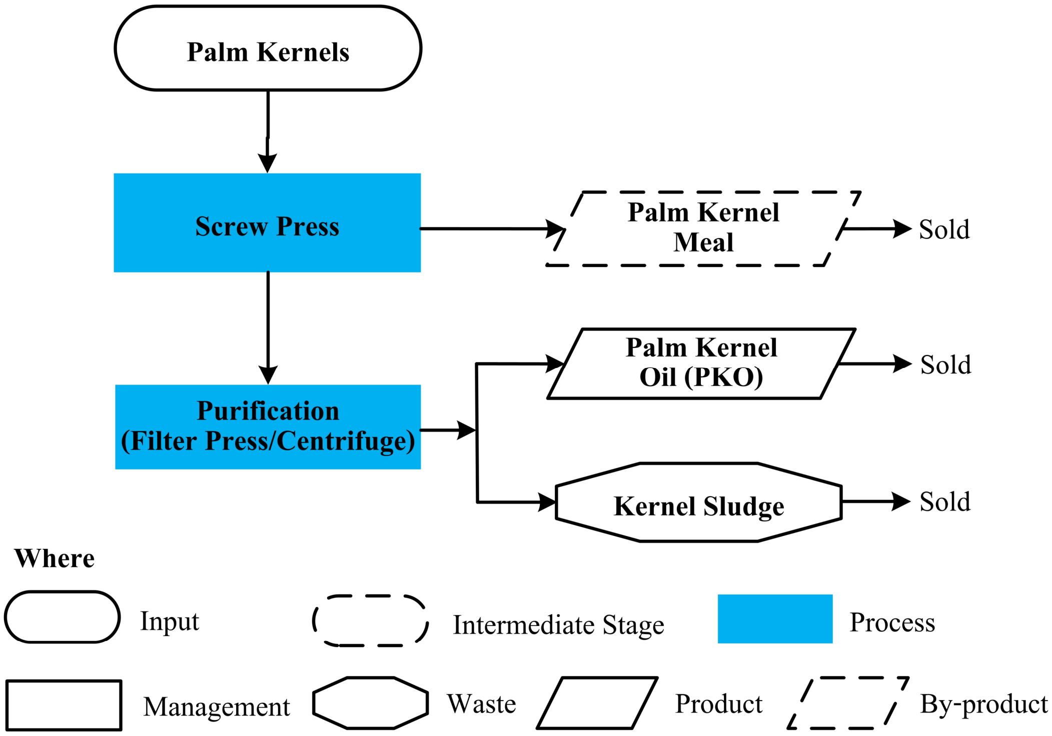

Figure 2.3 Schematic flow diagram of standard palm kernel oil (PKO) production

2.6 Environmental pollution of the conversion of FFB to CPO by the wet extraction process

The whole CPO process does not demand any chemicals as to aid in processing. Therefore, the total of products, by-products, and wastes originate from the FFB. However, solid wastes, wastewater, and air pollution are generated from this process and require good system management.

Extracting of CPO from FFB requires a large amount of water. This is the cause of a large quantity of wastewater. Therefore, most palm oil mills were located close to a river or reservoir (Rock 2002). When palm oil mill effluent (POME) is discharged into a watercourse, pollutant in POME is added significantly to surface water. The POME contains acid and has a high organic matter. It effects the depleting of the dissolved oxygen in the water and makes the water unsuitable for consumption.

Palm oil mills apply conventional biological treatment system to treat their POME. The system consists of anaerobic and aerobic or facultative processes. The palm oil mills employ the POME treatment options including scenario (I) contains anaerobic and facultative ponds in series (64%), scenario (II) contains anaerobic and aerobic lagoons in series (29%) and scenario (III) contains an anaerobic digestion tank and facultative ponds in series (7%) (Chavalparit 2006a). It was found that almost all mills in Thailand were unable to treat their wastewater to meet the effluent standard. Environmental impact problem from POME generally occur in the rainy season, especially, for the mills that were established close to communities and/or the mills that did not have their own oil palm plantation. The overflow from the wastewater treatment plant caused violent water pollution to the area nearby.

The anaerobic ponds result in releasing of methane and carbon dioxide into the air. Methane and carbon dioxide are green house gases (GHGs) that addressed by the Kyoto protocol (UNFCCC 1998). Chavalparit (2006a) reported that POME discharged from extracting one Mt of FFB could produce methane and carbon dioxide of 9 and 3.7 m^3, respectively. Additional problem for mills that are established nearby communities is smell from poorly managed treatment system. Moreover, POME includes high oil and grease, which is difficultly decomposed by anaerobic bacteria. The oil and grease accumulate and cover the surface of the ponds and cause emission of bad odor.

Palm oil mills also generate significant amounts of by-products or solid waste, such as EFB, fibers, shells, decanter cake and ash from the boiler. The problems of solid waste in palm oil mills are the unsuitable storage and handling of solid waste materials. These wastes can cause bad smell and dust that could affect the environment. Above-mentioned, most palm oil mills are generally self-sufficiency in terms of energy due to using fibers and shells as biomass fuel in the boiler for electricity and steam generation. However, the problems associated with the burning of fibers and shells are emission of dark smoke and carbon dioxide. In order to avoid these problems, the palm oil mills employ a cyclone as equipment to control air pollution.

2.7 Greenhouse gases (GHGs)

Human activities result in GHG emission of four kinds: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and the halocarbons. These GHGs are accumulated in the atmosphere of the Earth and cause concentration to increase with time. From Figure 2.4, it can be seen that important increases of GHGs have appeared in the industrial era. This represent that the GHGs increases are attributable to human activities (Forster *et al.* 2007) as follows:

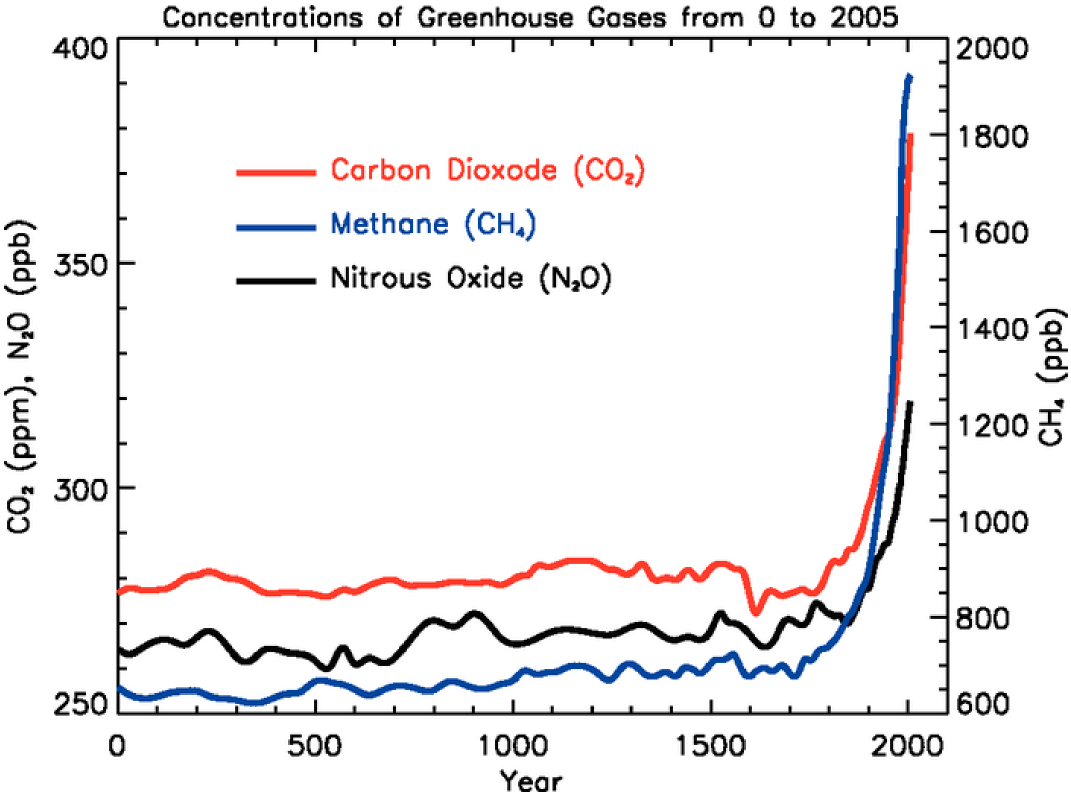

Figure 2.4 Atmospheric concentrations of important long-lived GHG over the last 2,000 years. Increases since about 1750 are attributed to human activities in the industrial era. Concentration units are parts per million (ppm) or parts per billion (ppb), indicating the number of molecules of the GHG per million or billion air molecules, respectively, in an atmospheric sample.

Source: Forster *et al.* (2007)

- Fossil fuels used in transportation, building heating and cooling and the manufacture of cement and other goods are the cause of increasing CO_2 in the atmosphere. Moreover, CO_2 is emitted from deforestations and natural processes such as the decay of organic matter.

• The human activities related to agriculture, natural gas distribution and landfills result in releasing CH_4. In addition, CH_4 is also released from occurring natural processes such as in rice cultivation.

• N_2O is emitted by human activities such as nitrogen fertilizer use and fossil fuel burning. Natural processes in soils and the oceans also release N_2O.

• Halocarbon gas concentration has increased primarily due to human activities. Natural processes are a small source. Most important halocarbons include the chlorofluorocarbons, which were used extensively as refrigeration agents and in other industrial processes.

• Ozone is a GHG that is continually produced and destroyed in the atmosphere by chemical reactions. In the troposphere, human activities have increased ozone through the release of gases such as carbon monoxide, hydrocarbons and nitrogen oxide, which chemically react to produce ozone.

Global warming is a critical issue that requires to be addressed. In 1997, governments from around the world have assembled at Kyoto and agreed to reduce emissions of six principal GHG including CO_2, CH_4, N_2O, Hydro fluorocarbons (HFCs), per fluorocarbons (PFCs), and sulphur hexafluoride (SF_6) (UN 1998). The Kyoto Protocol has determined legally binding targets for industrialized countries to decrease GHG emission during 2008–2012 by an average of 5% from the 1990 levels. The Cancun Agreement, approved during the sixteenth session of the conference of the parties (COP 16) in 2010, did not determine an obvious reduction target from 2012. However, this has encouraged developed countries to reduce their emissions by 25–40% below their 1990 levels by the year 2020 (UN 2010).

2.8 Existing GHG calculation methodologies

1. The Intergovernmental Panel on Climate Change (IPCC): Good Practice Guidance (IPCC 2006)

This is the methodology that is to be used for preparing the National Inventories for submission to the United Nation Framework Convention on Climate Change (UNFCCC). This methodology was developed for estimating GHG emissions on a national basis, and there is no obligation to use it for individual bio-energy projects. Many of the values and methods provided in these guidelines can be applied for this study. The 2006 IPCC Guidelines are in five volumes.

Volume 1 describes the basic steps in inventory development and offers the general guidance in GHG emissions. It also offers removals estimates based on the authors' understanding of accumulated experiences of countries over the period since the late 1980s, when national GHG inventories started to appear in significant numbers. Volumes 2 to 5 offer the guidance for estimates in different sectors of economy.

2. United Nation Framework Convention on Climate Change (UNFCCC): Clean Development Mechanism (CDM) and Joint Implementation (JI) Methodologies

For each type of CDM project a specific methodology has to be approved by the UNFCCC. Examples of project types include grid-connected electricity generation from biomass residues, fuel switching from fossil fuels to biomass residues in boilers for heat generation and afforestation/reforestation.

The CDM methodologies include a detailed discussion of concepts of "additionality" and "baselines" (the reference case, i.e. a scenario providing a reasonable representation of the anthropogenic emissions from GHG sources that would occur in the absence of the proposed project activity). The same principles apply to JI methodologies. In the case of joint implementation (JI) methodologies, accounting principles are also set out for use in GHG calculations that cover such notions as "project-specific", the extent of GHG "sources" and "sinks", a "conservative" baseline, "leakage" (i.e. accounting for alternative biomass use) and "local energy systems". In some cases additional procedures, such as monitoring of project participants, may also be applicable.

3. International Energy Agency (IEA): Bio-energy Task 38 Methodologies

Under its "Task 38", IEA aims to demonstrate and promote the use of a standard GHG balance methodology and has published a number of reports, articles and case studies. The IEA Task 38 documentation has provided the life cycle assessment (LCA) methodology for bio-energy systems and discussed critical issues. The BIOMITRE calculation tool has been designed to compare fossil fuel and bio-energy systems on a project basis. The flexible system boundary settings used in BIOMITRE. Many LCA tools might be employed in the Dutch calculators as a means of optionally including certain aspects of the biomass chain like land-use change and reference production. The use of different “tiers” (with a corresponding “entry mask” on the data input form) might also be adopted.

4. International Sustainability and Carbon Certification (ISCC)

ISCC is recognized by the European Commission for all member countries without restriction. ISCC is a global scheme covering all kinds of biomass and is applicable in the European market and abroad.

The ISCC scheme documents the production of bio-energy with a mass balance system along the complete supply chain–starting at the farm or plantation, towards the mineral oil companies, power plant-operators or other users. The ISCC certificate is a reliable and persistent proof that biomass was produced according to European sustainability legislations. The ISCC GHG balance system records how much GHGs are saved through the certified bio-energy compared to fossil fuels.

5. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET Model)

Argonne’s GREET model is widely acknowledged as the “gold standard” for estimating and comparing the energy and environmental impacts of transportation fuels and advanced vehicles. The GREET model is an analytical tool that simulates the use of energy and emission output of more than 85 vehicle or fuel combinations over a whole life cycle. The GREET model is the free software program for researchers. More than 14,000 users of the GREET model worldwide consist of the government agencies, the auto and energy industries, research institutions, universities and public interest groups.

6. Harmonised Calculations of Biofuel Greenhouse Gas Emissions in Europe (BioGrace)

The BioGrace project started up since 2010 to deal with the harmonisation of GHG emission calculations of biofuels throughout the European Union. The BioGrace GHG calculations tools were designed to evaluate and analyze own biofuel GHG emissions. The tool allows the reproduction of the calculation of the Annex V default values of the Renewable Energy

Directive (2009/28/EC) (RED) for biofuel production pathways as well as to perform individually adapted calculations. The calculations use the BioGrace list of standard values and follow the methodology laid down in the RED.

CHAPTER 3

DEVELOPMENT OF CALCULATION METHODOLOGY OF GHG EMISSION FOR PALM OIL MILLS IN THAILAND

3.1 Introduction

The expansion of the palm oil industry in Thailand is continuously increasing because of the consumption of edible oil and biodiesel production. During the years 2006-2010, the quantity of palm oil produced in the world increased by an average rate of 6.41% per year (Office of Agricultural Economics, OAE 2010a). In the year 2010, 1.29 million metric tons (Mt) or 2.81% of the total world palm oil production was produced in Thailand (Department of Internal Trade, DIT 2011). The palm oil industry in Thailand has developed rapidly to support the demand by consumers in both domestic and export markets. Its production chain consists of the oil palm plantations, crude palm oil (CPO) extraction, the refining of edible oil, and/or biodiesel production. The oil palm plantation area in Thailand expanded from approximately 0.46 million hectares in the year 2008 to 0.57 million hectares in the year 2010. Most of the plantations are located in the southern Thailand with an area about 88.6% of the total plantation area (OAE 2010b). The yield of fresh fruit bunches (FFB) production averaged 16.9 Mt FFB per hectare per year on wet basis (OAE 2010c) with a moisture content of about 35.3% (DIT 2007).

CPO production is divided into wet extraction and dry extraction processes. The wet extraction process is generally used in the conversion of FFB to CPO due to the high production capacity and self-sufficiency regarding energy. However, solid wastes, wastewater, and air pollution are generated from this process and require good system management. In order to promote sustainable CPO production, it is necessary to reduce the environmental impacts including the production of solid wastes, wastewater and greenhouse gas (GHG) emission. The increasing of GHG emissions, such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfurhexafluoride (SF_6) has been considered worldwide as the major cause of global warming.

The well-known international organizations that propose the calculation of GHG emission are the Intergovernmental Panel on Climate Change (IPCC) and the United Nation Framework Convention on Climate Change (UNFCCC). The calculation of GHG emission was developed for GHG emission of the nation (IPCC 2006a) and for the clean development mechanism (CDM) projects (UNFCCC 2010a). The International Sustainability and Carbon Certification (ISCC 2011) process provided the methodology for calculating GHG emissions and GHG audits along the supply chain of biomass and bioenergy. The ISCC methodology focuses on several types of raw materials used as biofuel including corn, rapeseed, soy bean, sugar beet, sugar crane, rye, sunflower, and wheat. The default or individually determined values can be used in the calculation. The emission factors (EFs) for converting the input quantities to GHG emissions and for waste and wastewater treatments are provided from reliable sources such as BioGrace (2011), Stichnothe and Schuchardt (2010), and Ecoinvent (2010). BioGrace (2011) developed the BioGrace GHG calculation tool for biofuel production pathways. The BioGrace methodology also focuses on several types of biofuel production as presented in the ISCC methodology. The EFs for converting the input quantities to GHG emissions are provided.

Both the ISCC and BioGrace methodologies are verified for compliance with the European Renewable Energy Directive (EU RED). Greenhouse gases, Regulated Emissions, and Energy Use in Transportation (GREET) model (U.S. Department of Energy 2011) has been developed for the GHG calculation of many fuel production pathways. ISCC, Biograce, and GREET methodologies focus on several biofuel types; therefore, there is no specific methodology for the calculation of GHG from palm oil mills. The EFs are mostly used in the calculation, there is no methodology for GHG calculation for palm oil mill that uses the actual value of organic removal by wastewater treatment in the GHG calculation. In addition, all previous methodologies were developed by the palm oil utilization side. A methodology for calculating GHG emission from the palm oil production side is not currently available.

Some researchers have studied and proposed emission values for GHG. Vijaya *et al.* (2010) studied the GHG emission from a palm oil mill in Malaysia. The system boundary of the gate to gate assessment was set with 12 mills participating. The GHG emission calculation of wastewater treatment plant was calculated according to the study of Ma *et al.* (1999). The GHG emission values for 1 Mt CPO from the mills without biogas capture systems were 987 kgCO_2eq whereas the mills with biogas capture systems emitted GHG of 225 kgCO_2eq. There are a few publications related to the GHG calculation and GHG emissions of the wet extraction process in Thailand. H-Kittikun *et al.* (2009) determined the GHG emission from 2 palm oil mills in Thailand. The cradle to gate was used as system boundary. The calculation of GHG emission of wastewater treatment plants was done in accordance with the study of Chong and Phillip (2001) and Shirai *et al.* (2003). GHG emissions from oil palm plantation for CPO production in Thailand were about 2,000 – 2,289 kgCO_2eq per Mt CPO. Chuchuoy *et al.* (2009) studied the GHG emission from palm oil mills. The system boundary of cradle to gate was used. GHG emissions due to chemicals, chemical packaging, fossil fuels, and electricity production and the transportation of FFB to mills, chemicals and packaging to mills, and fossil fuel to mills were cut off. 1 Mt of CPO production in Thailand with and without a biogas system could emit 698 and 1,009 kgCO_2eq, respectively. In this study, for the wastewater treatment plant without biogas capture system, the GHG emission was determined according to IPCC (2006b). The wastewater treatment plant with a biogas capture system was considered to have no GHG emissions. It can be stated that there are no methodologies of GHG calculation that cover all practices in palm oil mills. In addition, by considering the wastewater treatment process, most previous calculation used the EFs in the calculation. There is no GHG calculation methodology that uses the actual value of organic removal by wastewater treatment in GHG calculation.

The main objective of this research, therefore, was to develop the methodology for the calculation of GHG emission for the conversion of FFB to CPO by the wet extraction process. Six palm oil mills with a capacity of 11.9% of the total CPO production in Thailand in the year 2010 that covered all practices participated in this study. The EFs in terms of kg CO_2eq per 1 Mt of each main product and co-products of palm oil mills were determined for further utilization in the calculation of GHG emission of the next processing in the biodiesel supply chain or going through another supply chain. In addition, the GHG emission hot spots of the wet extraction process could be investigated and the option for the optimization GHG emission could be recommended.

3.2 Methodology

3.2.1 Goal and system boundary of research

The goal of this research was to develop a methodology for calculating GHG emission and to determine the GHG emission values for the conversion of FFB to CPO by the wet extraction process in Thailand. The GHG emission calculation was developed according to the life cycle assessment (LCA) concept based on cradle to gate (C2G) evaluation (International Organization for Standardization, ISO 2006a, 2006b). All GHG emissions from raw material production, transportation, processing, and waste disposal were counted in this study (Figure 3.1).

The FFB are produced from oil palm cultivation and considered as the major raw material input for CPO production. In this study, the EFs of FFB production were obtained from the study of German International Cooperation (GIZ) (Thailand Greenhouse Gas Management Organization (Public Organization), TGO 2011a) and this is given in Appendix B. Oil palm cultivation consists of four unit processes including soil preparation, cultivation, maintaining, and harvesting, respectively. The GHG emissions from the production of seedling (age 8-12 months), chemical fertilizers, energy such as fuel and electricity, agro-chemicals, auxiliary products used such as detergents, and organic fertilizers and transportation of all raw materials to oil palm plantations were included. The N_2O emission from chemical and organic fertilizer used is counted in the GIZ study. The CO_2, CH_4, and N_2O addressed by the Kyoto protocol (UNFCCC 1998) were taken into account in this study. The functional unit (FU) was defined as 1 Mt of CPO.

3.2.2 Technology

The wet extraction of palm oil from FFB includes five major sections: 1) the primary production process; 2) the oil room; 3) the dry section; 4) the wastewater treatment system; and 5) utility. The CPO production process is presented as follows: sterilization, fruit separation, digestion, oil extraction and oil purification. Large amounts of water and energy are required to convert FFB into CPO. In this research, the FFB was identified as raw material and the CPO was considered as the main product. The palm kernel (PK), shells, and fibers were counted as co-products. In some mills, PK was directly brought for pressing by screw press followed by filtration process to produce palm kernel oil (PKO) and palm kernel meal (PKM). PKO and PKM, therefore, were also counted as co-products. In this case, the actual quantity of PK was difficult to record. GHG emissions of CPO conversion, therefore, should be allocated to PKO and PKM. It must be noted that PKO and PKM can be produced on-site or off-site. To avoid any confusion, the GHG emission value for producing of 1 Mt PKO and PKM must be reported in terms of kgCO_2eq per Mt PKO (on-site) and kgCO_2eq per Mt PKM (on-site), respectively. The empty fruit bunches (EFB) and decanter cakes generated during the process were classified as waste as shown in Figure 3.1.

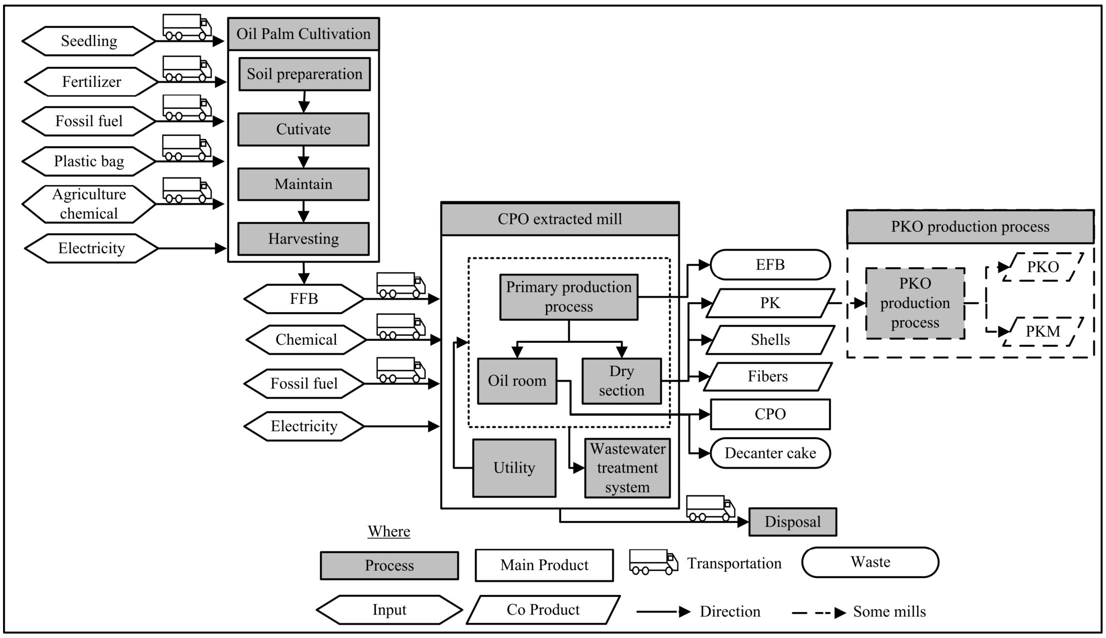

Figure 3.1 System boundary of this LCA study

The wastewater from the wet extraction process is discharged to wastewater treatment plants. The traditional practice uses stabilization ponds consisting of anaerobic ponds, aerobic ponds and detention ponds for treating the wastewater. The treated wastewater is discharged into the oil palm fields or stored in the detention ponds. Currently, the wastewater treatment plants of several palm oil mills have been upgraded to the biogas system. The biogas is used to generate the electricity by a gas engine. The electricity produced is used in the factory and the excess electricity is sold to Provincial Electricity Authority (PEA), Thailand by grid connection.

3.2.3 Developing a methodology for the calculation of GHG

In this study, the existing GHG emission calculation methodologies of several organizations such as IPCC (IPCC 2006a), UNFCCC (UNFCCC 2010b), European Union (EU) (EU 2009), ISO (ISO 2006c), International Sustainability & Carbon Certification (ISCC) (ISCC 2011), Thailand Greenhouse Gas Management Organization (Public Organization) (TGO) (TGO 2010) were reviewed. This was done to set up the Thai GHG methodology of calculation for the conversion of FFB to CPO by the wet extraction process. The background data for a 1 year period and the factors for converting GHG emissions into CO_2eq from IPCC (2007) were used. The manufacturing of equipment, buildings and other capital goods were not included. The palm oil mills were divided into two scenarios in accord with their wastewater treatment plant: scenario (I) included palm oil mills with biogas capture; scenario (II) included palm oil mills without biogas capture. In addition, the total average GHG emission value from six mills and the best observed case were analyzed. The data related to the "Thai GHG methodology of calculation" were collected to calculate the GHG emission value for each scenario. At the final stage, a total of GHG emission values were allocated to the main product and the co-products of palm oil mills. The GHG emission values allocated are expressed in CO_2eq per Mt of all kinds of products.

The allocation by energy, mass, and price values was introduced for this study. This is because the EF of CPO and the co-products will be used in the next processing of the bio-energy supply chain or going through another supply chain, such as biodiesel production and in the electricity generation plant using biomass fuel. Lower heating values (LHVs) of the main product, co-products and wastes were determined in this study by using a Leco automatic calorimeter (AC-500 Model).

3.2.4 Data collection

The 6 palm oil mills that participated in this study were located at Chonburi, Phangnga, Krabi, Suratthani, Trang and Satun provinces. They were divided into scenarios as follows: scenario (I) 4 mills; and scenario (II) 2 mills. The CPO production capacity of the participating mills ranged from 15 to 90 Mt FFB per hour. They accounted for approximately 11.9% of total CPO production capacity in Thailand in the year 2010. In the calculation of GHG emission, there are two types of data to be collected - activity data and EFs. Activity data refers to the amounts of inputs (such as raw materials, chemicals and energy inputs) and outputs (such as products, co-products and wastes) involved in the production and utility processes, transportation and waste disposal. EFs represent values that attempt to convert these quantities into the resulting GHG emission. These factors are expressed as the amount of GHG emitted per unit of activity data.

Both activity data and EFs could be derived from primary or secondary sources. The sampling strategy of primary activity data included on site interviews, surveying, questionnaires, and on site sampling for analysis. These were applied to develop the life cycle inventory (LCI) on the basis of a one year period in the year 2010. The CPO, PKO, PK, EFB, fibers, shells, PKM, and decanter cake were collected for LHV analysis. The LHV results of these products are presented in Table 3.1. For the mills with biogas capture, the wastewater from processing, the wastewater before and after the biogas recovery system, and the effluent from the detention pond was collected in order to analyze parameters for the calculation of the GHG emission. For the mills without biogas capture, the wastewater from processing and effluent from detention pond were used. The EFs were collected from the literatures, and the respective sources and publications are indicated as shown in Appendix B. Moreover, the LCI data of this study was used in the calculation of the GHG emission using the ISCC methodology for purposes of comparison.

Table 3.1 Lower heating values of products, co-products, and wastes from palm oil mills

Products	**Range of heating value (MJ/ Mt)**	**Range of moisture (percent)**	**Average heating value (MJ/ Mt)**	**Average moisture (percent)**
CPO	39,080 – 39,343	0.00 – 0.45	39,212 ± 106	0.15 ± 0.21
PKO	37,669 – 37,807	0.00 – 0.66	37,736 ± 69	0.22 ± 0.38
Palm kernel	24,945 – 26,712	7.00 – 7.69	25,947 ± 907	7.24 ± 0.39
EFB	7,109 – 9,043	54.8 – 62.7	8,036 ± 970	59.4 ± 4.09
Fibers	13,054 – 15,127	28.2 – 32.5	14,166 ± 992	30.2 ± 2.10
Shells	15,788 – 17,078	14.7 – 24.0	16,639 ± 598	18.9 ± 3.88
Palm kernel meal	18,175 – 20,021	8.67 – 12.0	18,915 ± 976	10.8 ± 1.86
Decanter cake	3,622 – 4,183	77.3 – 82.5	3,832 ± 305	78.3 ± 1.08

3.3 Results and discussion

3.3.1 Wet extraction process

In the palm oil mill the materials used for the production of CPO were composed of FFB, chemicals, diesel oil, electricity and water supply as shown in Table 3.2. The averaged FFB of 5.88 Mt (6 mills) was required to produce 1 Mt of CPO. From this study it was found that the oil extraction rate (OER) ranged from 15.2 to 19.3% with an average value of 17.0%. The previous research reported an average OER of 18% in Thailand (Department of Alternative Energy Development and Efficiency, DEDE 2006). The OER obtained was lower than that in Malaysia which was 20.45% (Malaysian Palm Oil Board, MPOB 2011). This could be because of the differences in the breeds of oil palm and the efficiency of CPO production.

The utility section consisted of the water supply process and electricity generation. The raw water supply is commonly drawn from a river or reservoir. The water supply of about 4.59 m^3/Mt CPO was generally produced by coagulation, flocculation, sedimentation, and filtration processes. The water supply produced was purified by the demineralization process prior to feeding the boiler. Several kinds of chemicals were used in this system. Polyaluminium chloride, anionic polymer, sodium chloride, hydrochloric acid, and sodium hydroxide were the major chemicals used in the utility section.

For the dry section, kaolin of about 12.75 kg/Mt CPO was used for separating the palm kernel from shells. For the electricity consumption, two important sources of electricity were supplied to the mills. Firstly, the major supply was produced from the steam turbine generator in the mill in which fibers were used as biomass fuel for the boiler. Secondly, it was supplied from the grid connection of the PEA for the start-up process only. Diesel of about 3.71 L/Mt CPO was used in some mills to generate the electricity for the start-up process. The diesel oil was the major fossil fuel used for the diesel generator and all diesel machines. In addition, in some mills there were gas engines to produce the electricity from biogas for using in mills and for selling to the PEA.

The average percentage of output per Mt FFB on a wet basis from six mills in this study were CPO of 17.0%, PK of 5.5%, shells of 5.1%, fibers of 6.2% (surplus amount from using in boilers), EFB of 16.3%, and decanter cake of 3.0%. The moisture content of the outputs is presented in Table 3.1. The percentage of outputs obtained in this study corresponded with the study of the Department of Agriculture (DOA) (DOA 2008) which proposed the range of output per Mt FFB as follows: CPO of 15-18%; PK of 5-6%; shells of 5-6%; fibers of 12-14%; and EFB of 25-27%. Due to the loss of moisture in production, especially the purification of the CPO, the sum of the percentage of outputs did not add up to 100 %. The palm oil mills used fibers as biomass fuel for boilers to generate steam and electricity. The shells were sold outside as a biomass fuel. Some EFB were used as the biomass fuel in the mill but some were sold as biomass to a power plant or a bio-fertilizer plant. For the mill that produced PKO from PK there were PKO 2.2% and PKM 2.6%.

The CPO production caused a large amount of wastewater. Processing 1 Mt of FFB generated average wastewater of about 0.44 m^3 (6 mills). DEDE found that the palm oil mill produced wastewater of 0.56 m^3/Mt FFB (DEDE 2006). The wastewater treatment plants of the palm oil mills in scenario (I) had a chemical oxygen demand (COD) of raw wastewater, wastewater inlet to biogas, wastewater outlet from biogas, and treated wastewater from the final pond of 53,082–124,342, 52,576-92,516, 3,902-31,982, and 488-13,437 mg/L, respectively. For the organic contaminant of the wastewater treatment plants of the palm oil mills in scenario (II), it had the COD of raw wastewater and treated wastewater from the final pond of 44,350-79,048 and 1,020-1,515 mg/L, respectively. In the best case observed, the COD of raw wastewater, wastewater inlet to biogas, wastewater outlet from biogas, and treated wastewater from the final pond were 53,082, 56,146, 5,555, and 488 mg/L, respectively.

Table 3.2 LCI for production of 1 Mt CPO

Parameter	Unit	Amount (per Mt CPO)			
		Scenario (I) (4 Mills)*	Scenario (II) (2 Mills)*	Average GHG emission (6 Mills)*	Best observed case (1 Mill)*
Inputs					
FFB	Mt	5.92	5.71	5.88	6.49
Water consumption in factories	m^3	4.41	5.41	4.59	1.06
Electricity consumption from grid	kWh	5.76	52.59	14.36	25.95
Diesel oil consumption	liter	3.85	3.09	3.71	5.60
Chemicals usage**					
- Kaolin	kg	12.204	15.173	12.750	12.669
- Polyaluminium chloride	kg	0.591 (3 mills)	0.228 (1 mill)	0.530 (4 mills)	0.338
- Anionic polymer	kg	0.002 (3 mills)	0.237 (1 mill)	0.042 (4 mills)	0.008
- Sodium chloride	kg	0.872	0.513	0.806	4.780
- Sodium sulfite	kg	0.054 (3 mills)	0.032	0.049 (5 mills)	0.051
- Magnesium	kg	0.758 (1 mill)	-	0.758 (1 mill)	-
- Soda ash	kg	0.059 (2 mills)	0.319 (1 mill)	0.104 (3 mills)	-
- Phosphate	kg	0.089 (2 mills)	0.030	0.073 (4 mills)	-
- Chlorine	kg	0.088 (2 mills)	0.022 (1 mill)	0.081 (3 mills)	-
Outputs					
Main product					
- CPO	Mt	1.00	1.00	1.00	1.00
Co-products					
- PKO	Mt	0.13 (2 mills)	-	0.13 (2 mills)	0.14
- PK	Mt	0.34 (2 mills)	0.27	0.32 (4 mills)	
- Fibers***	Mt	0.40	0.22	0.37	0.71
- Shells	Mt	0.35	0.10	0.30	0.41
- PKM	Mt	0.16 (2 mills)	-	0.16 (2 mills)	0.17
Solid waste					
- EFB	Mt	0.99	0.83	0.96	0.31
- Decanter cake	Mt	0.18	0.11 (1 mill)	0.17 (5 mills)	0.25

Table 3.2 LCI for production of 1 Mt CPO

Parameter	Unit	Amount (per Mt CPO)			
		Scenario (I) (4 Mills)*	Scenario (II) (2 Mills)*	Average GHG emission (6 Mills)*	Best observed case (1 Mill)*
Wastewater					
- Palm oil mill effluent (POME)	m^3	2.43	3.29	2.59	2.79
- COD wastewater****	mg/L	93,044	61,699	82,596	53,082
- COD inlet to biogas****	mg/L	73,027	-	73,027	56,146
- COD outlet from biogas****	mg/L	16,085	-	16,085	5,555
- COD final pond****	mg/L	4,694	1,268	3,552	488
Biogas	m^3	67.42	-	67.42 (4 mills)	32.97
Electricity connect to grid	kWh	68.77	-	68.77 (4 mills)	155.06

Remark: * Weighted average,

** Sodium hydroxide, inhibitor, neutralizing amine blend, were used in the production with amount of less than 1% of total chemicals used.

*** Surplus amount from using in boiler

**** Average by factories

3.3.2 GHG emitted sources and calculation

From Figure 3.1 it can be seen that the GHG emissions of the wet extraction process of palm oil mill originated from: (1) the acquisition of raw materials; (2) chemicals input to the mill and disposal of chemical packaging waste; (3) energy input to the mill; and (4) wastewater management. The data for these were as follows.

The GHG emission of FFB came from the FFB production during plantation and harvesting ($E_{FFB,\ production}$), and the transportation of FFB to the mills ($E_{FFB,\ transport}$) as shown in equation (3.1). The FFB could be directly transported from the plantation to the mills or from the plantation to a collection point and from this point to the mills. All transportation was included in the calculation.

$$E_{FFB} = E_{FFB,\ production} + E_{FFB,\ transport} \quad (3.1)$$

The GHG emission from the usage of chemicals in the mills was composed of five components: the emission of production ($E_{\text{Chemical, production}}$) of those chemicals, the transportation ($E_{\text{Chemical, transport}}$) of those chemicals to the mills, the emission of chemical packaging production ($E_{\text{Chemical packaging, production}}$), transportation of chemical packaging waste to disposal site ($E_{\text{Chemical packaging waste, transport}}$) and disposal of chemical packaging waste ($E_{\text{Chemical packaging waste, disposal}}$) as shown in equation (3.2).

$$\begin{aligned} E_{\text{Chemical}} &= E_{\text{Chemical, production}} + E_{\text{Chemical, transport}} + E_{\text{Chemical packaging, production}} \\ &\quad + E_{\text{Chemical packaging waste, transport}} + E_{\text{Chemical packaging waste, disposal}} \end{aligned} \tag{3.2}$$

The energy usage in the mill came from fossil fuel and electricity. Therefore, the GHG emission of energy included the emission of fossil fuel production ($E_{\text{Fuel, production}}$), transportation ($E_{\text{Fuel, transport}}$) and combustion ($E_{\text{Fuel, combustion}}$) and the electricity used in the process ($E_{\text{Electricity}}$) as equation (3.3).

$$\begin{aligned} E_{\text{Energy}} &= E_{\text{Fuel}} + E_{\text{Electricity}} \\ &= E_{\text{Fuel, production}} + E_{\text{Fuel, transport}} + E_{\text{Fuel, combustion}} + E_{\text{Electricity}} \end{aligned} \tag{3.3}$$

In practice, fibers are used in the boiler as biomass fuel. However, GHG emission from the consumption of fibers was considered as “zero” since it is an internal recycling within the boundary. Therefore, the calculated GHG values were not allocated to fibers. For the shells, they are usually sold to other factories as biomass fuel. The GHG emission from the combustion phase of shells is carbon neutral which is equal to zero.

With regard to the GHG emission of electricity, it could be stated that the mill utilized the electricity from four sources: (1) electricity from the PEA; (2) electricity from steam turbines; (3) electricity from biogas plants; and (4) electricity from diesel engines. In the calculation of GHG, the electricity from the PEA and diesel engine was included. The electricity from steam turbines and biogas plants was not counted because it was produced from biomass fuel. The kilowatt hour per year of electricity used from the PEA was obtained from the mill. For the electricity from diesel engines, the amount of diesel used per year was collected and used in the calculation of the E_{Fuel} section.

The GHG emission calculation of each section as described above was the result of multiplying the activity data (such as kg FFB, kg Chemicals, L diesel fuel used, kWh electricity used) by EF (TGO 2010) as in equation (3.4).

$$\text{GHG emission value } (CO_2eq) = \text{Activity data (mass, volume, kWh or km) x EF } (CO_2eq \text{ per unit}) \qquad (3.4)$$

For the GHG emission from the wastewater treatment system, Many CDM projects for methane recovery in wastewater treatment plants in accordance with UNFCCC method have already been developed by palm oil mills in Thailand (TGO 2011b). Therefore, the UNFCCC methodology was used for the calculation of GHG emission from the wastewater treatment system in this study (UNFCCC 2010c). The wastewater treatment system was classified into two, with and without biogas recovery system according to equation (3.5) and (3.6) respectively.

$E_{Wastewater}$

Case I, Wastewater treatment system with biogas recovery system

$$= E_{Wastewater,\ treatment} + E_{Sludge,\ treatment} + E_{Wastewater,\ discharge} + E_{Sludge,\ final} + E_{Fugitive} + E_{Flaring} \qquad (3.5)$$

Case II, Wastewater treatment system without biogas recovery system

$$= E_{Wastewater,\ treatment} + E_{Sludge,\ treatment} + E_{Wastewater,\ discharge} + E_{Sludge,\ final} \qquad (3.6)$$

For the mills with a biogas recovery system, the GHG emission was the summation of (1) anaerobic conversion of wastewater treatment system ($E_{Wastewater,\ treatment}$); (2) sludge treatment system ($E_{Sludge,\ treatment}$); (3) degradable organic carbon in treated wastewater ($E_{Wastewater,\ discharge}$); (4) anaerobic decay of the final sludge produced ($E_{Sludge,\ final}$); (5) methane emissions from biogas release in capture systems ($E_{Fugitive}$); and (6) methane emissions due to incomplete flaring ($E_{Flaring}$). In general, the palm oil mills utilized the treated wastewater for oil palm plantations or retention.

When there was no wastewater discharge to natural water sources, $E_{Wastewater,\ discharge}$ was considered to be zero. For the application of treated wastewater in palm oil plantations, in practice the treated wastewater was not stored in the plantations until anaerobic degradation occurred like a paddy filed. The treated wastewater was promptly used by palm trees. $E_{Wastewater,\ discharge}$ was also considered to be zero in this study. In addition, during the operation of a wastewater treatment plant, the waste sludge from a biogas system was settled in a series of anaerobic ponds. There was no sludge treatment so the $E_{Sludge,final}$ and $E_{Sludge,treatment}$ were considered to be zero.

In the other case, the wastewater treatment system without biogas the recovery system was considered as GHG emission from $E_{Wastewater,\ treatment}$, $E_{Sludge,\ treatment,}$ $E_{Wastewater,\ discharge}$ and $E_{Sludge,\ final}$. As stated previously, $E_{Sludge,\ treatment,}$ $E_{Wastewater,\ discharge}$ and $E_{Sludge,\ final}$ was considered to be zero, therefore, only the $E_{Wastewater,}$ treatment was counted in this case. The $E_{Wastewater,\ treatment}$ can be calculated by an equation (3.7) as follows:

$$E_{Wastewater,treatment} = \sum_i Q_{ww,i,y} \text{ x } COD_{removed,i,y} \text{ x } MCF_{ww,treatment,BL,i} \text{ x } B_{o,ww} \text{ x } UF_{BL} \text{ x } GWP_{CH4} \quad (3.7)$$

Where: $E_{wastewater\ ,treatment}$= the GHG emission from wastewater treatment system (Mt CO_2eq); $Q_{ww,i,y}$ = volume of wastewater treated in wastewater treatment system i in year y (m^3); $COD_{removed,i,y}$ = chemical oxygen demand removed by treatment system i in year y (Mt/m^3), measured as the difference between inflow COD and the outflow COD in system I; $MCF_{ww,treatment,BL,I}$ = methane correction factor for wastewater treatment systems i (MCF values as per Table 6.8 in (IPCC 2006b); i = index for wastewater treatment system; $B_{o,ww}$ = Methane producing capacity of the wastewater (IPCC value of 0.25 kg CH_4/kg COD (IPCC 2006b)); UF_{BL} = model correction factor to account for model uncertainties (0.89 (UNFCCC 2003)); GWP_{CH4} = global Warming Potential for methane (value of 25 CO_2eq (IPCC 2007)).

The fugitive emission through the capture inefficiency in the anaerobic wastewater treatment systems was calculated. It must be noted that a default value of capture efficiency of the biogas recovery equipment was set to be 90% (UNFCCC 2010c). The major fugitive emission of 10% could have come from: 1) the breaking of the seal weld of the plastic sheet and the seal weld between the plastic sheet and biogas recovery tank; 2) and the breaking of the flexible pipe due to the vibration of the pump. Moreover, the methane emissions due to incomplete flaring ($E_{Flaring}$) (UNFCCC 2006) must be calculated in this study as equation (3.8).

$$E_{Flaring} = TM_{RG,h} \times (1 - \eta_{Flare,h}) \times GWP_{CH4}/1000 \qquad (3.8)$$

Where: $E_{flaring}$ = Methane emissions due to incomplete flaring ($MtCO_2eq$); $TM_{RG,h}$ = Mass flow rate of methane in the residual gas in hour h (kg/h); $\eta_{Flare,h}$ = flare efficiency in hour h. For the reduction of GHG emission due to the replacing of fossil fuel with the selling of generated electricity from biogas to the PEA, Thailand by grid connection, it was not included in this study. This was because it was already included in the calculation for EF of the PEA electricity (Hinchiranan 2009). From the overall diagram Figure 3.1 illustrates that the total GHG emission value (E_{Total}) was derived from the sum of emissions of each section related to the palm oil production in the plant. The calculation is summarized as the following equation (3.9):

$$\mathbf{E_{Total} = E_{FFB} + E_{Chemical} + E_{Energy} + E_{Wastewater}} \qquad (3.9)$$

Finally, the total GHG value was apportioned to all generated products. As mentioned previously, the palm oil mills did not produce only CPO. Shells, fibers, EFB, decanter cake, PK or PKO and PKM were also generated. In this study, CPO, shells, PK or PKO and PKM must be shared with the GHG burdens in accord with their respective portions after the total emission of the process was determined. Both EFB and decanter cake have no GHG emission values attached to them because they were considered as biomass wastes. It must be noted that with regard to the eradication and promotion of waste utilization practices for palm oil mills in Thailand, EFB and decanter cake generally were not disposed of under the conditions that could generate methane (CH_4) or nitrous oxide (N_2O). EFB and decanter cake were dumped inside the mill at a shallow depth for a few days. After that there are several means of EFB application, such as mushroom cultivation, as soil conditioning material in plantations or as biomass fuel for electricity generation in the boiler. In addition, decanter cake may be used in a composting process outside the mill and as soil conditioner.

In CPO production, kaolin is used only in the dry section of the process. Therefore, the GHG emitted from kaolin usage must be allocated to the generated products from the dry section only, including PK, shells, PKO and PKM. Factors allocating these GHG are shown in Table 3.3.

The total quantity of GHG that was emitted within the system boundary except from kaolin usage was shared to all products by the allocation factors as shown in Table 3.3.

Table 3.3 Allocation factors from production process

Scenario	Allocation factors					
	The emitted GHG from kaolin usage			**The emitted GHG within the system boundary except from kaolin usage**		
	Allocated by price	**Allocated by LHV**	**Allocated by mass**	**Allocated by price**	**Allocated by LHV**	**Allocated by mass**
Scenario (I) palm oil mills with biogas capture						
1. CPO (4 mills)	-	-	-	0.841	0.734	0.601
2. PKO (on-site, 2 mills)	0.383	0.166	0.094	0.061	0.044	0.038
3. PK (2 mills)	0.403	0.328	0.270	0.064	0.087	0.108
4. Shells (4 mills)	0.142	0.408	0.525	0.023	0.109	0.210
5. PKM (on-site, 2 mills)	0.072	0.098	0.111	0.011	0.026	0.044
Scenario (II) palm oil mills without biogas capture						
1. CPO (2 mills)	-	-	-	0.891	0.818	0.730
2. PK (2 mills)	0.939	0.815	0.739	0.103	0.148	0.200
3. Shells (2 mills)	0.061	0.185	0.261	0.007	0.034	0.071
Average GHG emission: Both palm oil mills with and without biogas capture						
1. CPO (6 mills)	-	-	-	0.850	0.748	0.667
2. PK (4 mills)	0.471	0.387	0.323	0.071	0.098	0.131
3. Shells (6 mills)	0.132	0.381	0.495	0.020	0.096	0.202
Best observed case						
1. CPO (1 mill)	-	-	-	0.816	0.719	0.582
2. PKO (on-site, 1 mill)	0.726	0.351	0.198	0.134	0.099	0.083
3. Shells (1 mill)	0.139	0.444	0.570	0.026	0.125	0.238
4. PKM (on-site, 1 mill)	0.135	0.205	0.232	0.025	0.058	0.097

Considering Table 3.3, the factors of allocation by mass were used to compare this with the study of the MPOB. The MPOB allocated GHG emission to CPO, shells and PK by mass only. The percentage allocation of CPO, shells, and PK were 61, 14, and 25%, respectively (Subramaniam *et al.* 2010). For the Thailand average from 2 mills with biogas capture and 2 mills without biogas capture, the percentage allocation of CPO, shells, and PK were 63, 17, and 20 %, respectively.

3.3.3 GHG emission from palm oil mills and hot spots

GHG emissions without allocation to products are illustrated in Table 3.4. The averaged GHG emission values in the scenario (I) of mills with biogas capture and the scenario (II) of mills without biogas capture were 883 and 1,164 kg CO_2eq/Mt CPO, respectively. The biogas capture system could reduce the GHG emission by 24%. The average GHG emission value of six mills was 935 kg CO_2eq/Mt CPO. The least GHG emission from the best observed case was 548 kg CO_2eq/Mt CPO. This lowest value was due to the best performance of a biogas recovery plant in reducing the COD. This GHG emission level should be the goal for other mills, since 38% of GHG emission was reduced from the scenario (I) study.

The GHG emission value for 1 Mt CPO from the mills in Malaysia without biogas capture system was 987 kgCO_2eq whereas the mills with biogas capture system emitted GHG of 225 kgCO_2eq (Vijaya *et al.* 2010). The GHG emission from the mills in Thailand, therefore, was significantly higher than that of Malaysia. This was due to the system boundary difference between the two studies. In the study of Vijaya *et al.* (2010), the GHG emission from the acquisition of FFB, chemicals usage and disposal of chemical packaging waste were not counted. In this present study, these GHG emissions were included. This study utilized the UNFCCC equation for calculation of GHG from wastewater treatment plants, whereas, the study of Vijaya *et al.* (2010) utilized the value from the study of Ma *et al.* (1999). They reported that 1 Mt of palm oil mill effluent (POME) produced 28 m^3 of biogas. This value was used for converting the amount of biogas to GHG emission values of wastewater treatment plant. In addition, the study of Vijaya *et al.* (2010) included GHG emission from the boiler stack whereas it was not counted in this study. The FFB production of 8.22 million Mt was obtained in Thailand in the year 2010 (OAE 2011). During the same period, CPO was produced about 1.29 million Mt in Thailand

(Food and agriculture organization of the United Nations, FAO 2011). The palm oil mill with a wet extraction process in Thailand emitted GHG of approximately 1.20 million Mt CO_2eq in year 2010. It could be stated that the results obtained covered all practices of the palm oil mills in Thailand. These could be used to represent the GHG value of palm oil mills in Thailand and could be useful for environmental policy makers as detailed information for promulgating the policy to reduce GHG emission.

Table 3.4 The GHG emission values without allocation from CPO production

Scenario	GHG Emission ($kgCO_2eq$/ Mt CPO)	
	Average[1]	**Min – max**[2]
Thai Methodology		
Scenario (I) palm oil mills with biogas capture	883	674 - 1,102
Scenario (II) palm oil mills without biogas capture	1,164	1,133 - 1,218
Average GHG emission: both palm oil mills with and without biogas capture	935	674 - 1,218
Best observed case	548	-
ISCC Methodology		
Scenario (I) palm oil mills with biogas capture	512	506 - 548
Scenario (II) palm oil mills without biogas capture	931	872 - 1,032
Average GHG emission: both palm oil mills with and without biogas capture	589	506 - 1,032
Best observed case	422	-

Remark: [1]Weighted average, [2]the values were obtained from individual mill

The ISCC methodology is in compliance with the EU-RED. A comparison between the Thai methodology of calculating GHG and the ISCC methodology was undertaken. The difference could be explained as follows. The ISCC methodology included the GHG emission from land use change, carbon capture and sequestration, and carbon capture and replacement. The Thai methodology did not include all of these. In addition, the ISCC offered EFs from the

BioGrace project (BioGrace 2011). However, as there were no available values from BioGrace project, the other accepted databases of the ISCC have been used. For the Thai methodology, the values of EFs were mainly obtained from the TGO; the EFs of chemicals, transportation, and other activities were gathered from acceptable databases such as Ecoinvent and the Thailand databases. In addition, the ISCC methodology used a displacement allocation on the GHG emission saving from generated electricity by bio-energy by exporting to the grid. This study did not use the displacement allocation.

For GHG emission from wastewater treatment processes, there are two major types of wastewater treatment processes in the ISCC methodology. These are (I) POME treatment in open ponds and (II) POME treatment in close ponds and flaring (required gas-tight pond cover, methane capture and flaring). The EF values of treatment type (I) and (II) were 0.51 and 0.00 kgCO_2eq/kg CPO, respectively. However, the UNFCCC method was applied to the Thai methodology to calculate the GHG emission from both anaerobic ponds and biogas recovery plants due to the using of actual values in the calculation. The actual values, such as amount of wastewater, COD, amount of sludge discharge, COD in the effluent, and others were required for the calculation. In addition, the biogas recovery plants consisted of three treatment units: (I) an anaerobic pond (open pond) before biogas recovery unit; (II) a biogas recovery unit; and (III) an anaerobic pond (open pond) after biogas recovery unit. Therefore, it is inappropriate to use a single value of the EFs from the ISCC in the calculation. Moreover, the ISCC method did not consider the leakage of biogas recovery in the calculation.

For the EFB management, the ISCC methodology provided the EF values for each case of EFB management. These were: EFB burning; EFB dumping and returning EFB as mulch; and EFB and POME for co-composting and POME treatment in open ponds. In Thailand, the EFB is used in many ways. However, the Thai methodology did not count the GHG emission from EFB management. The results of using LCI data (Table 3.2) from this study to calculate GHG emission according to the ISCC methodology are shown in Table 3.4. The GHG emissions from the mills in scenario (I) and (II) were 512 and 931 kg CO_2eq/Mt CPO respectively. The GHG emission of 589 and 422 kgCO_2eq/Mt CPO were determined for the average GHG emission value of six mills and best observed case, respectively. The biogas system could reduce GHG emission by 45% when it was calculated by the ISCC methodology. This was a considerably higher percentage reduction compared with the 24% GHG reduction by the biogas recovery system in the Thai methodology of calculating. The GHG emission calculated by the Thai methodology in scenario (I) and (II) was 42 and 20% higher than that of the ISCC methodology. The major difference could come from the wastewater treatment section.

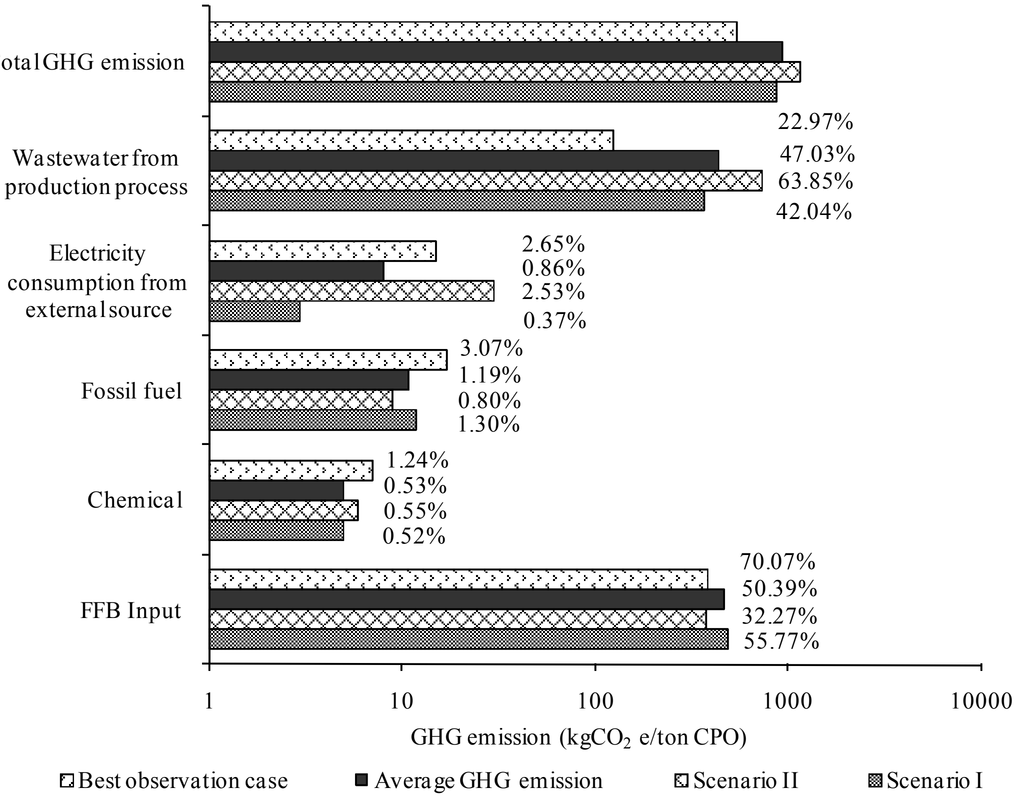

Figure 3.2 The sources of GHG emission from CPO production.

The sources of GHG emission from the wet extraction process can be classified as two major sections: (1) the acquisition of FFB; and (2) the wastewater treatment system. As shown in Figure 3.2 and Table 3.5, the major GHG emission sources of the mills with biogas capture were FFB acquisition and the wastewater treatment plants. The plantation giving the FFB emitted a GHG of 49.6% of the total GHG emission. The wastewater treatment plant emitted 42.0% of the total GHG emission where the major GHG emission sources were: the open pond before biogas system of 18.5%; stabilization pond of 16.2 %; and a biogas system of 7.4%.

Table 3.5 Breakdown of GHG emission from wet extraction process of CPO production

Emission source	**Percent breakdown of GHG emission (%)**			
	Scenario (I)	**Scenario (II)**	**Average GHG emission**	**Best observed case**
1 FFB Input	**55.77**	**32.27**	**50.39**	**70.07**
- Production	49.59	29.11	44.90	61.23
- Transportation	6.18	3.16	5.49	8.84
2 Chemicals	**0.52**	**0.55**	**0.53**	**1.24**
- Production	0.40	0.41	0.40	0.84
- Transportation	0.10	0.12	0.11	0.35
- Packaging disposal	0.02	0.02	0.02	0.05
3 Fossil fuel	**1.30**	**0.80**	**1.19**	**3.07**
- Production	0.12	0.07	0.11	0.28
- Transportation	0.01	0.01	0.01	0.02
- Combustion	1.17	0.72	1.07	2.77
4 Electricity consumption from external source	**0.37**	**2.53**	**0.86**	**2.65**
5 Wastewater from production process	**42.04**	**63.85**	**47.03**	**22.97**
- Open pond	18.46	-	-	0.00
- Biogas system	7.42	-	-	11.48
- Stabilization pond	16.16	-	-	11.49
Total	**100**	**100**	**100**	**100**

For the mills without biogas capture, the FFB acquisition emitted GHG of about 32.3% and the wastewater treatment plant emitted GHG of about 63.9% of total GHG emission. In the best observed case, the FFB acquisition emitted GHG 70.1% and the wastewater treatment plant emitted 23.0%. In addition, it was found that the GHG emission from the production process is considered as a small value when compared with the acquisition of FFB and the wastewater treatment system. The major GHG that were emitted in the FFB acquisition section arising from nitrogen fertilization results in nitrous oxide (N_2O) emission (Wicke *et al.* 2008)

This may due to the fact that the wet extraction process generated a large amount of wastewater with high organic content. This was treated in the wastewater treatment plant with anaerobic conditions especially open ponds. In wastewater treatment ponds, anaerobic conditions occur and the biodegradable carbon was converted to methane (CH_4) and carbon dioxide (CO_2) in large quantities.

Considering the GHG emission values after allocation, as shown in Figure 3.3, the GHG emission values of the main product and the co-products from the mills with biogas capture, the mills without biogas capture, the average value of six mills, and best observed case are shown in Table 3.6. For the GHG emission results of PKO and PKM, it must be noted that there were two major sources for producing PKO and PKM. These were: (1) production inside the palm oil mills; and (2) production by other factories outside the mills. Therefore, the GHG emission of PKO and PKM in this study could be used as being representative of scenario (I) only.

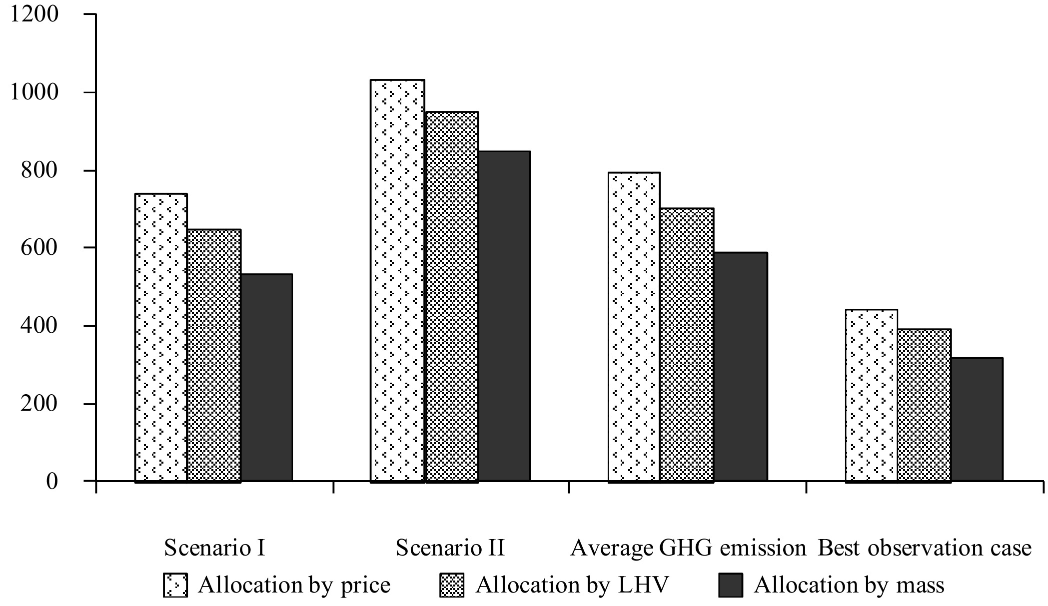

Figure 3.3 The GHG emission values of CPO after allocation

Table 3.6 GHG emission value of output from palm oil mill process after allocation by price, lower heating value and mass

Wet extraction process		**GHG Emission (kgCO$_2$eq/ unit)**					
		Allocation by price		**Allocation by LHV**		**Allocation by mass**	
With biogas recovery system							
Products	**Unit**	**Amount**[1]	**Min – Max**[2]	**Amount**[1]	**Min – Max**[2]	**Amount**[1]	**Min – Max**[2]
1. CPO (4 mills)	Mt	739.5286	545.8522-908.0571	647.1921	481.1936-812.1840	530.7973	389.6041-669.9575
2. PKO (on-site, 2 mills)	Mt	979.6117	652.6423-1,069.1698	723.9847	474.1942-792.4031	615.8806	395.8941-676.1357
3. Palm kernel (2 mills)	Mt	282.6203	269.0444-299.1561	373.2754	351.4468-399.8632	457.0311	424.9377-496.1218
By-products							
1. Shells (4 mills)	Mt	58.1202	43.4602-71.1972	278.0051	209.0942-349.4073	534.2714	395.8941-676.1357
2. PKM (on-site, 2 mills)	Mt	155.5870	103.5940-169.7095	363.1139	237.6846-397.1833	616.2752	395.8941-676.1357
Without biogas recovery system							
Products	**Unit**	**Amount**[1]	**Min – Max**[2]	**Amount**[1]	**Min – Max**[2]	**Amount**[1]	**Min – Max**[2]
1. CPO (2 mills)	Mt	1,032.8533	1,011.5058-1,069.4721	949.0442	947.7737-951.2236	848.2543	812.8319-868.9043
2. Palm kernel (2 mills)	Mt	451.2581	438.3948-473.0537	641.5027	638.6317-646.3674	860.3668	827.1030-879.9983
By-products							
1. Shells (2 mills)	Mt	85.0420	79.8812-86.1966	413.5981	409.5442-414.5050	836.7731	827.1030-879.9983

Table 3.6 GHG emission value of output from palm oil mill process after allocation by price, lower heating value and mass

Wet extraction process		**GHG Emission (kgCO$_2$eq/ unit)**					
		Allocation by price		**Allocation by LHV**		**Allocation by mass**	
With and without biogas recovery system							
Products	**Unit**	**Amount**[1]	**Min – Max**[2]	**Amount**[1]	**Min – Max**[2]	**Amount**[1]	**Min – Max**[2]
1. CPO (6 mills)	Mt	793.3994	545.8522 - 1,069.4721	702.6290	481.1936 - 951.2236	589.1002	389.6041- 868.9043
2. Palm kernel (4 mills)	Mt	325.5816	269.0444 - 473.0537	441.6076	351.4468 - 646.3674	559.7828	424.9377-879.9983
By-products							
1. Shells (6 mills)	Mt	59.7008	43.4602 - 86.1966	285.9656	209.0942 - 414.5050	552.0307	395.8941- 879.9983
Best Observed Case[3]							
Products	**Unit**	**Amount**[1]	**Min – Max**[2]	**Amount**[1]	**Min – Max**[2]	**Amount**[1]	**Min – Max**[2]
1. CPO (1 mill)	Mt	443.2054	-	390.7057	-	316.3395	-
2. PKO (on-site, 1 mill)	Mt	534.2449	-	387.1130	-	322.6295	-
By-products							
1. Shells (1 mill)	Mt	35.5759	-	170.6961	-	322.6295	-
2. PKM (on-site, 1 mill)	Mt	84.8008	-	194.0361	-	322.6295	-

Remark [1]Weighted average, [2]the values were obtained from individual mill, and [3]Best Cast was obtained from the mill which has lowest GHG emission values.

3.3.4 GHG emission mitigation from palm oil production

To ensure the sustainable production of palm oil, the GHG emission reduction from the important sources of emission must be managed. According to the GHG calculation, the major GHG emission sources are FFB production and wastewater treatment. In order to minimize the GHG emission for the conversion of FFB to CPO, the miller should pay attention throughout the whole production process as follows. (i) The FFB must be harvested at the right time, transported to the mills and processed within 24 hours. The vehicle uses for transportation must be appropriate. The cultivators should organize the transport of FFB in full loads. (ii) Palm fibers must be mainly used as fuel in the boiler. The boiler must be efficiently operated in order to save fibers and selling what are left to the power plant. Thus, the more fibers sold to the power plant the more GHG reduction due to the utilization of fibers as biomass fuel instead of using fossil fuel for electricity generation. (iii) Most GHG emission in palm oil mill is from wastewater treatment without a biogas system. Therefore, biogas recovery systems must be employed to capture methane gas for electricity generation. (iv) The operation of biogas plants must be optimized. In the case of mesophilic digesters, which operate at room temperature, mill effluent must be cooled down before pumping it into the digester. Currently, an anaerobic pond is used to cool down the temperature and high GHG emissions are emitted. The cooling tower should be used to minimize the lag time for reducing temperatures and, consequently, to reduce GHG emitted from the pond (the equalization pond). Generated biogas should be used 100% to produce electricity. It is necessary to avoid using flaring biogas. (v) Zero waste discharge must be set as the ultimate goal of the mill. All solids wastes, fibers, EFB, shells and decanter cake must be managed and utilized appropriately. Most of these solid wastes can be used as biomass for electricity generation. EFB and decanter cake also can be used to produce good composts. However, These GHG optimizations were the preliminary options. The detail on GHG optimization is presented in Chapter 4.

3.4 Conclusions

This research has considered the methodology of calculating GHG emission for the conversion of FFB to CPO by the wet extraction process along its chain from the FFB acquisition to CPO production as a final product. The GHG emissions from the acquisition of raw material, chemicals used, energy used, transportation and wastewater management were counted. The GHG emission values of CPO by energy from the mills with biogas capture, the mills without biogas capture, the average GHG emission, and best observed scenarios were 647, 949, 703 and 391 kgCO_2eq/Mt CPO, respectively. For GHG emission values of CPO were allocated by market price of about 740, 1,033, 793 and 443 kgCO_2eq/Mt CPO from the mills with biogas capture, the mills without biogas capture, the average GHG emission, and best observed case respectively. In the case of allocation by mass, the GHG emission amounts from the mills with biogas capture, the mills without biogas capture, the average GHG emission, and best observed case were 531, 848, 589 and 316 kgCO_2eq/Mt CPO, respectively.

The total CPO production in Thailand in year 2010 by a wet extraction process emitted a total GHG of approximately 1.20 million Mt CO_2eq. The major sources of GHG emission were the acquisition of FFB and the wastewater treatment system. Therefore, these sources of GHG emission must be managed well for the purpose of sustainable palm oil production. The information on GHG emission gained from the palm oil mills could be utilized by policy makers to set up a national plan for the palm oil mill industry and by the mill owners to minimize GHG emission from the palm oil mills. The information on GHG emission can be used for the development of the carbon footprint of the products. Eventually, the consumers could have GHG information to make a decision in selecting a low carbon product in order to reduce their GHG emission through the supply chain

CHAPTER 4

REDUCTION OPTIONS OF GREENHOUSE GAS EMISSION FROM PALM OIL MILL IN THAILAND

4.1 Introduction

The latest information on the greenhouse gas (GHG) emission level in 2009 for the group of countries participating in the Kyoto protocol was lower than the level in 1990 by 14.7% of base year emission. Whereas the GHG emission of developing countries continued to grow led by Asia and the Middle East. The global GHG emission increased from 20.97 giga metric tons (Mt) in 1990 to 28.99 giga Mt in 2009 (38.3% of increased emission) (International energy agency, IEA 2011). It showed an alarming trend in relation to a large increase of GHG amount in the world. The mitigation of GHG emission by developing countries, therefore, should be promptly established. This solicitation is the cause of alertness of related agencies in Thailand. The definitely clear goal to reduce GHG emission for creating international acceptances is necessary for Thailand.

Palm oil extraction industry is one of the most important industries in Thailand. The crude palm oil (CPO) extraction processes are classified into wet and dry extraction. The wet extraction process is commonly used in the palm oil mills regard to the high production capacity and self-sufficient regarding energy. The fresh fruit bunches (FFB) from cultivators or collection points are transported to the palm oil mill by pick-up trucks or trucks for immediate processing. The wet extraction process of CPO includes: sterilization, fruit separation, digestion, oil extraction and oil purification. The CPO and palm kernel (PK) are the main products of the palm oil mills. Shells and fibers are by-products. Empty fruit brunches (EFB) and decanter cakes are considered as wastes. For some mills, PK is pressed in order to produce palm kernel oil (PKO) as product. In wet extraction, GHG is emitted from the acquisitions of raw material, energy use, chemicals use, processing, transportation and wastewater treatment. From the previous chapter, the total CPO production in Thailand in year 2010 by wet extraction process emitted total GHG approximately 1.20 million Mt of CO_2eq. The major GHG emitted sources were from

FFB production and wastewater treatment system. The installation of biogas capture system in the wastewater treatment plant of palm oil mill without biogas capture system could reduce GHG emission by 24% of total GHG emission from the mill. This can be proud that palm oil mills have a potential to reduce GHG emission. For the mills with biogas capture system, they could emit GHG of 883 kgCO_2eq/Mt CPO. However, GHG reduction options for the wastewater treatment plant of the mills with biogas capture system have never been reported. In order to promote the sustainable palm oil production, GHG emissions from the wet extraction process with and without biogas capture system are required to be reduced. The main objective of this study, therefore, is to provide the GHG emission optimizations for the CPO production by wet extraction mills with and without biogas capture system.

4.2 Methodology

The research is aimed to develop GHG emission optimization options and to estimate GHG reduction for palm oil mills in Thailand. This study was conducted for CPO production by wet extraction process. Six palm oil mills with CPO production capacity from 15 to 90 Mt FFB per hour were selected for the study. They were accounted approximately for 11.9 % of total CPO production capacity in Thailand in the year 2010. The selected mills were located at Chonburi, Phangnga, Krabi, Suratthani, Trang and Satun provinces. This study considers GHG addressed by the Kyoto protocol (UNFCCC 1998). GHG emission values of the mills in this study were calculated on 2 scenarios according to the wastewater treatment plants: scenario (I) mills with biogas capture plants (4 mills) and scenario (II) mills without biogas capture plants (2 mills). The study used methodology developed in the previous chapter to calculate GHG emission from the mills. The life cycle assessment (LCA) (International Organization for Standardization, ISO 2006a, 2006b) was applied to estimate GHG emitted source through cradle to gate analysis. The system boundary of analysis included production of inputs (FFB, chemicals, fossil fuel, and electricity), transportation, manufacturing process along with management of generated waste (wastewater and chemical packaging) as shown in Figure 4.1. Both primary and secondary inventory data in relation to GHG calculation for a period of one year in 2010, for instance, amount of raw materials, distance of transportation, volume of wastewater and wastewater quality were collected from each mill. Questionnaires, on site interview, surveying and sampling were strategy for primary data collection. The secondary data, emission factors (EFs) and global warming potentials (GWP) of GHG used for calculation in the study were taken from TGO (2011a) and Intergovernmental Panel on Climate Change (IPCC) (2007). After analyzing of GHG emission from each section within the scope of the study, sources of GHG emission from most to least could be estimated. The potential alternatives for GHG reduction have been identified and designed without taking the cost into account. Moreover, the GHG emission reduction value of each alternative was determined.

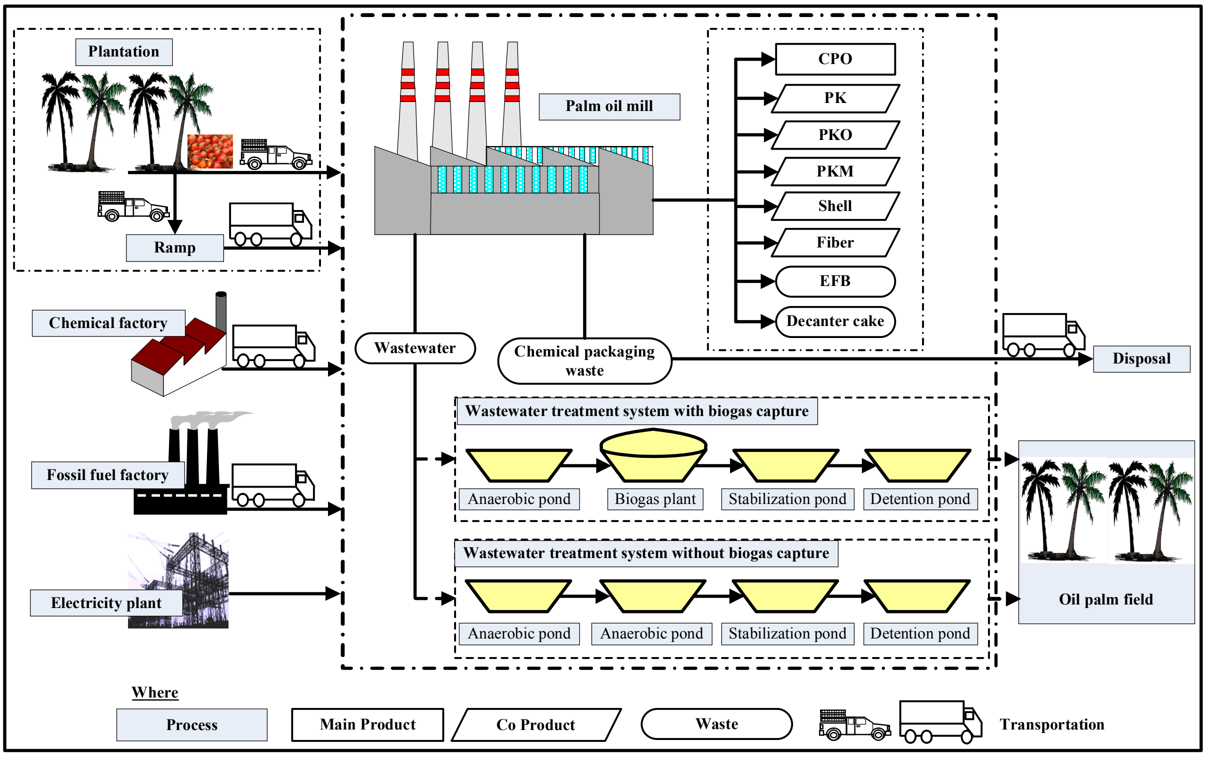

Figure 4.1 System boundary of this study

4.3 Results and discussion

4.3.1 Amount of GHG emission from the palm oil mills

The GHG was emitted at various points in system boundary including (1) indirect emission from production of inputs (FFB, chemicals, fossil fuels and electricity) (2) direct emission from transportation of inputs to mill, (3) direct emission related to production process and waste treatment at the mill such as on-site fossil fuel combustion, wastewater treatment and packaging disposal. The GHG emission contributions of scenario (I), scenario (II), average GHG emissions (both mills with and without biogas capture), and best observed case are shown in Table 4.1. For comparison, 1 Mt of CPO production in scenario (I), scenario (II), average GHG emission, and best observed case emitted 883, 1,164, 935, and 548 $kgCO_2eq$ respectively. The different values of GHG emission between scenario (I) and scenario (II) in this study were due to wastewater treatment with and without biogas capture system. From Table 4.1, the mills with biogas capture had GHG emission less than the mills without biogas capture by 24% on average. Moreover, the average GHG emission value of these results can be used to calculate total GHG emission from CPO production in Thailand. By multiplying the average value of GHG emission with total CPO production was approximately 1,287,510 Mt in 2010 (Food and Agriculture Organization of the United Nations, FAO 2012). The palm oil mills would cause GHG emission about 1.20 million Mt of CO_2eq.

4.3.2 GHG emitted sources

GHG emission sources were divided into 3 sources: (1) FFB acquisition, (2) wastewater treatment system and (3) processing. The major GHG emission source in Figure 4.2 for scenario (I) were from FFB acquisition 55.8% of the total GHG emission followed by 42.0 and 2.20% GHG emission from wastewater treatment system and processing, respectively. GHG emission from scenario (II) were most observed to be from wastewater treatment system of 63.9% of the total GHG emission, followed by the FFB acquisition of 32.3% and processing of 3.80%. By considering the average GHG emission value, the FFB acquisition was the dominant GHG emitted sources for 6 mills. It accounted for 50.4% of total GHG emission followed by 47.0 and 2.60% GHG emission from wastewater treatment system and processing, respectively. In the case of the mill with emitted the lowest GHG, 70.1% of total GHG emission came from the acquisition of FFB, followed by wastewater treatment system of 23.0% and processing of 6.90 %.

In summary, the FFB acquisition and the wastewater treatment process generated GHG more than 90% of total GHG emission from the mills. The less was from using chemicals, fossil fuel and electricity in the process.

Table 4.1 GHG emission of palm oil production by wet extraction process

Emission source	GHG emission[1] (kgCO$_2$ eq/ Mt CPO)			
	Scenario (I)	**Scenario (II)**	**Average GHG emission**	**Best observed case**
1 FFB acquisition	**493**	**376**	**471**	**384**
- Production	438	339	420	336
- Transportation	54.6	36.8	51.4	48
2 Chemicals	**4.57**	**6.36**	**4.90**	**6.77**
- Production	3.49	4.83	3.74	4.58
- Transportation	0.92	1.35	1.00	1.94
- Packaging disposal	0.16	0.18	0.16	0.25
3 Fossil fuel	**11.5**	**9.27**	**11.1**	**16.8**
- Production	1.05	0.84	1.01	1.53
- Transportation	0.04	0.06	0.04	0.11
- Combustion	10.4	8.37	10.0	15.2
4 Electricity consumption from external source	**3.23**	**29.5**	**8.06**	**14.6**
5 Wastewater from production process	**371**	**744**	**440**	**126**
Total	**883**	**1,164**	**935**	**548**

Remark: [1]Weighted average

4.3.2.1 FFB acquisition

Considering the breakdown of average GHG emission of the FFB acquisition from 6 mills is presented in Figure 4.3. The major source of GHG emission originated from plantation of 89.1% of total GHG emission in part of the FFB acquisition and from transportation of 10.9% of total GHG emission. GHG emission sources in section of oil palm plantation arose from (1) production of inputs such as fossil fuel, agrochemicals, electricity, organic and inorganic fertilizers, (2) transportation of inputs to oil palm plantation, (3) applying of inputs and (4) waste disposal from oil palm plantation (Deutsche Gesellschaft für Internationale Zusammenarbeit, GIZ 2012). A lot of GHG was emitted due to production and application of organic and inorganic nitrogen fertilizers. It caused nitrous oxide (N_2O) emission to atmosphere (Wicke *et al.* 2008). GWP of N_2O for 100 years is 298 times of CO_2eq (Forster *et al.* 2007). Therefore, the optimization of GHG emission of the acquisition of FFB must be emphasized promptly.

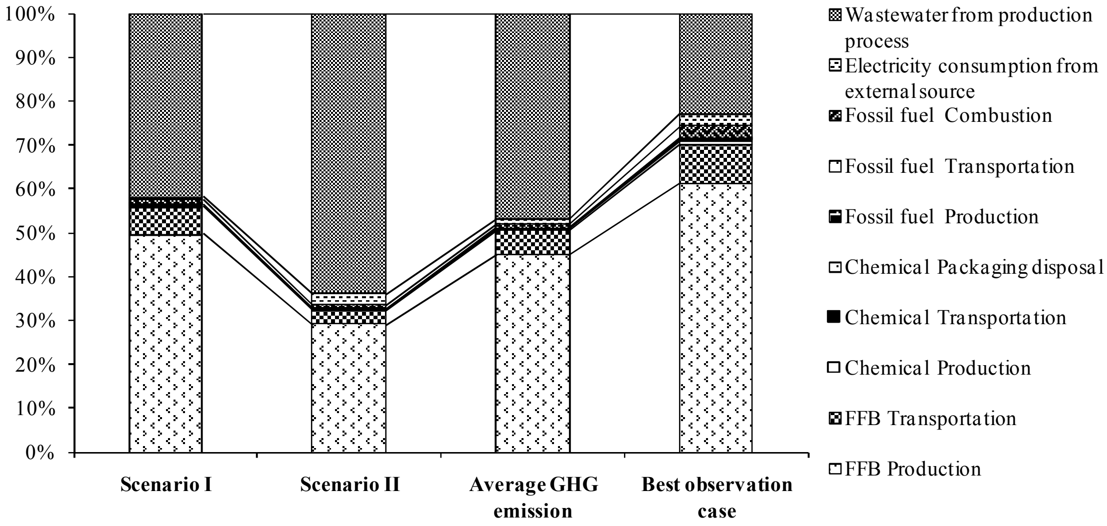

Figure 4.2 Percent distributions of GHG emission from palm oil mills

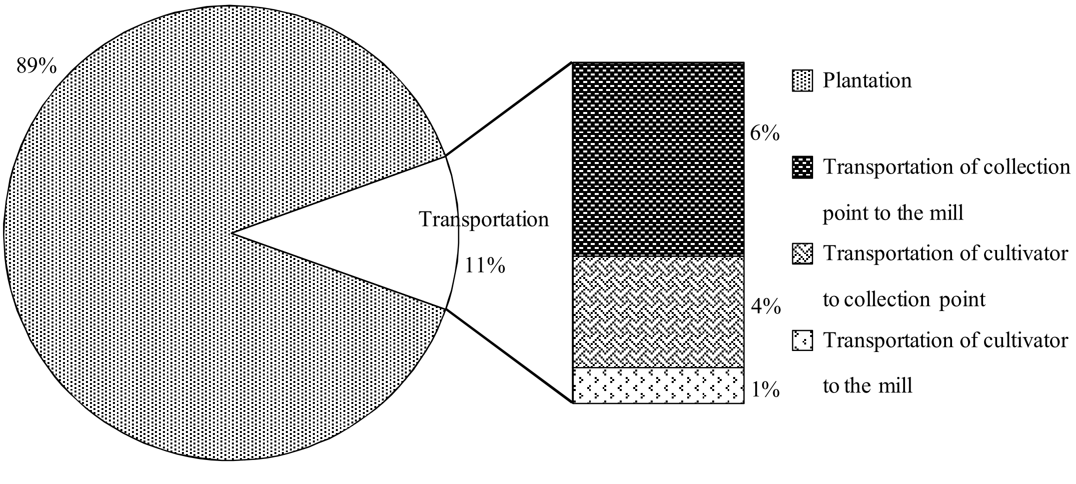

Figure 4.3 Breakdown of GHG emission of the FFB acquisition

4.3.2.2 Wastewater treatment plant

The traditional practice uses waste stabilization ponds which consist of anaerobic ponds, aerobic ponds and retention ponds for treating the wastewater from process. Currently, the wastewater treatment is upgraded to biogas system and biogas is used to generate the electricity by gas engine. The produced electricity is used in the mill and the excess electricity is sold to provincial electricity authority (PEA), Thailand by grid connection. The treated wastewater from biogas plant is flowed to the stabilization ponds. Then, it is stored in the retention ponds or discharged into palm oil plantation fields.

In general, the tradition wastewater treatment process, GHG was emitted from anaerobic and unmanaged aerobic ponds. For the wastewater treatment process with biogas system, sources of GHG emission originated from open ponds before biogas system, flaring of biogas, fugitive emission due to inefficient biogas capture system, and stabilization ponds after biogas system. Figure 4.4 shows average percent distributions of GHG emission of each process in wastewater treatment plants of 4 mills in scenario (I), 2 mills in scenario (II), and 1 mill in best observed case. As can be seen in Figure 4.4, the open ponds were the main cause of action that emitted GHG by 44% of total GHG emission in scenario (I) followed by 18% from biogas system and 38% from stabilization ponds. For scenario (II), total GHG emission arose from only open ponds. By considering the best observed case, the mill used sedimentation tank and tower system instead of open pond to cool down temperature of wastewater from the production process, therefore, there was no GHG emission from this system. GHG emissions from biogas system and stabilization ponds were 50% of total GHG emission.

4.3.2.3 Wet extraction process

In processing section, the major sources of GHG emission were chemicals used, fossil fuel used, and electricity supply from PEA. Since, fibers has been used as the biomass fuel in the boiler to produce steam to generate electricity for using in the mills, therefore, they required only less amount of electricity from PEA.

In some mills, there was a diesel generator for the start up of the process but some mills started up the process by electricity from PEA. In the case of the mills with biogas capture system, 0.52, 0.37 and 1.30% of total GHG emission were due to the use of chemicals, electricity and fossil fuel, respectively, as shown in Figure 4.2. For the mills without biogas capture system, 0.55, 2.53 and 0.80% of total GHG emission were from chemicals, electricity and fossil fuel used, respectively. Considering the average value, the GHG emission of 0.53, 0.86 and 1.19% were generated from the chemicals, electricity and fossil fuel used, respectively. In the case of best observed case, 1.24, 2.65 and 3.07% of total GHG emission were due to utilization of chemicals, electricity and fossil fuel, respectively. Regard to the low GHG emission from this section, it may be an unnecessary attempt to reduce GHG emission from the production process.

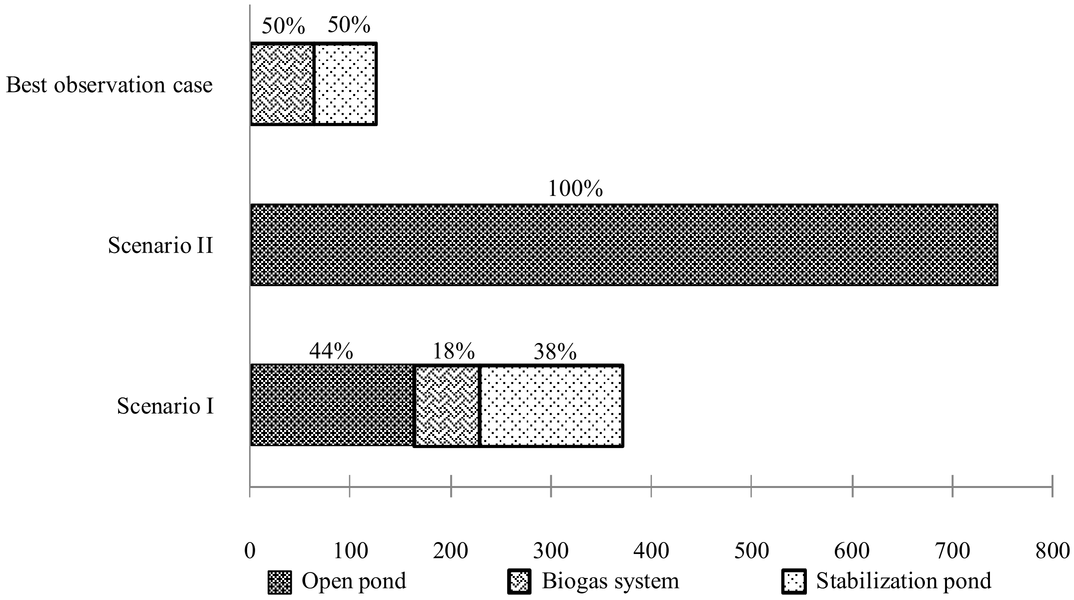

Figure 4.4 Breakdown percent distributions of GHG emission from wastewater treatment plant

4.3.3 GHG optimization

4.3.3.1 FFB Management

FFB are the main raw material in CPO production. FFB acquisition was accounted for 50.4% of the total GHG emission from 6 mills. The main cause is from nitrogen fertilizer usage in oil palm plantation (GIZ 2012), which accounted for approximately 80% of all GHG emission. Many studies suggesting the reduction of GHG emission from using nitrogen fertilizer include Ball *et al.* (2004), Smith *et al.* (2008), International Federation of Organic Agriculture Movements, IFOAM (2009) and International Fertilizer Industry Association (2010). Nitrogen use efficiency of oil palm must be improved to mitigate N_2O emission by reducing losses from volatilization, de-nitrification, leaching and surface run-off (Schlesinger 1999; Department of Agricultural Extension, DOAE 2011). The application of osmocote fertilizer which is slowly soluble could gradually release nitrogen nutrients over a chosen period of time (Limpiyaparapant *et al.*2002). It could control microbial transformation for slowing down N_2O emission (Ball *et al.* 2004). Moreover, fertilizer should be fed according to the required amount of plant to avoid nitrogen in excess of oil palm need, since the available nitrogen amount in soil correlates with N_2O emission (Smith and Conen 2004; Oenema *et al.* 2005; McSwiney and Robertson 2005). The partial nitrogen fertilizer was commonly applied on the surface, hence, fertilization by injecting into the soil, near the more accessible zone to root uptake should be performed. This practice help to both increase nitrogen use efficiency of oil palm and reduce nitrogen loss which result in mitigating of GHG emission (Paustian *et al.* 2006). Furthermore, substitution of organic fertilizer for inorganic fertilizer was proposed by GIZ (2012). The minimal amounts of several nutrients (P, K, N, Ca, Mg, S, Fe, Cu, Zn, Mn, B, and Mo) are included in animal manures. From the study of GIZ (2012), 1 kg of nitrogen nutrients from inorganic fertilizer can be replaced by 62 kg of animal manure or 57 kg of pellet-organic fertilizer. This can reduce GHG emission about 2.6 and 2.7%, respectively.

Considering oil extraction from FFB, if the oil yield in FFB is increased, the mill will gain large amount of CPO after extraction. The GHG emission per Mt of CPO, therefore, must be reduced. It means that in addition to the good agricultural practice, cultivators should select and plant the best palm seeds to get a high quality of FFB. Cultivators must harvest the FFB at the right time and transport to the mill within 24 hours. The mill should provide incentive to the cultivators for supplying high quality FFB.

The transport of FFB to the mill accounted about 5.49% of the GHG emission from 6 mills. Therefore, the logistic approach should be used for transportation of FFB. If most of the cultivators use pickup trucks to transport FFB from far away farm to the mill, more GHG emission will occur. At 10 km away from the mill, transportation by pickup truck will emit 1.84 kg CO_2eq per Mt FFB while at 30 km away from the mill; it could generate 5.53 kg CO_2eq per Mt FFB. The use of collection point to collect FFB and transport full load of 10-wheel truck will help reduce GHG emission by 51.4% from transportation by pickup trucks. However, the mill and the government should give advice to the collection point to transport FFB to the mill within 24 hours.

4.3.3.2 Process optimization

The objective of palm oil extraction is to get high oil extraction rate (OER) from the FFB. The OER of palm oil mills in this study ranged from 15.2 to 19.3% and the average OER of 6 mills was 17.0%. The GHG emission from FFB plantation was 420 kgCO_2eq per Mt CPO. By multiplying with total CPO of 1,287,510 Mt in year 2010, 0.54 million Mt of CO_2eq per year will be emitted. The higher OER, the more CPO will be obtained and the less GHG emission will occur. If the OER has improved to a maximum value at 19.3% less amount of FFB will be used to extract 1 Mt of CPO. Therefore, the improving of OER from the average of 17.0% to the maximum value of 19.3% can reduce GHG emission by 15.0% of total GHG emission from FFB acquisition or 0.10 million Mt of CO_2eq per year in 2010.

During processing 2 sources of electricity are used, one from PEA and another from the steam turbine by using the fibers as the biomass fuel. Some mills use diesel engine to generate electricity to start up the process. By using the PEA electricity to start up the process, it could reduce the GHG emission from diesel. The mill generates electricity from steam turbine to use in all process. Palm fibers must be mainly used as fuel in the boiler. The boiler must be efficiently operated in order to save fibers and selling what are left to the power plant. Thus, the more fibers sold to the power plant the more GHG reduction due to the utilization of fibers as biomass fuel instead of using fossil fuel for electricity generation. How to operate the boiler efficiency, firstly, fibers must be dried which will increase calorific value. Secondly, process optimization must be operated to minimize steam used in the processing line. Thirdly, an economizer must be applied and some heat lost must be recovered to warm up the feed water or to pre-heat the combustion air before using in the boiler. Fourthly, excellent treatment of water for high quality feed water is needed and the automatic controlled blow down is required due to huge energy losses through the blow down.

During processing, the oil loss must be monitored and kept under control. The oil loss to fibers, decanter cake and wastewater must be minimized in order to get more CPO. The loss of the palm kernel to the fibers and shells during air (density) separation must be reduced (Energy & Eco-efficiency in Agro Industry 2006a, 2006b)

Many heavy machines in the mill such as screw press, decanter, separator, EFB presser and cutter are used. All machines must be used at full capacity with minimal empty load. Improvement of operational procedures and preventive maintenance are needed to ensure that the equipment is efficiently utilized and does not break down. The energy management must be implemented to identify the factors causing bad performance. The actions must be taken to find the cause and develop operational guideline to prevent machine break down. The energy efficient equipment must also be used to replace obsolete ones.

4.3.3.3 Wastewater management

4.3.3.3.1 Wastewater treatment process without biogas capture system

For the wastewater treatment process without the biogas capture system, the simple practice is to establish the biogas capture system in the wastewater treatment plant, since the biogas capture system could reduce GHG emission from wastewater treatment by 50%. The full upgraded the wastewater treatment plant to biogas capture system could provide the better efficiency in treating of wastewater and producing the biogas for electricity generation. Chavalparit *et al.* (2006b) reported that construction costs of a closed anaerobic tank system for a mill with capacity of 45 Mt FFB per day including gas engines for electricity production from biogas with capacity of 300-400 kilowatts were estimated at 19 million Baht (or 10,000 Baht/m^3 of wastewater per day). The payback time for this system, when calculating the saved electricity as an income, was thus about 4.3 years. However, the investment cost of this system is considerably high. The covered anaerobic pond could be done since it is more economic. Although the biogas system was employed, it still emitted GHG in some points due to the open ponds, fugitive emission of biogas system, flaring of biogas, and stabilization ponds. It must be advantageous to consider the GHG reduction methods of these sources in the next section.

4.3.3.3.2 Wastewater treatment process with biogas capture system

The major source of GHG emission from wastewater treatment process with biogas capture system are 1) open ponds before biogas system 2) flaring of biogas and fugitive emission due to inefficient biogas capture system, and 3) the stabilization ponds after biogas system. In general, the variation of influent wastewater flow rate, biochemical oxygen demand (BOD) and chemical oxygen demand (COD), and wastewater temperature could affect the performance of wastewater treatment plant. The equalization tank, therefore, is used to overcome this variation. Presently, several wastewater treatment plants of the mills utilize the open ponds as equalization unit for reducing wastewater temperature from approximately 80 °C to 55 °C. After temperature is decreased, the wastewater is feed to the biogas system.

Regard to the high COD value in influent wastewater into the open pond, the anaerobic degradation occurred. In this study, the average COD of raw wastewater of 93,044 mg/L could be decreased by anaerobic degradation in the open pond by 22% to 73,027 mg/L. This lost organic was converted to GHG of about 216 kg CO_2eq /Mt CPO. The aim of this section, therefore, is to provide the practical methods to reduce the GHG emission from the open ponds, biogas system, and stabilization ponds after biogas system as shown in Figure 4.5.

Option I: Using air-stripping tower to reduce wastewater temperature

In general, the open pond was employed for reducing the temperature and the variation of raw wastewater. It emitted high amount of GHG. In order to avoid this GHG emission, an air stripping is introduced to be instead used. By using the air stripping tower, the GHG emissions from the anaerobic degradation was considerably minimized, however, it required the energy to pump the wastewater up to the certain level. The total yearly amount of CPO, wastewater volume, characteristic of raw wastewater and treated wastewater through COD reduction efficiency of biogas system were averaged from 4 mills in scenario (I) as shown in Table 4.2. In calculation, the height of air stripping tower was defined at 15 meters and 1.5 kilowatts of pump was required for operating 24 hours per day in 300 days per year. The GHG emission of 0.19 kg CO_2eq/Mt CPO was generated from electricity demand by using the air stripping tower. So, the total GHG emission reduction should be 216 kg CO_2eq/Mt CPO or 99.9% if the air stripping tower is used instead of open pond in wastewater treatment system. Palm oil mill wastewater contains high oil and grease. If it could not be removed properly from wastewater, it could decrease the performance of the air stripping tower. The setting tank or oil traps, therefore, must be installed to remove oil and grease from wastewater prior to feeding to air stripping tower.

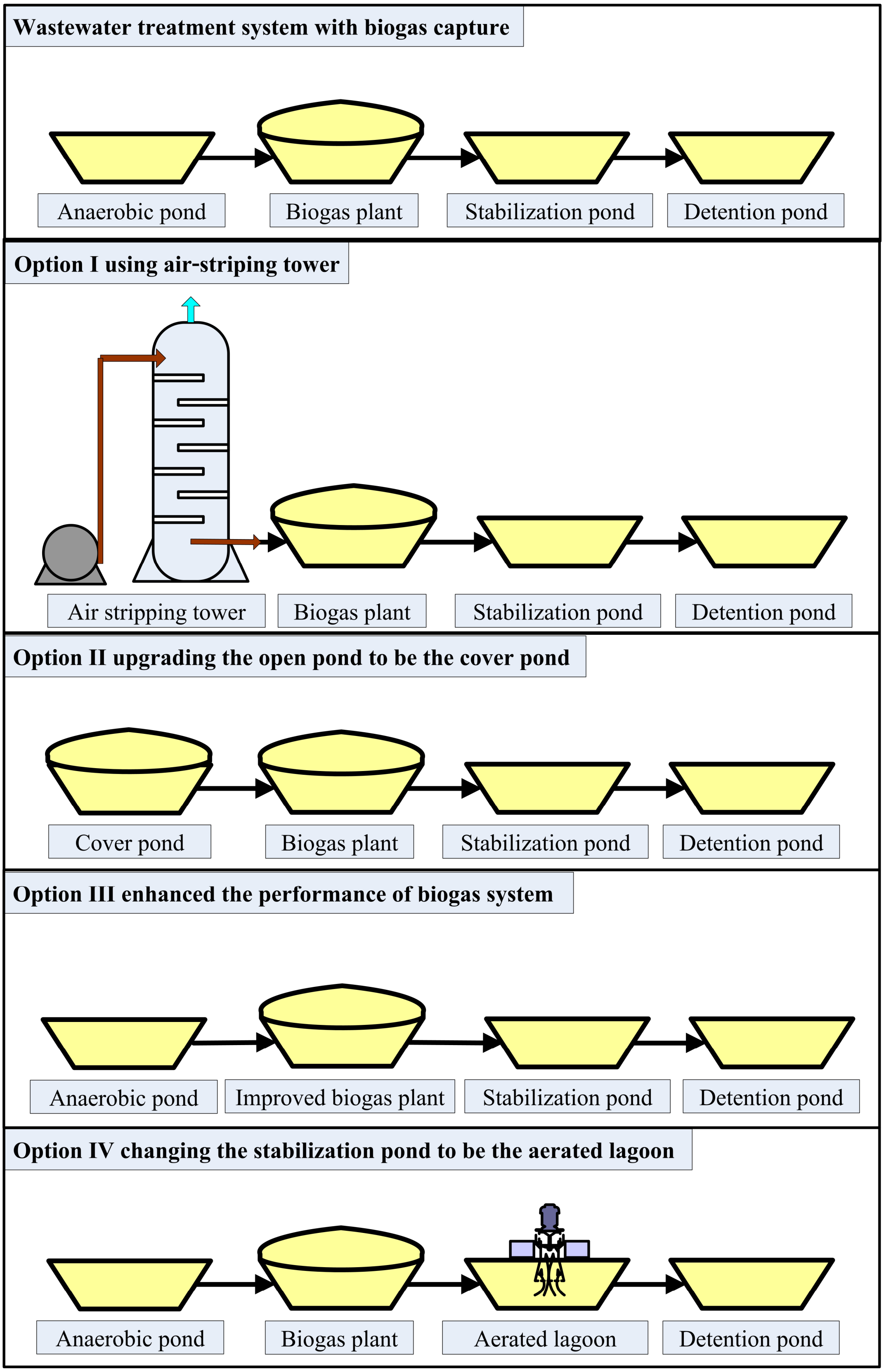

Figure 4.5 Options for wastewater treatment process with biogas capture system

Table 4.2 Total yearly amount of CPO, wastewater volume, characteristic of raw wastewater and treated wastewater, and COD reduction efficiency of biogas system

Parameters	Average values[1]	minimum-maximum[2]
Total yearly amount of CPO, Mt	31,297	11,840 - 46,251
Wastewater volume, m^3/year	75,929	33,075 - 107,000
COD of influent wastewater, mg/L	93,044	53,082 - 124,342
COD of influent into biogas system, mg/L	73,027	52,576 - 92,516
COD of effluent from final pond, mg/L	4,694	488 - 13,437
COD reduction efficiency of biogas system, percent	81	65 - 93

Remark: [1]The average value of 4 mills

[2]The values were obtained from individual mill

Option II: Upgrading the open pond to be the covered pond

From this study, wastewater of palm oil mills was discharged at temperatures about 65-80 °C which in fact wastewater can be treated at both thermophilic and mesophilic temperatures (Poh and Chong 2009). Several researches have been studied the practicability of wastewater treatment from palm oil mill in thermophilic temperature range such as Choorit and Wisarnwan (2007) and Sattaphai (2009). Cail and Barford (1985) reported that palm oil mill effluent (POME) treatment at the thermophilic temperature had treatment rates more than four times faster than treatment at the mesophilic temperature. This confirms that biogas can be actually generated in open pond.

As stated previously, the GHG emission from the open pond was 216 kg CO_2eq /Mt CPO. By upgrading the open pond to be the covered pond and using biogas for electricity generation, the GHG emission of about 21.6 kg CO_2eq/Mt CPO could come from the fugitive emission. The GHG reduction is 194 kg CO_2eq/Mt CPO. In addition, the collected biogas could be used to generate the electricity by gas engine. Chotwattanasak and Puetpaiboon (2011) reported that electricity of 2.5 kilowatt hours can be generated from 1 m^3 of biogas. Chavalparit *et al.* (2006b) estimated amount of the produced biogas in the first anaerobic pond of about 0.3 m^3 per kg BOD removed or 6 m^3 of CH_4 per Mt FFB.

By using the data in Table 4.2, the generated amount of biogas and electricity could be calculated. The COD/BOD ratio of POME was of about 1.56 (Choorit and Wisarnwan 2007). It can be used to convert the COD removal of 20,017 mg/L in open ponds to BOD removal of 12,831 mg/L. This BOD removal is converted to biogas of about 292,283 m^3 per year by using the value of 0.3 m^3 biogas per kg BOD removed. The amount of biogas produced can be used to generate the electricity of 730,707 kilowatt hours per year. The GHG reduction due to the replacing of electricity from fossil fuel by electricity from biogas is 13.1 kg CO_2eq/Mt CPO. The total GHG emission reduction for applying this option is 208 kg CO_2eq/Mt CPO. However, increasing efficiency of the covered pond can be achieved by fully recovering oil and grease with oil traps prior to feeding wastewater into the covered pond.

Option III: Enhanced the performance of biogas system

Regard to this study, the efficiency of biogas plants in scenario (I) ranged from 65 to 93% with the average value of 81%. As mentioned earlier, the treated wastewater from the biogas system was fed to the stabilization ponds. The remaining organic in this wastewater was treated under anaerobic condition in stabilization ponds and emitted GHG in significant values. By enhanced the performance of the biogas system, the level of organic matter in treated wastewater should be decreased. It could lead to the decreasing of GHG emission from anaerobic degradation in the stabilization pond system.

The calculation of GHG reduction by enhanced the performance of the biogas system was conducted by using the data in Table 4.2. The lowest and highest efficiency of biogas system was set at 65 and 93%, respectively. The incremental of biogas efficiency of 5% was used in calculation and the base value of biogas efficiency was set at 80%. The practices to improve the performance of the biogas system consist of many factors. The few major factors are pH, nutrients for bacteria, temperature for operating, mixing and organic loading rates into the digester (Poh and Chong 2009). The pH should be maintained near 7.0 and the COD: N: P ratio during startup is 300:5:1, during steady state operation of COD: N: P could be lower to 600:5:1. Moreover, the optimal temperature for operating of biogas is classified into two ranges (1) 25- 38 °C and (2) 50-70 °C. The alkalinity ranged from 2,000 to 4,000 mg/L as $CaCO_3$ are typically required (Metcaft and Eddy 2004). However, the study of Chaiprapat and Laklam (2011) reported that producing the biogas in higher quantity and methane composition from POME by using the anaerobic sequencing batch reactor (ASBR) could be achieved at high organic loading, shorter cycle time and longer hydraulic retention time. This shown that it is necessary to expand the size of the biogas system so that POME can remain in the system longer.

The summary of GHG emission from enhanced performance of biogas system is presented in Figure 4.6. By improving the efficiency of the biogas system from 65% to the base value of 80%, the GHG emission was reduced by 106 kgCO_2eq/Mt CPO. In the case of increasing in efficiency from 65% to the highest value of 93%, the GHG emission was reduced by 199 kgCO_2eq/Mt CPO. Moreover, only increasing in efficiency from the base value of 80% to the highest value of 93%, it could reduce GHG emission of 92.2 kgCO_2eq/Mt CPO.

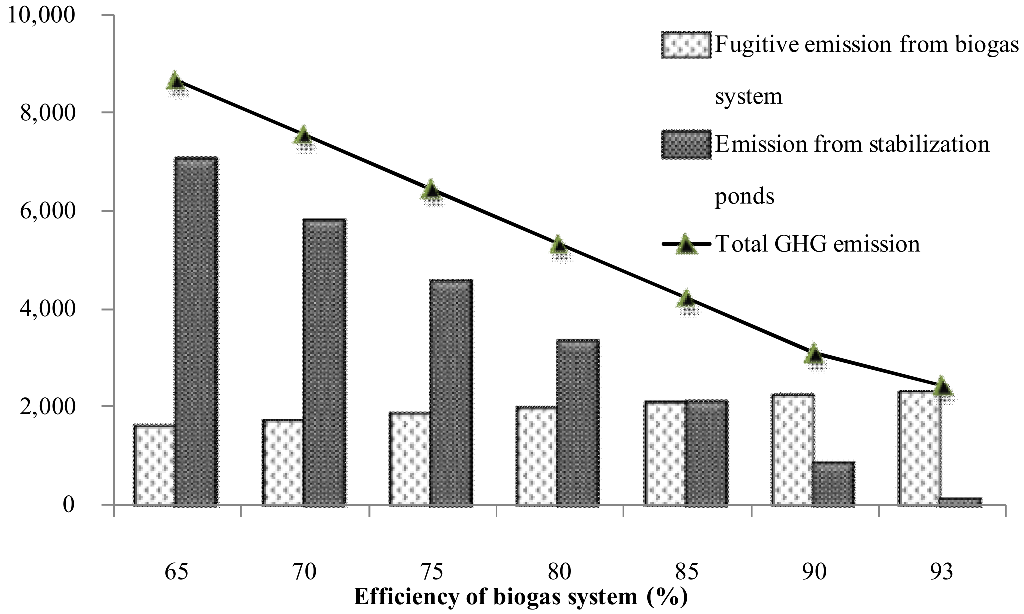

Figure 4.6 GHG emissions from biogas system and stabilization ponds based on efficiency of biogas system

Option IV: Changing the stabilization pond to be the aerated lagoon

In this case, the aerated lagoon is introduced to use instead of stabilization pond. By using the aerated lagoon, it could avoid the anaerobic degradation in the anaerobic pond. According to the information of IPCC (2006), methane correction factor (MCF) of aerobic treatment is divided into 2 cases (1) aerobic treatment, well managed, and (2) aerobic treatment, poorly managed or overload. However, the aerobic treatment with well manage is considered in this study. When the aerated lagoon is applied, it is required the electricity for operation of aerators. This electricity consumption must be taken into the GHG emission calculation. For calculation results, the stabilization pond emitted GHG of about 107 kg CO_2eq/Mt CPO, whereas by using the aerated lagoon, the GHG emission is 23.6 kg CO_2eq/Mt CPO. Therefore, the total GHG emission reduction is equal to 83.5 kg CO_2eq/Mt CPO or 78.0%.

4.4 Conclusions

This study has analyzed GHG emission sources and proposed approaches to reduce GHG emission from palm oil production by wet extraction process in Thailand. The FFB acquisition and wastewater treatment system were estimated as hot spots of GHG emitted sources from palm oil mills. GHG emission mitigation from oil palm plantation could be achieved by improving the efficiency of nitrogen use by oil palm. The losses from volatilization, de-nitrification, leaching and surface run-off of nitrogen fertilizer should be minimal. A new policy from government or related agencies to control and stimulate for good management of cultivator must be promulgated and established. For processing, by increasing the percent yield of CPO production by 1% from the average percent yield, it could reduce GHG emission by 27.0 kg CO_2eq/Mt CPO. However, significant GHG emission reduction can be accomplished through management of the wastewater treatment plant with and without biogas capture system. By establishing the biogas capture system, it could reduce GHG by 372 kg CO_2eq/Mt CPO of the total GHG emission from wastewater treatment process without the biogas capture system. For the existing wastewater treatment plant with biogas capture system, option I using air stripping tower for cooling down the temperature, the GHG reduction of 216 kg CO_2eq/Mt CPO was obtained. Option II, the covered pond practice could reduce GHG emission by 208 kg CO_2eq/Mt CPO. Option III the practical method of enhancing the performance of biogas system was introduced. By improving the efficiency of the biogas system from 65% to the base value of 80%, the GHG emission was reduced by 106 kgCO_2eq/Mt CPO. In the case of increasing in efficiency from 65% to the highest value of 93%, the GHG emission was reduced by 199 kg CO_2eq/Mt CPO. Moreover, only increasing in efficiency from the base value of 80% to the highest value of 93%, it could reduce

GHG emission by 92.2 kg CO_2eq/Mt CPO. Finally, option IV by changing the stabilization pond to aerated lagoon system; it could reduce GHG emission by 83.5 kg CO_2eq/Mt CPO.

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APPENDICES

APPENDIX A

EXAMPLE OF DATA COLLECTION TEMPLATE

Example of data collection template

As data requirement for calculation, the examples of table for data gathering are provided as the following.

1) Production process data

Table A-1: List of engine used in production process

No.	Section	Name of engine	Quantity	Capacity (kW)	Total capacity (kW)

2) Input

Table A-2: Detail of FFB and palm fruit transport (yearly data)

Departure-Arrival	Supplier	Distance (km)	Type and size of vehicle	Type of fuel use in vehicle	% FFB Purchase
Farmer-Factory	No.1				
	No.2				
	No.3				
	No.4				
	No.5				
	No.6				
	No.7				
Collection point-Factory	No.1				
	No.2				
	No.3				
	No.4				
	No.5				
	No.6				
	No.7				

Table A-3: Yearly FFB and palm fruit purchasing

Month	FFB		Palm fruit		Total palm (Mt)
	Quantity (Mt)	Average price (bath/ Mt)	Quantity (Mt)	Average price (bath/ Mt)	
January					
February					
March					
April					
May					
June					
July					
August					
September					
October					
November					
December					
Total					

Table A-4: Detail of chemicals and material transport (yearly data)

Chemical/ Material Name	Supplier	Departure-Arrival	Distance (km)	Type and size of vehicle	Type of fuel use in vehicle	Quantity (kg)

Table A-5: Yearly water supply

Month	Water consumption (m^3)	Chemicals use in water supply		
		No.1 (kg)	No.2 (kg)	No.3 (kg)
January				
February				
March				
April				
May				
June				
July				
August				
September				
October				
November				
December				
Total				

Remarks: 1) Chemical No.1 is …………………………

2) Chemical No.2 is ……………………….....

3) Chemical No.3 is ……………………….....

Table A-6: Yearly electricity consumption

Month	Electricity consumption (kWh)				Remark
	Sold from PEA	Generated in stream boiler (Biomass)	Generated in diesel generator	Generated in gas engine (Biogas)	
January					
February					
March					
April					
May					
June					
July					
August					
September					
October					
November					
December					
Total					

Table A-7: Detail of fuel (biomass, diesel fuel) transport (yearly data)

Fuel Type	Supplier	Departure-Arrival	Distance (km)	Type and size of vehicle	Type of fuel use in vehicle	Quantity (kg/L)

Table A-8: Quantity of biomass fuel use in boiler and stream generation

Month	Biomass Fuel no.1 (Mt)	Biomass Fuel no.2 (Mt)	Stream generation (Mt /hr)	Electricity Generation (kWh)	Remark
January					Biomass fuel no.1 is ……………..
February					1) Moisture content ……….%
March					2) LHV …..…BTU/kg
April					Biomass fuel no.2 is ……………..
May					3) Moisture content ……….%
June					4) LHV …..…BTU/kg
July					
August					
September					
October					
November					
December					
Total					

Table A-9: Fossil fuel consumption

Month	Diesel generator (L)		Internal transport (L)		Other use (L)	
	Fuel oil	Diesel	Diesel B5	Diesel	Diesel	Diesel B5
January						
February						
March						
April						
May						
June						
July						
August						
September						
October						
November						
December						
Total						

Table A-10: Chemicals consumption (excluding in water supply)

Month	Chemicals use in boiler (kg)		Chemicals use in production process (kg)		Chemicals use in wastewater treatment system (kg)		
	No.1	No.2	No.3	No.4	No.5	No.6	No.7
January							
February							
March							
April							
May							
June							
July							
August							
September							
October							
November							
December							
Total							

Remarks:
1) Chemical No.1 is ………………………… Formula …………………….
2) Chemical No.2 is ……………………….... Formula …………………….
3) Chemical No.3 is ……………………….... Formula …………………….
4) Chemical No.4 is ……………………….... Formula …………………….
5) Chemical No.5 is ……………………….... Formula …………………….
6) Chemical No.6 is ……………………….... Formula …………………….
7) Chemical No.7 is ……………………….... Formula …………………….

3) Output

Table A-11: Production of CPO, CPKO and Palm kernel

Month	CPO		CPKO		Palm Kernel		Remark
	Quantity (Mt)	Average price (bath/ Mt)	Quantity (Mt)	Average price (bath/ Mt)	Quantity (Mt)	Average price (bath/ Mt)	
January							
February							
March							
April							
May							
June							
July							
August							
September							
October							
November							
December							
Total							

Table A-12: By-product generation

Month	EFB		Fiber		Shell		PKE		Decanter cake	
	Quantity (Mt)	Average price (bath/ Mt)	Quantity (Mt)	Average price (bath/ Mt)	Quantity (Mt)	Average price (bath/ Mt)	Quantity (Mt)	Average price (bath/ Mt)	Quantity (Mt)	Average price (bath/ Mt)
January										
February										
March										
April										
May										
June										
July										
August										
September										
October										
November										
December										
Total										

Table A-13: By-product management

By-product	Management method	Quantity (Mt)	Quantity (%)	Remark
EFB	1)			
	2)			
	3)			
Fiber	1)			
	2)			
	3)			
Shell	1)			
	2)			
	3)			
PKE	1)			
	2)			
	3)			
Decanter cake	1)			
	2)			
	3)			

Table A-14: Wastewater quality data

Month	Wastewater (m^3)	COD wastewater (mg/L)	COD Inlet to biogas (mg/L)	COD Outlet from biogas (mg/L)	COD Final pond (mg/L)	Remark
January						
February						
March						
April						
May						
June						
July						
August						
September						
October						
November						
December						
Total						

Table A-15: Biogas recovery system data

Month	Biogas generated (m^3)	Biogas Composition (%)					Electricity generated from biogas (KWh)	Flare gas (m^3)	Flare Temperature (°C)	Remark
		CH_4	CO_2	H_2S						
January										
February										
March										
April										
May										
June										
July										
August										
September										
October										
November										
December										
Total										

APPENDIX B

EMISSION FACTOR

Emission factor

Name	Emission Factor (EF)		Source of data
	Unit	Amount	
FFB production			
Small plantation in eastern part of Thailand	kg CO_2e/ Mt	71.253	Part II: Oil palm cultivation
Large plantation in eastern part of Thailand	kg CO_2e/ Mt	75.731	Part II: Oil palm cultivation
Small plantation in upper southern part of Thailand	kg CO_2e/ Mt	57.768	Part II: Oil palm cultivation
Large plantation in upper southern part of Thailand	kg CO_2e/ Mt	51.729	Part II: Oil palm cultivation
Small plantation in east southern part of Thailand	kg CO_2e/ Mt	81.579	Part II: Oil palm cultivation
Large plantation in east southern part of Thailand	kg CO_2e/ Mt	73.291	Part II: Oil palm cultivation
Small plantation in west southern part of Thailand	kg CO_2e/ Mt	71.135	Part II: Oil palm cultivation
Large plantation in west southern part of Thailand	kg CO_2e/ Mt	64.099	Part II: Oil palm cultivation
Mill with methane capture			
CPO (average from 10 mills)	kg CO_2e/ Mt	713.9768	Part III: Conversion to CPO
Shell (average from 10 mills)	kg CO_2e/ Mt	443.6784	Part III: Conversion to CPO
PK (average from 4 mills)	kg CO_2e/ Mt	507.3315	Part III: Conversion to CPO
PKO (average from 6 mills)	kg CO_2e/ Mt	632.3899	Part III: Conversion to CPO
PK meal (average from 6 mills)	kg CO_2e/ Mt	350.3400	Part III: Conversion to CPO

Name	Emission Factor (EF)		Source of data
	Unit	Amount	
Mill without methane capture			
CPO (average from 4 mills)	kg CO$_2$e/ Mt	1,034.6548	Part III: Conversion to CPO
Shell (average from 4 mills)	kg CO$_2$e/ Mt	642.9574	Part III: Conversion to CPO
PK (average from 4 mills)	kg CO$_2$e/ Mt	689.8240	Part III: Conversion to CPO
Average 14 Mills			
CPO (average from 14 mills)	kg CO$_2$e/ Mt	828.6325	Part III: Conversion to CPO
Shell (average from 14 mills)	kg CO$_2$e/ Mt	513.9268	Part III: Conversion to CPO
PK (average from 8 mills)	kg CO$_2$e/ Mt	612.5633	
Best Case (PKO + With biogas)			
CPO (average from 1 mills)	kg CO$_2$e/ Mt	415.2250	Part III: Conversion to CPO
Shell (average from 1 mills)	kg CO$_2$e/ Mt	262.6861	Part III: Conversion to CPO
PKO (average from 1 mills)	kg CO$_2$e/ Mt	409.4982	Part III: Conversion to CPO
PK meal (average from 1 mills)	kg CO$_2$e/ Mt	205.2591	Part III: Conversion to CPO
Energy			
Electricity used	kg CO$_2$e/kWh	0.5610	TC Common data, TGO
Diesel fuel-Production	kg CO$_2$e/L	0.4293	IPCC 2007, DEDE
Diesel fuel - Combustion	kg CO$_2$e/L	2.7080	IPCC 2007, DEDE

Name	Emission Factor (EF)		Source of data
	Unit	Amount	
Transportation - Transportation of FFB from plantation to collection point (10 km)	kg CO_2e/ Mt	3.93	Part II: Oil palm cultivation
- Transportation of FFB from plantation to collection point (20 km)	kg CO_2e/ Mt	7.86	Part II: Oil palm cultivation
- Transportation of FFB from plantation to collection point (30 km)	kg CO_2e/ Mt	11.79	Part II: Oil palm cultivation
- 4 wheel Pickup, 7 Mt (Full load)	kg CO_2e/ Mt -km	0.1472	TH database, TGO
- 4 wheel Pickup, 7 Mt (No load)	kg CO_2e/km	0.3270	TH database, TGO
- 10 wheel Truck-B5, 16 Mt (Full load)	kg CO_2e/ Mt -km	0.0425	TH database, TGO
- 10 wheel Truck-B5, 16 Mt (No load)	kg CO_2e/km	0.5429	TH database, TGO
- 18 wheel Truck, 32 Mt (Full load)	kg CO_2e/ Mt -km	0.0459	TH database, TGO
- 18 wheel Truck, 32 Mt (No load)	kg CO_2e/km	0.9065	TH database, TGO
- 20 wheel Truck, 32 Mt (Full load)	kg CO_2e/ Mt -km	0.0464	TH database, TGO
- 20 wheel Truck, 32 Mt (No load)	kg CO_2e/km	0.8773	TH database, TGO
- 22 wheel Truck, 32 Mt (Full load)	kg CO_2e/ Mt -km	0.0475	TH database, TGO
- 22 wheel Truck, 32 Mt (No load)	kg CO_2e/km	1.0655	TH database, TGO
- Bulk carrier	kg CO_2e/ Mt -km	0.002	TGO, European environment agency transport and environmental reporting mechanism report, 2009
- Refuse collection vehicle 10 wheel Truck-B5, 16 Mt (Full load)	kg CO_2e/ Mt -km	0.0548	TH database, TGO

Name	Emission Factor (EF)		Source of data
	Unit	Amount	
- Refuse collection vehicle 10 wheel Truck-B5, 16 Mt (No load)	kg CO_2e/km	0.5401	TH database, TGO
Chemicals Used - Alum	kg CO_2e/kg	0.2770	Ecoinvent, TGO
- Anionic polymer	kg CO_2e/kg	5.3500	Ecoinvent, TGO
- Acrylic resin	kg CO_2e/kg	2.8600	Ecoinvent 2.0, TGO IPCC 2007 GWP100a
- Acrylic acid	kg CO_2e/kg	1.4100	TGO, Ecoinvent, TGO
- Cationic polymer	kg CO_2e/kg	1.4300	TGO, Ecoinvent, TGO
- Disodium phosphate	kg CO_2e/kg	3.7700	Ecoinvent 2.0, TGO IPCC 2007 GWP100a
- Hydrochloric acid	kg CO_2e/kg	0.8960	ETH-ESU, TGO
- Kaolin	kg CO_2e/kg	0.217	Sima pro 7.0, China clay, BUWAL 250)
- Monosodium phosphate	kg CO_2e/kg	2.9500	Ecoinvent 2.0, TGO IPCC 2007 GWP100a
- Sodium carbonate	kg CO_2e/kg	1.1900	Ecoinvent 2.0, TGO IPCC 2007 GWP100a
- Sodium chloride	kg CO_2e/kg	0.2020	Ecoinvent 2.0, TGO IPCC 2007 GWP100a
- Sodium hydrosulfite (sodium dithionite)	kg CO_2e/kg	3.6000	Ecoinvent 2.0, TGO IPCC 2007 GWP100a

Name	Emission Factor (EF)		Source of data
	Unit	Amount	
- Sodium hydroxide	kg CO_2e/kg	1.2000	Ecoinvent 2.0, TGO IPCC 2007 GWP100a
- Silica	kg CO_2e/kg	0.0211	Ecoinvent 2.0, TGO IPCC 2007 GWP100a
- Urea	kg CO_2e/kg	5.5300	Ecoinvent 2.0, TGO IPCC 2007 GWP100a
- Polypropylene	kgCO_2e/kg	2.3990	Ecoinvent 2.0, TGO IPCC 2007 GWP100a
Solid waste disposal -Paper	kg CO_2e/kg	2.9300	IPCC 2006 Vol.5
-Textile	kg CO_2e/kg	2.0000	IPCC 2006 Vol.5
- Food/Sludge	kg CO_2e/kg	2.5300	IPCC 2006 Vol.5
-Wood	kg CO_2e/kg	3.3300	IPCC 2006 Vol.5
-Garden & Park	kg CO_2e/kg	3.2700	IPCC 2006 Vol.5
-Nappies	kg CO_2e/kg	4.0000	IPCC 2006 Vol.5
-Rubber and leather	kg CO_2e/kg	3.1300	IPCC 2006 Vol.5

APPENDIX C

GHG EMISSION CALCULATION METHODOLOGY AND EQUATIONS

GHG emission calculation

1. GHG calculation equation

1) Wet extraction process

For the wet extraction process, the GHG emission from raw material (FFB) acquisition, chemicals used and disposal of chemical packaging waste, energy used, transportation, and wastewater management are counted to calculate GHG emissions. From the overall diagram, the calculation is summarized as the following equation:

Each component is composted of sub-section illustrated as follow.

$$\mathbf{E}_{\mathbf{FFB}} = \mathrm{E}_{\text{FFB, production}} + \mathrm{E}_{\text{FFB, transport}}$$

The GHG emissions of FFB come from the production of FFB during plantation ($\mathrm{E}_{\text{FFB, production)}}$ and after harvesting including the transportation of EFB to the mills. For the transportation, the FFB may directly transport from the plantation to the mills or transport from the plantation to collection point and from collection point to the mills. All this transportation must be included in the calculation.

$$\mathbf{E}_{\mathbf{Chemicals}} = \mathrm{E}_{\text{Chemicals, production}} + \mathrm{E}_{\text{Chemicals, transport}} + \mathrm{E}_{\text{chemical packaging, production}} + \mathrm{E}_{\text{chemical packaging waste, transport}} + \mathrm{E}_{\text{chemical packaging waste, disposal}}$$

The GHG emission from the chemicals used in the mill are composed of 5 components: the emission of production of those chemicals, the transportation of those chemicals to the mills, the emission of production of chemical packaging, transportation of chemical packaging waste to disposal site and disposal of chemical packaging waste.

$$\mathbf{E_{Energy}} = E_{Fuel} + E_{Electricity}$$
$$= E_{Fuel,\ production} + E_{Fuel,\ transport} + E_{Fuel,\ combustion} + E_{Electricity}$$

The energy used in the mill comes from fuel and electricity. Therefore, the GHG emission of energy includes the emission of production, transportation and combustion of fuel and also the generation of electricity.

$\mathbf{E_{Wastewater}}$

Case I, Wastewater treatment system with biogas recovery system

$$= E_{Wastewater,\ treatment} + E_{Sludge,\ treatment} + E_{Wastewater,\ discharge}$$
$$+ E_{Sludge,\ final} + E_{Fugitive} + E_{Biomass} + E_{Flaring}$$

Case II, Wastewater treatment system without biogas recovery system

$$= E_{Wastewater,\ treatment} + E_{Sludge,\ treatment} + E_{Wastewater,\ discharge}$$
$$+ E_{Sludge,\ final}$$

Where:

E_{Total}	is the total GHG emissions from production process
$E_{FFB,\ production}$	is the GHG emission from FFB production
$E_{FFB,\ transport}$	is the GHG emission from FFB transport
$E_{Chemicals,\ production}$	is the GHG emission from chemicals production
$E_{Chemicals,\ transport}$	is the GHG emission from chemicals transport
$E_{chemical\ packaging,\ production}$	is the GHG emission from production of chemical packaging
$E_{Chemical\ packaging\ waste,\ transport}$	is the GHG emission from transport of chemical packaging waste to disposal site
$E_{Chemical\ packaging\ waste,\ disposal}$	is the GHG emission from chemical packaging waste disposal
$E_{Fuel,\ production}$	is the GHG emission from fuel production
$E_{Fuel,\ transport}$	is the GHG emission from fuel transport
$E_{Fuel,\ combustion}$	is the GHG emission from fuel combustion

$E_{Electricity}$	is the GHG emission from electricity consumption
$E_{Wastewater,\ treatment}$	is the GHG emission from wastewater treatment system
$E_{Sludge,\ treatment}$	is the GHG emission from sludge treatment system
$E_{Wastewater,\ discharge}$	is the GHG emission from degradable organic carbon in treated wastewater
$E_{Sludge,\ final}$	is the GHG emission from anaerobic decay of the final sludge produced
$E_{Fugitive}$	is methane emissions from biogas release in capture systems
$E_{Flaring}$	is methane emissions due to incomplete flaring *(Tool to determine project emissions from flaring gases containing methane, UNFCCC, 2010)*
$E_{Biomass}$	is methane emissions from biomass stored under anaerobic conditions (*Tool to determine methane emissions avoided from disposal of waste at a solid waste disposal site, UNFCCC, 2010)*

Total GHG emission value is derived from the sum of emissions of each section related to the palm oil production in plant. The calculation of each section is the result of multiplying the activity data (e.g. kg FFB, L diesel fuel used, kWh electricity used) by emission factors as the below equation. It should be noted that, at the end, all type of GHGs will be converted to carbon dioxide equivalent (CO_2e) value by using the Global Warming Potential (GWP) over 100 years timeframe

The GHG emission calculation for each component is separately shown in details as follows. The calculation example is presented in Appendix D

1) Emission of FFB input (E_{FFB})

$$E_{FFB,\ production} = \text{FFB (Mt /yr)} \ \text{x} \ EF_{FFB,production} \text{ (kg } CO_2 \text{ e/ Mt)}$$

Remark: The value of $EF_{FFB,production}$ is obtained from the cultivation section

$$E_{\text{FFB, transport}} = \sum (\text{FFB (Mt /yr)} \times \text{One-way distance, arrival (km)} \times EF_{\text{Transport, load}} \text{ (kg } CO_2\text{e/ Mt -km)} + \text{Numbers of trip} \times \text{One-way distance, departure (km)} \times EF_{\text{Transport, noload}} \text{ (kg } CO_2\text{e/ km)}$$

Remark: The value of $EF_{\text{Transport, load}}$ *and* $EF_{\text{Transport,no load}}$ *must be obtained from the National Guideline Carbon Footprint of Products (in Thai), TGO, 2010)*

2) Emission of chemicals input ($E_{\text{Chemicals}}$)

$$E_{\text{Chemicals, production}} = \sum (\text{Chemicals consumption (kg/yr)} \times EF_{\text{Chemicals, production}} \text{ (kg } CO_2\text{e/kg)}$$

$$E_{\text{Chemicals, transport}} = \sum (\text{Chemicals (Mt /yr)} \times \text{One-way distance, arrival (km)} \times EF_{\text{Transport, load}} \text{ (kg } CO_2\text{e/ Mt -km)} + \text{Numbers of trip} \times \text{One-way distance, departure (km)} \times EF_{\text{Transport, noload}} \text{ (kg } CO_2\text{e/ km))}$$

$$E_{\text{Chemical packaging, production}} = \sum (\text{Chemical packaging (kg/yr)} \times EF_{\text{Chemical packing, production}} \text{ (kg } CO_2\text{e/kg)}$$

$$E_{\text{Chemical packing waste, transport}} = \sum (\text{Chemical packaging waste (Mt /yr)} \times \text{One-way distance to disposal site, arrival (km)} \times EF_{\text{Transport, load}} \text{ (kg } CO_2\text{e/ Mt -km)} + \text{Numbers of trip} \times \text{One-way distance to disposal site, departure (km)} \times EF_{\text{Transport, noload}} \text{ (kg } CO_2\text{e/ km)}$$

$$E_{\text{Chemical packaging waste, disposal}} = \sum (\text{Chemical packaging (kg/yr)} \times EF_{\text{Chemical packing waste, disposal}} \text{ (kg } CO_2\text{e/kg)}$$

Since, kaolin is used only in the dry section, therefore, this GHG emission from kaolin must be allocated to products and by-products produced from dry section only.

Remark: The value of $EF_{Chemicals,\ production}$ *must be obtained from the National Guideline Carbon Footprint of Products (in Thai), TGO 2010)*

3) Emission of energy input (E_{Fuel} and $E_{Electricity}$)

E_{Fuel}

$$E_{Fuel,\ production} = \sum \text{(Fuel consumption (L/yr)} \times EF_{Fuel,\ production} \text{ (kg } CO_2\text{e/L))}$$

$$E_{Fuel,\ transport} = \sum \text{[Fuel (Mt /yr)} \times \text{One-way distance, arrival (km)} \times EF_{Transport,\ load} \text{ (kg } CO_2\text{ e/ Mt -km)]} + \text{[Numbers of trip} \times \text{One-way distance, departure (km)} \times EF_{Transport,\ noload} \text{ (kg } CO_2\text{ e/ km)]}$$

$$E_{Fuel,\ combustion} = \sum \text{(Fuel consumption (L/yr)} \times EF_{Fuel,\ combustion} \text{ (kg } CO_2\text{e/L))}$$

Remark: The value of $EF_{Fuel,\ production}$ *and* $EF_{Fuel,\ combustion}$ *must be obtained from the National Guideline Carbon Footprint of Products (in Thai), TGO, 2010)*

$E_{Electricity}$

Regard to the GHG emission of electricity, it could be stated that the mill utilize the electricity from four sources: (1) electricity from Provincial Electricity Authority (PEA), (2) electricity from steam turbine (3) electricity from biogas plant and (4) electricity from diesel engine. In calculation, the electricity from PEA and diesel were included, while the electricity from steam turbine and biogas plant were not counted. The kWh per year of electricity used from PEA was obtained from the mill and multiplied by emission factor (TGO, 2010) to get GHG emission as shown in the following equation.

$$E_{Electricity} = \text{Electricity consumption (kWh/yr)} \times EF_{Elec} \text{ (kg } CO_2\text{e/kWh)}$$

Remark: The value of $EF_{Electricity,\ Production}$ *must be obtained from National Guideline Carbon Footprint of Products (in Thai), TGO, 2010)*

For the electricity from diesel engine, the amount of diesel used per year was collected. The GHG calculation use emission factor (TGO 2010) included production, transportation, and combustion of diesel as mentioned in the E_{Fuel} section.

For biogas plant, the mill records the electricity production from biogas and the proportion of electricity utilization in the mill and supplying to grid. However, they were not counted in the calculation.

4) Emission of wastewater treatment system ($E_{Wastewater}$) *(Source: Methane recovery in wastewater treatment - version 16, AMS-III.H,* UNFCCC, 2010)

Since, many palm oil mills in Thailand have already developed the clean development mechanism (CDM) projects on methane recovery in wastewater treatment plant in accordance with UNFCCC method. Therefore, the UNFCCC methodology was used in this study.

4.1) $$E_{Wastewater,treatment} = \sum_i Q_{ww,i,y} \text{ x } COD_{removed,i,y} \text{ x } MCF_{ww,treatment,BL,i} \text{ x } B_{o,ww} \text{ x } UF_{BL} \text{ x } GWP_{CH4}$$

Where:

$E_{wastewater,treatment}$ = The GHG emission from wastewater treatment system

$Q_{ww,i,y}$ = Volume of wastewater treated in wastewater treatment system *i* in year *y* (m^3)

$COD_{removed,i,y}$ = Chemical oxygen demand removed by treatment system *i* in year *y* (Mt /m^3), measured as the difference between inflow COD and the outflow COD in system *i*

$MCF_{ww,treatment,BL,i}$ = Methane correction factor for wastewater treatment systems *i* (MCF values as per Table 6.8 IPCC, 2006)

i = Index for wastewater treatment system

$B_{o,ww}$ = Methane producing capacity of the wastewater (IPCC value of 0.25 kg CH_4/kg COD)

UF_{BL} = Model correction factor to account for model uncertainties (0.89)

GWP_{CH4} = Global Warming Potential for methane (value of 25 CO_{2e})

4.2) $E_{Sludge,treatment} = \sum_i S_{j,BL,y} \times MCF_{s,\ treatment,\ BL,\ j} \times DOC_s \times UF_{BL} \times DOC_F \times F \times 16/12 \times GWP_{CH4}$

Where:

$E_{Sludge,treatment}$ = The GHG emission from sludge treatment system

$S_{j,BL,y}$ = Amount of dry matter in sludge that would have been treated by the sludge treatment system *j* inyear *y* (Mt)

j = Index for sludge treatment system

DOC_s = Degradable organic content of the untreated sludge generated in the year (fraction, dry basis). Default values of 0.5 for domestic sludge and 0.257 for industrial sludge shall be used

$MCF_{S,\ treatment,\ BL,\ j}$ = Methane correction factor for the sludge treatment system j (MCF values as per Table III.H.1)

UF_{BL} = Model correction factor to account for model uncertainties (0.89)

DOC_F = Fraction of DOC dissimilated to biogas (IPCC default value of 0.5)

F = Fraction of CH_4 in biogas (IPCC default of 0.5)

4.3) $E_{Wastewater,\ discharge} = Q_{ww,y} \times GWP_{CH4} \times B_{o,ww} \times UF_{BL} \times COD_{ww,\ discharge,\ BL,\ y} \times MCF_{ww,BL,discharge}$

Where:

$E_{Wastewater,discharge}$ = The GHG emission from degradable organic carbon in treated wastewater (tCO_2e)

$Q_{ww,\ y}$ = Volume of treated wastewater discharged in year y (m^3)

UF_{BL} = Model correction factor to account for model uncertainties (0.89)

$COD_{ww,\ discharge,\ BL,\ y}$ = Chemical oxygen demand of the treated wastewater discharged into sea, river or lake in the baseline situation in the year y (t/m3). If the baseline scenario is the discharge of untreated wastewater, the COD of untreated wastewater shall be used

$MCF_{ww,\ BL,\ discharge}$ = Methane correction factor based on discharge pathway (e.g. into sea, river or lake) of the wastewater (fraction) (MCF values as per Table 6.8 IPCC, 2006)

4.4) $E_{Sludge,final}$ = $S_{Final,\,BL,\,y}$ x DOC_s x UF_{BL} x $MCF_{s,\,BL,\,final}$ x DOC_F x F x 16/12 x GWP_{CH4}

Where:

$E_{Sludge,final}$ = The GHG emission from anaerobic decay of the final sludge produced (tCO_2e)

$S_{Final,BL,y}$ = Amount of dry matter in the final sludge generated by the wastewater treatment systems in the year y (t).

$MCF_{s,BL,final}$ = Methane correction factor of the disposal site that receives the final sludge, estimated as per the procedures described in the “Tool to determine methane emissions avoided from disposal of waste at a solid waste disposal site”

UF_{BL} = Model correction factor to account for model uncertainties (0.89)

4.5) $E_{fugitive}$ = $E_{fugitive,ww}$ + $E_{fugitive,\,s}$

Where:

$E_{Fugitive}$ = Methane emissions from biogas release in capture systems (tCO_2e)

$E_{fugitive,\,ww}$ = Fugitive emissions through capture inefficiencies in the anaerobic wastewater treatment systems

$E_{fugitive,\,s}$ = Fugitive emissions through capture inefficiencies in the anaerobic sludge treatment systems

$E_{fugitive,\,ww}$ = (1- CEF_{ww}) x $MEP_{ww,\,treatment}$ x GWP_{CH4}

Where:

CFE_{ww} = Capture efficiency of the biogas recovery equipment in the wastewater treatment systems (a default value of 0.9 shall be used)

$MEP_{ww, treatment}$ = Methane emission potential of wastewater treatment systems equipped with biogas recovery system

It must be noted that a default value of capture efficiency of the biogas recovery equipment was set to be 90 percent. The major fugitive emission of 10 percent could be came from 1) the broken of the seal weld of the plastic sheet and the seal weld between the plastic sheet and biogas recovery tank 2) The broken of the flexible pipe due to the vibration of the pump.

$$MEP_{ww, treatment} = Q_{ww} \text{ x } B_{o,ww} \text{ x } UF_{PJ} \text{ x } \sum_{k} COD_{removed,PJ,k} \text{ x } MCF_{ww,treatment,PJ}$$

Where:

$COD_{removed, PJ, k}$ = The chemical oxygen demand removed by the treatment system k of the project activity equipped with biogas recovery (t/m3)

$MCF_{ww, treatment, PJ}$ = Methane correction factor for the project wastewater treatment system k equipped with biogas recovery equipment (MCF values as per Table 6.8 IPCC, 2006)

UF_{PJ} = Model correction factor to account for model uncertainties (0.89)

$$E_{fugitive, s} = (1- CEF_{s}) \text{ x } MEP_{s, treatment} \text{ x } GWP_{CH4}$$

Where:

CFE_{s} = Capture efficiency of the biogas recovery equipment in the sludge treatment systems (a default value of 0.9 shall be used)

$MEP_{s, treatment}$ = Methane emission potential of sludge treatment systems equipped with biogas recovery system

$$MEP_{s\ treatment} = \sum_{l} (S_{l,PJ} \text{ x } MCF_{s,treatment,PJ,l}) \text{ x } DOC_{s} \text{ x } UF_{PJ} \text{ x } DOC_{F} \text{ x } F \text{ x } 16/12$$

Where:

$S_{l, PJ}$ = Amount of sludge treated in the project sludge treatment system l equipped with a biogas recovery system (on a dry basis) (t)

$MCF_{s, treatment, PJ, l}$ = Methane correction factor for the sludge treatment system l equipped with biogas recovery equipment (MCF values as per Table 6.8 IPCC, 2006)

UF_{PJ} = Model correction factor to account for model uncertainties (0.89)

4.6) $E_{Biomass}$ Is methane emissions from biomass stored under anaerobic conditions (tCO_2e). *(Tool to determine methane emissions avoided from disposal of waste at a solid waste disposal site)*

4.7) $E_{Flaring} = TM_{RG,h} \times (1-\eta_{Flare,h}) \times GWP_{CH4}/1000$

Where:

$E_{flaring}$ = Methane emissions due to incomplete flaring in year y (tCO_2e)

$TM_{RG,h}$ = Mass flow rate of methane in the residual gas in hour h (kg/h)

$\eta_{Flare,h}$ = Flare efficiency in hour h

- In case of open flare, the flare efficiency in the hour h is 50%
- In case of enclosed flares, the flare efficiency in the hour h is 90%

GWP_{CH4} = Global Warming Potential of methane (value of 25)

$TM_{RG,h} = FV_{RG, h} \times fv_{CH4, RG, h} \times \rho_{CH4, n, h}$

Where:

$FV_{RG, h}$ = Volumetric flow rate of the residual gas in dry basis at normal conditions in hour h (Nm^3/h)

$fv_{CH4, RG, h}$ = Volumetric fraction of methane in the residual gas on dry basis in hour h

$\rho_{CH4, n, h}$ = Density of methane at normal condition (0.716 kg/m^3)

In general, the palm oil mills utilize the treat wastewater in palm oil plantation, $E_{Wastewater, discharge}$ is considered to be zero. In the case of sludge and biomass, regard to the operation of wastewater treatment plant, there are no sludge treatment and biomass storage, $E_{Sludge,final,}$ $E_{Sludge,treatment,}$ and $E_{Biomass}$ consider to be zero.

2. Allocation method

According to the output from process, CPO are counted as main product whereas palm kernel or PKO and palm kernel meal, and shell are counted as by-products of wet extraction process. EFB, fiber, and decanter cake are identified as wastes. In general, the allocation can be done based on mass, energy, and economic value (market price). According to the price fluctuation of CPO, the allocation by price was canceled out. Considering the allocation by mass, the GHG emission value after allocation of all products and by-products are the same. Therefore, the results of allocation by mass normally presented in term of percent allocation which is not suitable for this study. The allocation by energy, therefore, can be conducted in this study. Finally, the products and by-products are held their GHG emission values passing onto the next element in the bio-diesel supply chain or going through another processing step.

The following equation is used for the calculation:

$$\text{Emission}_{\text{Product, allocated}} = \text{Total GHG emission (kg } CO_2\text{e)} \times (\text{\% Energy distribution}_{\text{Product}})$$

$$\text{Emission}_{\text{By-product, allocated}} = \text{Total GHG emission (kg } CO_2\text{e)} \times (\text{\% Energy distribution}_{\text{By-product}})$$

And,

$$\text{\% Energy distribution}_{\text{Product}} = [\text{LHV}_{\text{Product}} \text{ (MJ/ Mt)} \times \text{Yield}_{\text{Product}} \text{ (Mt)}] / [\sum (\text{LHV}_{\text{Product}} \text{ (MJ/ Mt)} \times \text{Yield}_{\text{Product}} \text{ (Mt)}) + \sum (\text{LHV}_{\text{By-product}} \text{ (MJ/ Mt)} \times \text{Yield}_{\text{By-product}}))]$$

$$\text{\% Energy distribution}_{\text{By-product}} = [\text{LHV}_{\text{By-product}} \text{ (MJ/ Mt)} \times \text{Yield}_{\text{By-product}} \text{ (Mt)}] / [\sum (\text{LHV}_{\text{Product}} \text{ (MJ/ Mt)} \times \text{Yield}_{\text{Product}} \text{ (Mt)}) + \sum (\text{LHV}_{\text{By-product}} \text{ (MJ/ Mt)} \times \text{Yield}_{\text{By-product}}))]$$

Where:

$\text{LHV}_{\text{Product}}$	is the lower heating value of product (MJ/ Mt product)
$\text{LHV}_{\text{By-products}}$	is the lower heating value of by-product (MJ/ Mt by-product)

APPENDIX D

EXAMPLE OF GHG CALCULATION

Example of GHG calculation

1. Wet extraction process

From the overall equation

1) Emission of FFB input

$$\mathbf{E_{FFB}} = E_{\text{FFB, production}} + E_{\text{FFB, transport}}$$

1.1 Emission of FFB production (from oil palm cultivation and harvest)

From equation,

$$E_{\text{FFB, production}} = \text{FFB (Mt) x Emission Factor}_{\text{FFB, production}} \text{ (kg } CO_2\text{e/ Mt FFB)}$$

If assumed,

FFB input = 6.66 Mt/ Mt CPO

Emission Factor $_{\text{FFB, production}}$ = 81.579 (kg CO_2e/ Mt FFB) for small plantation

Emission Factor $_{\text{FFB, production}}$ = 73.291 (kg CO_2e/ Mt FFB) for large plantation

(Source: Appendix B)

100 percent of FFB production came from small plantation

Calculation result:

Emission $_{\text{FFB, production}}$ = 6.66 Mt FFB/ Mt CPO 81.579 kg CO_2e/ Mt FFB

= 543.31 kg CO_2e/ Mt CPO

1.2 Emission of FFB transportation

Transportation of FFB from plantation to collecting point

$$E_{\text{FFB, transport}} = \sum \text{(FFB (Mt /yr) x One-way distance, arrival (km) x } EF_{\text{Transport, load}} \text{ (kg } CO_2\text{ e/ Mt -km) + Numbers of trip x One-way distance, departure (km) x } EF_{\text{Transport, noload}} \text{ (kg } CO_2\text{ e/ km)}$$

Assumed, 87 percent of FFB was transferred from collection point to factory. The percent of FFB transportation based on the distance between plantations to collection point was divided into 80 percent of 10 km, 15 percent of 20 km and 5 percent of 30 km (*Source: appendix B*)

Calculation result:

Mt of FFB from plantation to collecting point

= 6.66 Mt FFB x 0.87 = 5.794 Mt

Emission $_{\text{FFB transportation}}$ = (5.794 Mt FFB x 0.8 x 3.93 kgCO$_2$/ Mt FFB) + (5.794 Mt FFB x 0.15 x 7.86 kgCO$_2$/ Mt FFB) + (5.794 Mt FFB x 0.05 x 11.79 kgCO$_2$/ Mt FFB)

= 18.21 + 6.83 + 3.42

= 28.46 kgCO$_2$/ Mt CPO

Transportation of FFB from collecting point and plantation to mill

From equation,

$$E_{\text{FFB, transport}} = \sum \big(\text{FFB (Mt)} \times \text{One-way distance, arrival (km)} \times EF_{\text{Transport, load}} (\text{kg CO}_2\text{e/ Mt-km}) + \text{Number of vehicle trip (trip)} \times \text{One-way distance, departure (km)} \times EF_{\text{Transport, noload}} (\text{kg CO}_2\text{e/ km})\big)$$

Transport condition:

FFB input = 6.66 Mt/ Mt CPO

Transport details:

1) 3% FFB, 4 wheels pick-up transport-B5 diesel (full load, 1.5 Mt), distance 10 km
2) 3% FFB, 10 wheels truck transport-B5 diesel (full load, 16 Mt), distance 10 km
3) 3% FFB, 18 wheels truck transport-B5 diesel (full load, 32 Mt), distance 10 km
4) 10% FFB, 4 wheels pick-up transport-B5 diesel (full load, 1.5 Mt), distance 20 km
5) 38% FFB, 10 wheels truck transport-B5 diesel (full load, 16 Mt), distance 20 km
6) 10% FFB, 18 wheels truck transport-B5 diesel (full load, 32 Mt), distance 20 km
7) 22% FFB, 10 wheels truck transport-B5 diesel (full load, 16 Mt), distance 30 km
8) 11% FFB, 18 wheels truck transport-B5 diesel (full load, 32 Mt), distance 30 km

Calculation result:

Emission $_{\text{FFB, transport}}$

= [(0.03 x 6.66 Mt x 10 km x 0.2247 kgCO_2e/ Mt -km)

+ ((0.03 x 6.66 Mt / 1.5 Mt) trips x 10 km x 0.2523 kgCO_2e/km)]

+ [(0.03 x 6.66 Mt x 10 km x 0.0425 kgCO_2e/ Mt -km)

+ ((0.03 x 6.66 Mt / 16 Mt) trips x 10 km x 0.5429 kgCO_2e/km)]

+ [(0.03 x 6.66 Mt x 10 km x 0.0459 kgCO_2e/ Mt -km)

+ ((0.03 x 6.66 Mt / 32 Mt) trips x 10 km x 0.9065 kgCO_2e/km)]

+ [(0.1 x 6.66 Mt x 20 km x 0.2247 kgCO_2e/ Mt -km)

+ ((0.1 x 6.66 Mt / 1.5 Mt) trips x 20 km x 0.2523 kgCO_2e/km)]

+ [(0.38 x 6.66 Mt x 20 km x 0.0425 kgCO_2e/ Mt-km)

+ ((0.38 x 6.66 Mt / 16 Mt) trips x 20 km x 0.5429 kgCO_2e/km)]

+ [(0.1 x 6.66 Mt x 20 km x 0.0459 kgCO_2e/ Mt -km)

+ ((0.1 x 6.66 Mt / 32 Mt) trips x 20 km x 0.9065 kgCO_2e/km)]

+ [(0.22 x 6.66 Mt x 30 km x 0.0425 kgCO_2e/ Mt -km)

+ ((0.22 x 6.66 Mt / 16 Mt) trips x 30 km x 0.5429 kgCO_2e/km)]

+ [(0.11 x 6.66 Mt x 30 km x 0.0459 kgCO_2e/ Mt -km)

+ ((0.11 x 6.66 Mt / 32 Mt) trips x 30 km x 0.9065 kgCO_2e/km)]

= [0.4490 + 0.3361] + [0.0849 + 0.0678] + [0.0917 + 0.0566] + [2.9930 + 2.2404]

+ [2.1512 + 1.7175] + [0.6114 + 0.3773] + [1.8681 + 1.4915] + [1.0088 + 0.6226]

= 16.17 kg CO_2e/ Mt CPO

Therefore, emission of FFB input

= [543.31 kg CO_2e/ Mt CPO] + [28.46 kg CO_2e/ Mt CPO] + [16.17 kg CO_2e/ Mt CPO]

= 587.94 kg CO_2e/ Mt CPO

2) Emission of chemicals consumption

$\mathbf{E_{Chemicals}}$ = $E_{\text{Chemicals, production}} + E_{\text{Chemicals, transport}} + E_{\text{chemical packaging, production}} + E_{\text{chemical packaging waste, transport}} + E_{\text{chemical packaging waste, disposal}}$

2.1 Emission of chemicals production

From equation,

$E_{\text{Chemicals production}}$ = $\sum$ (Chemicals (kg) x $EF_{\text{Chemicals}}$ (kg CO_2e/kg))

Chemicals consumption condition:

1) Kaolin input = 23.17 kg/ Mt CPO

Emission Factor $_{\text{Kaolin}}$ = 0.2170 (kg CO_2e/ Mt Kaolin) *(Source; Appendix B)*

2) Alum input = 0.18 kg/ Mt CPO

Emission Factor $_{\text{Alum}}$ = 0.2770 (kg CO_2e/ Mt alum) *(Source; Appendix B)*

3) Mono sodium phosphate input = 0.14 kg/ Mt CPO

Emission Factor $_{\text{mono sodium phosphate}}$ = 2.95 (kg CO_2e/ Mt) *(Source; Appendix B)*

Calculation result:

Chemicals Production for product from dry section

Emission $_{\text{chemicals production}}$ = 23.17 kg x 0.2170 kg CO_2e/kg $_{\text{Kaolin}}$

= 5.0279 kg CO_2e/ Mt CPO

Chemicals Production for the others product

Emission $_{\text{chemicals production}}$ = (0.18 kg x 0.2770 kg CO_2e/kg $_{\text{Alum}}$)

+ (0.14 kg x 2.95 kg CO_2e/kg $_{\text{mono sodium phosphate}}$)

= 0.0499 + 0.4130

= 0.4629 kg CO_2e/ Mt CPO

2.2 Emission of chemicals transportation

From equation,

$E_{\text{Chemicals, transport}}$ = $\sum$ (Chemicals (Mt) x One-way distance, arrival (km) x $EF_{\text{Transport, load}}$ (kg CO_2 e/ Mt -km) + Numbers of trip x One-way distance, departure (km) x $EF_{\text{Transport, no load}}$ (kg CO_2 e/ km))

Transport condition:

1) Kaolin input = 23.17 kg/ Mt CPO

Transport details:

- 100% Kaolin, 10 wheels truck transport-B5 diesel (full load, 16 Mt), distance 967 km

2) Alum input = 0.18 kg/ Mt CPO

Transport details:

- 100% alum, 10 wheels truck transport-B5 diesel (full load, 16 Mt), distance 814 km

3) mono sodium phosphate input = 0.14 kg/ Mt CPO

Transport details:

- 100% mono sodium phosphate, 10 wheels truck transport-B5 diesel (full load, 16 Mt), distance 814 km

Calculation result:

Chemicals transport for product from dry section

Emission$_{\text{Chemicals, transport}}$

= [(23.17/1,000 Mt x 967 km x 0.0425 kgCO_2e/ Mt -km)

+ ((23.17/1,000 Mt / 16 Mt) trips x 967 km x 0.5429 kgCO_2e/km)]

= [0.9522 + 0.7602]

= 1.7124 kg CO_2e/ Mt CPO

Chemicals Production for the others product

Emission$_{\text{Chemicals, transport}}$

= + [(0.18 /1,000 Mt x 814 km x 0.0425 kgCO_2e/ Mt -km)

+ ((0.18 /1,000 Mt / 16 Mt) trips x 814 km x 0.5429 kgCO_2e/km)]

+ [(0.14/1,000 Mt x 814 km x 0.0425 kgCO_2e/ Mt -km)

+ ((0.14/1,000 Mt / 16 Mt) trips x 814 km x 0.5429 kgCO_2e/km)]

= [0.0062 + 0.0050] + [0.0048 + 0.0039]

= 0.0199 kg CO_2e/ Mt CPO

2.3 Emission of chemical packing production

Kaolin packaging (polypropylene)

1 bag contain 25 kg of Kaolin and it had weight of 63 g

1 Mt of CPO, used 23.17 kg of Kaolin, the weight of PP bag of 58.3884 g

1) PP bag = 0.05839 kg/ Mt CPO

Emission Factor $_{\text{Kaolin}}$ = 2.3990 kgCO$_2$e/kg PP

Calculation result:

Chemicals Production for product from dry section

Emission $_{\text{chemical packing production}}$ = 0.05839 kg x 2.3990 kg CO$_2$e/kg PP

= 0.1401 kg CO$_2$e/ Mt CPO

2.4 Emission of chemical packing transport

= [(0.05839/1,000 Mt x 30 km x 0.0548 kgCO$_2$e/ Mt -km)

+ (0.05839/1,000 Mt / 16 Mt) trips x 30 km x 0.5401 kgCO$_2$e/km)]

= [9.6E-05 + 5.9E-05]

= 1.55E-04 kg CO$_2$e/ Mt CPO

2.5 Emission of chemical packing disposal

1) PP bag = 0.05839 kg/ Mt CPO

Emission Factor $_{\text{nappies}}$ = 4.0000 kgCO$_2$e/kg PP

Calculation result:

Chemicals for product from dry section

Emission $_{\text{chemical packing production}}$ = 0.05839 kg x 4.0000 kg CO$_2$e/kg PP

= 0.2336 kg CO$_2$e/ Mt CPO

Calculation result:

Emission for products from dry section

= 5.0279 + 1.7124+0.1401+1.55E-04 +0.2336 kg CO$_2$e/ Mt CPO

= 7.114 kg CO$_2$e/ Mt CPO

Emission for the others product

= 0.4629 + 0.0199 kg CO$_2$e/ Mt CPO

= 0.4828 kg CO_2e/ Mt CPO

3) Emission of fuel consumption

$$\mathbf{E}_{\mathbf{Fuel}} = E_{\text{Fuel, production}} + E_{\text{Fuel, transport}} + E_{\text{Fuel, combustion}}$$

3.1 Emission of fuel production

From equation,

$E_{\text{Fuel, production}}$ = Fuel consumption (L) x $EF_{\text{Fuel, production}}$ (kg CO_2e/L)

If assumed,

Diesel fuel consumption = 5.21 L/ Mt CPO

Emission Factor $_{\text{Diesel fuel, production}}$ = 0.4293 kg CO_2e/L *(Source: Appendix B)*

Calculation result:

Emission $_{\text{Diesel fuel, production}}$ = 5.21 L x 0.4293 kg CO_2e/L

= 2.2366 kg CO_2e/ Mt CPO

3.2 Emission of fuel transport

From equation,

$E_{\text{Fuel, transport}}$ = $\sum$ (Fuel (L) x One-way distance, arrival (km) x $EF_{\text{Transport, load}}$ (kg CO_2 e/ Mt -km) + Numbers of trip x One-way distance, departure (km) x $EF_{\text{Transport, no load}}$ (kg CO_2 e/ km)

Transport condition:

Diesel fuel input = 5.21 L/ Mt CPO

Density = 0.85 g/cm^3

Thus, diesel fuel input = 0.0044 Mt / Mt CPO

Transport details:

- 100 % diesel fuel, liquid bulk carrier, distance 823 km
- 100% diesel fuel, 10 wheels truck transport (full load, 16 Mt), distance 211 km

Calculation result:

Emission $_{\text{Diesel fuel, transport}}$

= [(0.0044 Mt x 823 km x 0.002 kgCO$_2$e/ Mt -km)

+ (0.0044 Mt/1,700,000 Mt x 823 x 0.002 kgCO$_2$e/ Mt -km)]

+ [(0.0044 Mt x 211 km x 0.0473 kgCO$_2$e/ Mt -km)

+ ((0.0044 Mt /16 Mt) trips x 211 km x 0.6001 kgCO$_2$e/km)]

= [0.0072 + very less] + [0.0439 + 0.0348]

= 0.0859 kg CO$_2$e/ Mt CPO

3.3 Emission of fuel combustion

From equation,

E$_{\text{Fuel, combustion}}$ = Fuel consumption (L) x EF$_{\text{Fuel, combustion}}$ (kg CO$_2$e/L)

If assumed,

Diesel fuel consumption = 5.21 L/ Mt CPO

Emission Factor $_{\text{Diesel fuel, combustion}}$ = 2.7080 kg CO$_2$e/L *(Source Appendix B)*

Calculation result:

Emission $_{\text{Diesel fuel, combustion}}$ = 5.21 L x 2.7080 kg CO$_2$e/L

= 14.11 kg CO$_2$e/ Mt CPO

Therefore, emission of fuel consumption part

= [2.2366 kg CO$_2$e/ Mt CPO] + [0.0859 kg CO$_2$e/ Mt CPO]

+ [14.11 kg CO$_2$e/ Mt CPO]

= 16.4325 kg CO$_2$e/ Mt CPO

4) Emission of electricity consumption (from external source)

From equation,

E $_{\text{Electricity consumption}}$ = Electricity consumption (kWh)

x EF$_{\text{Electricity}}$ (kg CO$_2$e/kWh)

If assumed,

Electricity consumption = 5.38 kWh/ Mt CPO

Emission Factor $_{\text{Electricity}}$ = 0.5610 kg CO$_2$e/kWh *(Source Appendix B)*

Calculation result:

Emission $_{\text{Electricity consumption}}$ = 5.38 kWh x 0.5610 kg CO_2e/kWh

= 3.02 kg CO_2e/ Mt CPO

5) Emission of Wastewater from production process

$$\mathbf{E}_{\textbf{Wastewater}} = E_{\text{Wastewater, treatment}} + E_{\text{Sludge, treatment}} + E_{\text{Wastewater, discharge}} + E_{\text{Sludge, final}} + E_{\text{Fugitive}} + E_{\text{Biomass}} + E_{\text{Flaring}}$$

5.1 Wastewater treatment system with biogas recovery system

(Source: Methane recovery in wastewater treatment - version 15, AMS-III.H.)

From equation,

$$E_{\text{wastewater}} = E_{\text{ww,treatment}} + E_{\text{s,treatment}} + E_{\text{ww,discharge}} + E_{\text{s,final}} + E_{\text{fugitive}} + E_{\text{biomass}} + E_{\text{flaring}}$$

If assumed,

Wastewater treatment system condition:

Volume of wastewater treated in wastewater treatment system = 4.04 m^3/ Mt CPO

COD wastewater from production process (inflow COD) = 60,000 mg/L

COD inlet to biogas system = 52,000 mg/L

COD outlet from biogas system = 12,000 mg/L

COD treated wastewater in final pond (outflow COD) = 1,500 mg/L

No discharging of treated water

No sludge treatment system and no sludge dredging

No biomass treatment

90 % efficiency of biogas capture system

Flare condition

- Volumetric flow rate of the residual gas = 0.53 m^3/ Mt CPO
- Volumetric fraction of methane in the residual gas = 73 %
- Flare efficiency (Enclosed flares) = 90 %

From sub-equation,

1) $E_{ww,treatment} = \sum_i Q_{ww,i,y} \text{ x } COD_{removed,i,y} \text{ x } MCF_{ww,treatment,BL,i} \text{ x } B_{o,ww} \text{ x } UF_{BL} \text{ x } GWP_{CH4}$

Calculation result:

1) Oxidation pond of biogas system

$E_{ww,treatment, oxidation pond}$ = $(4.04 \text{ m}^3 \text{ x } (60{,}000 - 52{,}000) \text{ mg/L x } 0.8 \text{ x } 0.25 \text{ kg } CH_4/\text{kg COD x } 0.89 \text{ x } 25$

= 143.824 kg CO_2e / Mt CPO

2) Final pond

$E_{ww,treatment,final pond}$ = $(4.04 \text{ m}^3) \text{ x } (12{,}000 - 1{,}500) \text{ mg/L x } 0.8 \text{ x } 0.25 \text{ kg } CH_4/\text{kg COD x } 0.89 \text{ x } 25$

= 188.769 kg CO_2e/ Mt CPO

Thus,

Emission $_{ww,treatment}$ = (143.824 + 188.769) kg CO_2e/ Mt CPO

= 332.593 kg CO_2e/ Mt CPO

2) $E_{Sludge,treatment} = \sum_i S_{j,BL,y} \text{ x } MCF_{s, treatment, BL, j} \text{ x } DOC_s \text{ x } UF_{BL} \text{ x } DOC_F \text{ x } F \text{ x } 16/12 \text{ x } GWP_{CH4}$

Calculation result:

Emission $_{s,treatment}$ = 0 kg CO_2e/ Mt CPO (No sludge treatment)

3) $E_{Wastewater, discharge} = Q_{ww,y} \text{ x } GWP_{CH4} \text{ x } B_{o,ww} \text{ x } UF_{BL} \text{ x } COD_{ww, discharge, BL, y} \text{ x } MCF_{ww,BL,discharge}$

Calculation result:

Emission $_{ww,discharge}$ = 0 kg CO_2e/ Mt CPO (No discharging of treated water)

4) $E_{Sludge,final} = S_{Final, BL, y} \text{ x } DOC_s \text{ x } UF_{BL} \text{ x } MCF_{s, BL, final} \text{ x } DOC_F \text{ x } F \text{ x } 16/12 \text{ x } GWP_{CH4}$

Calculation result:

Emission $_{s,final}$ = 0 kg CO_2e/ Mt CPO (No sludge dredging)

5) $E_{fugitive}$ = $E_{fugitive,ww}$ + $E_{fugitive,\ s}$

$E_{fugitive,\ ww}$ = $(1 - CEF_{ww})$ x $MEP_{ww,\ treatment}$ x GWP_{CH4}

$E_{fugitive,\ s}$ = $(1 - CEF_{s})$ x $MEP_{s,\ treatment}$ x GWP_{CH4}

$MEP_{ww,\ treatment}$ = Q_{ww} x $B_{o,ww}$ x UF_{PJ} x $\sum_k COD_{removed,PJ,k}$ x $MCF_{ww,treatment,PJ}$

$MEP_{s\ treatment}$ = $\sum_l (S_{l,PJ}$ x $MCF_{s,treatment,PJ,l})$ x DOC_s x UF_{PJ} x DOC_F x F x 16/12

Calculation result:

Emission $_{fugitive,ww}$ = (1- 0.9) x $MEP_{ww,\ treatment}$ x 25

= (1- 0.9) x (4.04 m^3 x 0.25 kg CH_4/kg COD x 0.89 x (52,000 -12,000) mg/L x 0.8) x 25

= 71.912 kg CO_2e/ Mt CPO

Emission $_{fugitive,s}$ = 0 kg CO_2e/ Mt CPO

Then, Emission $_{fugitive}$ = (71.912 + 0) kg CO_2e/ Mt CPO

= 71.912 kg CO_2e/ Mt CPO

6) $E_{biomass}$ = 0 kg CO_2e/ Mt CPO

7) $E_{Flaring}$ = $TM_{RG,y}$ x $(\eta - 1_{Flare,y})$ x $GWP_{CH}1000/_4$

$TM_{RG,h}$ = $FV_{RG,\ h}$ x $fv_{CH4,\ RG,\ h}$ x $\rho_{CH4,\ n,\ h}$

Calculation result:

Emission $_{flaring}$ = 0.53 m^3 x (0.73) x (0.716 kg/m^3) x (1 – 0.9) x 25 / 1000

= 0.0007 kg CO_2e/ Mt CPO

Therefore, emission of wastewater from production process part

Emission $_{wastewater}$ = (332.593 + 0 + 0 + 0 + 71.912 + 0 + 0.0007) kg CO_2e

= 404.5057 kg CO_2e/ Mt CPO

Finally,

Total emission = (587.94 + 7.114 + 0.4828+ 16.4325 + 3.02 + 404.5057) kg CO_2e/ Mt CPO

= 1,019.495 kg CO_2e/ Mt CPO

Summary GHG emission of wet extraction process

Emission Source		GHG value (kg CO_2 e/ Mt CPO)	Remark
1	**Emission from FFB input**		
	- FFB production	543.31	
	- FFB transport	44.63	
2	**Emission from chemicals input**		
	- Chemicals production	0.4629	
	- Chemicals transport	0.0199	
3	**Emission from fuel consumption**		
	- Fuel production	2.2366	
	- Fuel transport	0.0859	
	- Fuel combustion	14.11	
4	**Emission from electricity consumption**	3.02	
5	**Emission from wastewater treatment system**	404.5057	
	Total	1,012.381	

Remark: GHG Emission of 7.114 kg CO_2e/ Mt CPO from the chemicals used in dry section will be allocated to the products and by-product from dry section only. Therefore, it is not counted in the Table.

APPENDIX E

EXAMPLE OF ALLOCATION CALCULATION

Example of allocation calculation

1) Allocation by energy

The following equation is used for the calculation:

$$\text{Emission}_{\text{Product, allocated}} = \text{Total GHG emission (kg CO}_2\text{e)} \times (\%\ \text{Energy distribution}_{\text{Product}})$$

$$\text{Emission}_{\text{By-product, allocated}} = \text{Total GHG emission (kg CO}_2\text{e)} \times (\%\ \text{Energy distribution}_{\text{By-product}})$$

And,

$\%$ Energy distribution $_{\text{Product}}$

$$= [\text{LHV}_{\text{Product}}\ (\text{MJ/ Mt}) \times \text{Yield}_{\text{Product}}\ (\text{Mt})] / [\sum (\text{LHV}_{\text{Product}}\ (\text{MJ/ Mt}) \times \text{Yield}_{\text{Product}}\ (\text{Mt})) + \sum (\text{LHV}_{\text{By-product}}\ (\text{MJ/ Mt}) \times \text{Yield}_{\text{By-product}}))]$$

$\%$ Energy distribution $_{\text{By-product}}$

$$= [\text{LHV}_{\text{By-product}}\ (\text{MJ/ Mt}) \times \text{Yield}_{\text{By-product}}\ (\text{Mt})] / [\sum (\text{LHV}_{\text{Product}}\ (\text{MJ/ Mt}) \times \text{Yield}_{\text{Product}}\ (\text{Mt})) + \sum (\text{LHV}_{\text{By-product}}\ (\text{MJ/ Mt}) \times \text{Yield}_{\text{By-product}}))]$$

Where:

$\text{LHV}_{\text{Product}}$	Is the lower heating value of product (MJ/ Mt product)
$\text{LHV}_{\text{By-product}}$	Is the lower heating value of by-product (MJ/ Mt by-product)

1) Allocation of GHG to the products

The examples of allocation of each process are described as following.

If assumed,

Total GHG emission = 25,000 x 1,012.381

= 25,309,525 kg CO_2e

CPO

- Yield = 25,000 Mt
- Yield sold = 25,000 Mt
- LHV = 39,212 MJ/ Mt CPO

PKO

- Yield = 3,750 Mt

- Yield sold = 3,750 Mt
- LHV = 37,736 MJ/ Mt PKO

Shell

- Yield = 9,500 Mt
- Yield sold = 9,500 Mt
- LHV = 24,207MJ/ Mt Shell

Palm kernel meal

- Yield = 5,250 Mt
- Yield sold = 5,250 Mt
- LHV = 18,915 MJ/ Mt Palm kernel meal

Thus,

% Energy distribution $_{\text{CPO}}$

= (39,212 MJ/ Mt CPO x 25,000 Mt CPO) / [(39,212 MJ/ Mt CPO x 25,000 Mt CPO) + (37,736 MJ/ Mt PKO x 3,750 Mt PKO) + (24,207 MJ/ Mt shell x 9,500 Mt shell) + (18,915 MJ/ Mt palm kernel meal x 5,250 Mt palm kernel meal)]

= (980,300,000 MJ) / [(980,300,000 MJ) + (141,510,000MJ) + (229,966,500 MJ) + (99,303,750 MJ)]

= (980,300,000 MJ) / (1,451,080,250 MJ)

= 0.6756

% Energy distribution $_{\text{CPKO}}$

= (37,736 MJ/ Mt PKO x 3,750 Mt PKO) / [(39,212 MJ/ Mt CPO x 25,000 Mt CPO) + (37,736 MJ/ Mt PKO x 3,750 Mt PKO) + (8,036 MJ/ Mt EFB x 30,000 Mt EFB) + (24,207 MJ/ Mt shell x 9,500 Mt shell) + (18,915 MJ/ Mt palm kernel meal x 5,250 Mt palm kernel meal)]

= (141,510,000MJ) / [(980,300,000 MJ) + (141,510,000MJ) + (229,966,500 MJ) + (99,303,750 MJ)]

= (141,510,000MJ) / (1,451,080,250 MJ)

= 0.0975

% Energy distribution $_{\text{Shell}}$

= (24,207 MJ/ Mt shell x 9,500 Mt shell) / [(39,212 MJ/ Mt CPO x 25,000 Mt CPO) + (37,736 MJ/ Mt PKO x 3,750 Mt PKO) + (8,036 MJ/ Mt EFB x 30,000 Mt EFB) + (24,207 MJ/ Mt shell x 9,500 Mt shell) + (18,915 MJ/ Mt palm kernel meal x 5,250 Mt palm kernel meal)]

= (229,966,500 MJ)/ [(980,300,000 MJ) + (141,510,000MJ) + (229,966,500 MJ) + (99,303,750 MJ)]

= (229,966,500 MJ)/ (1,451,080,250 MJ)

= 0.1585

% Energy distribution $_{\text{Palm kernel meal}}$

= (18,915 MJ/ Mt palm kernel meal x 5,250 Mt palm kernel meal)] / [(39,212 MJ/ Mt CPO x 25,000 Mt CPO) + (37,736 MJ/ Mt PKO x 3,750 Mt PKO) + (24,207 MJ/ Mt shell x 9,500 Mt shell) + (18,915 MJ/ Mt palm kernel meal x 5,250 Mt palm kernel meal)]

= (99,303,750 MJ)/ [(980,300,000 MJ) + (141,510,000MJ) + (229,966,500 MJ) + (99,303,750 MJ)]

= (99,303,750 MJ)/ (1,451,080,250 MJ)

= 0.0684

Calculation result:

Emission $_{\text{CPO, allocated}}$ = 25,309,525 kg CO_2e **x** 0.6756

= 17,098,246.19 kg CO_2e

= 683.9298 kg CO_2e/ Mt CPO

Emission $_{\text{PKO, allocated}}$ = 25,309,525 kg CO_2e **x** 0.0975

= 2,468,196.29 kg CO_2e

= 658.1857 kg CO_2e/ Mt PKO

Emission $_{\text{Shell, allocated}}$ = 25,309,525 kg CO_2e **x** 0.1585

= 4,011,041.35 kg CO_2e

= 422.2149 kg CO_2e/ Mt Shell

Emission $_{\text{Palm kernel meal, allocated}}$ = 25,309,525 kg CO_2e **x** 0.0684

= 1,732,041.18 kg CO_2e

= 329.9126 kg CO_2e/ Mt Palm kernel meal

2) Allocation of GHG of chemicals to the products of dry process

If assumed,

Total GHG emission = 25,000 x 7.114

= 177,850 kg CO_2e

PKO

- Yield = 3,750 Mt
- Yield sold = 3,750 Mt
- LHV = 37,736 MJ/ Mt PKO

Shell

- Yield = 9,500 Mt
- Yield sold = 9,500 Mt
- LHV = 24,207MJ/ Mt Shell

Palm kernel meal

- Yield = 5,250 Mt
- Yield sold = 5,250 Mt
- LHV = 18,915 MJ/ Mt Palm kernel meal

Thus,

% Energy distribution $_{\text{PKO}}$

= (37,736 MJ/ Mt PKO x 3,750 Mt PKO) / [(37,736 MJ/ Mt PKO x 3,750 Mt PKO) + (8,036 MJ/ Mt EFB x 30,000 Mt EFB) + (24,207 MJ/ Mt shell x 9,500 Mt shell) + (18,915 MJ/ Mt palm kernel meal x 5,250 Mt palm kernel meal)]

= (141,510,000MJ) / [(141,510,000MJ) + (229,966,500 MJ) + (99,303,750 MJ)]

= (141,510,000MJ) / (470,780,250 MJ)

= 0.3005

% Energy distribution$_{\text{Shell}}$

= (24,207 MJ/ Mt shell x 9,500 Mt shell) / [(37,736 MJ/ Mt PKO x 3,750 Mt PKO) + (8,036 MJ/ Mt EFB x 30,000 Mt EFB) + (24,207 MJ/ Mt shell x 9,500 Mt shell) + (18,915 MJ/ Mt palm kernel meal x 5,250 Mt palm kernel meal)]

= (229,966,500 MJ)/ [(141,510,000MJ) + (229,966,500 MJ) + (99,303,750 MJ)]

= (229,966,500 MJ)/ (470,780,250 MJ)

= 0.4885

% Energy distribution$_{\text{Palm kernel meal}}$

= (18,915 MJ/ Mt palm kernel meal x 5,250 Mt palm kernel meal)] / [(37,736 MJ/ Mt PKO x 3,750 Mt PKO) + (24,207 MJ/ Mt shell x 9,500 Mt shell) + (18,915 MJ/ Mt palm kernel meal x 5,250 Mt palm kernel meal)]

= (99,303,750 MJ)/ [(141,510,000MJ) + (229,966,500 MJ) + (99,303,750 MJ)]

= (99,303,750 MJ)/ (470,780,250 MJ)

= 0.2109

Calculation result:

Emission$_{\text{PKO, allocated}}$ = 177,850 kg CO_2e **x** 0.3005
= 53,443.9 kg CO_2e
= 14.2517 kg CO_2e/ Mt PKO

Emission$_{\text{Shell, allocated}}$ = 177,850 kg CO_2e **x** 0.4885
= 86,879.7 kg CO_2e
= 9.1452 kg CO_2e/ Mt Shell

Emission$_{\text{Palm kernel meal, allocated}}$ = 177,850 kg CO_2e **x** 0.2109
= 37,508.6 kg CO_2e
= 7.1444 kg CO_2e/ Mt Palm kernel meal

The GHG emission

CPO = 683.9298 kg CO_2e/ Mt CPO
PKO = 658.1857 + 14.2517 = 672.4374 kg CO_2e/ Mt PKO
Shell = 422.2149 + 9.1452 = 431.3601 kg CO_2e/ Mt Shell
Palm kernel meal = 329.9126 + 7.1444 = 337.0570 kg CO_2e/ Mt Palm kernel meal

APPENDIX F

EXAMPLE OF GHG EMISSION REDUCTION

Example of GHG emission Reduction

1. Using air-striping tower to reduce wastewater temperature

The total yearly amount of CPO, amount and characteristic of wastewater and treated wastewater, COD reduction efficiency are assumed and depicted in Table F-1

Table F-1 Total yearly amount of CPO, wastewater volume, characteristic of raw wastewater and treated wastewater, and COD reduction efficiency of biogas system

Parameters	Averaged values
Total yearly amount of CPO, Mt	31,297
Average wastewater volume, m^3/year	75,929
Average COD of influent wastewater, mg/L	93,044
Average COD of influent into biogas system, mg/L	73,027
Average COD of effluent from final pond, mg/L	4,694
Average COD reduction efficiency of biogas system, percent	81

The calculation example,

$$E_{\text{open pond}} = \sum Q_{ww} \text{ x } COD_{removed} \text{ x } MCF_{ww,treatment} \text{ x } B_{o,ww} \text{ x } UF \text{ x } GWP_{CH4}$$

$E_{\text{open pond}}$ = The GHG emission from open ponds

$Q_{ww,\ y}$ = Volume of wastewater treated in the open pond in year *y* (m^3)

$COD_{removed,y}$ = Chemical oxygen demand removed by the open pond in year *y* (Mt/m^3), measured as the difference between inflow COD and the outflow COD in open pond

$MCF_{ww,\ treatment,\ BL}$ = Methane correction factor for wastewater treatment systems (0.80)

$B_{o,ww}$ = Methane producing capacity of the wastewater (IPCC value of 0.25 kg CH_4/kg COD)

UF_{BL} = Model correction factor to account for model uncertainties (0.89)

GWP_{CH4} = Global warming potential for methane (value of 25)

(Source: Methane recovery in wastewater treatment - version 16, AMS-III.H, UNFCCC, 2010)

Calculation result:

$E_{\text{open pond}}$ = (75,929 m^3/year) x [(93,044 – 73,027 mg/L)/1000] x 0.8 x 0.25 kg CH_4/kg COD x 0.89 x 25

= 6,763,425 kg CO_2e

= 216.10 kg CO_2e / Mt CPO

Assumed, the height of air striping tower is 15 m, it require 1.5 kW pump.

The electricity consumption

= 1.5 x 24h/day x 300 days/year

= 10,800 kWh/year

$E_{\text{pump, electricity}}$ = 0.5610 kg CO_2/kWh x 10,800 kWh/year

(EF from, Thailand Greenhouse Gas Management Organization, TGO, 2011)

= 6,059 kg CO_2e

= 0.1936 kg CO_2e/ Mt CPO

The total GHG emission reduction by using the air stripping instead of the open pond

= 6,763,425 – 6,059 kg CO_2e

= 6,757,366 kg CO_2e

= 215.91 kg CO_2e/ Mt CPO (99.91 percent reduction)

2. Upgrading the open pond to be the cover pond

As stated previously, the GHG emission from the open pond is 6,763,425 kg CO_2e. By upgrading the open pond to be the cover pond and using biogas for electricity generation, the GHG emission could come from the fugitive emission and can be computed as shown in the following.

Regard to UNFCCC (2010), the default value of fugitive emission from biogas system is 10 % of GHG captured.

$E_{\text{cover pond, fugitive emission}}$ = 0.1 x 6,763,425 kg CO_2e
= 676,343 kg CO_2e
= 21.61 kg CO_2e / Mt CPO

The GHG reduction = 6,763,425 - 676,343 kg CO_2e
= 6,087,083 kg CO_2e / Mt CPO (90 percent reduction)
= 194.49 kg CO_2e / Mt CPO

In addition, the collected biogas could be used to generate the electricity by gas engine. According to study results of Chotwattanasak and Puetpaiboon (2011) reported that electricity of 2.5 kWh can be generated from 1 m^3 of biogas. Moreover, the study of Chavalparit, et al. (2006) that estimated amount of the produced biogas in the first anaerobic pond of about 0.3 m^3 per kg BOD removed or 6 m^3 of CH_4 per Mt FFB. It was measured gas composition of about 71 % of CH_4 and 29 % of CO_2. Since the COD/BOD ratio of POME is about 1.56 (Choorit and Wisarnwan 2007), it can be calculated electricity amount. The details are as follows:

COD/BOD = 1.56
When COD removal = 20,017 mg/L
BOD removal = 12,831.4 mg/L

The electricity generation= (75,929 m^3wastewater/year) x (12,831.4 g/m^3) x (1 kg/1,000 g)
x (0.3 m^3biogas/1 kg BOD removal) x 2.5 kWh/1 m^3biogas) x
= 730,707 kWh/year

The GHG reduction = 730,707 kWh x 0.561 kg CO_2/kWh
= 409,926.69 kg CO_2e
= 13.10 kg CO_2/ Mt CPO

The GHG reduction by upgrading the open pond to be the cover pond

= 194.49 + 13.10 kg CO_2e/ Mt CPO

= 207.59 kg CO_2e/ Mt CPO

3. Enhanced the performance of biogas system

The calculation of GHG reduction by enhanced the performance of the biogas system was conducted by using the data in Table F-1. The lowest and highest efficiency of biogas system was set at 65 and 93 percent, respectively. The average value of biogas efficiency from 4 mills was 80 percent. Regard to UNFCCC (2010), the default value of fugitive emission from biogas system is equal to 10 percent of GHG captured.

Assumed, the efficiency of biogas system was 65 percent.

1) $E_{\text{biogas system, Fugitive emission}}$ = 0.1 ($Q_{ww,,y}$ x $COD_{removed,\ y}$ x $MCF_{ww,treatment,BL}$ x $Bo_{,ww}$ x UF_{BL} x GWP_{CH4})

= 0.1 [(75,929 m^3/year) x [(73,027 – 25,559 mg/L) /1000] x 0.8 x 0.25 kg CH_4/kg COD x 0.89 x 25]

= 0.1 (16,038,680 kg/CO_2e)

= 1,603,868 kgCO_2e /year

= 51.25 kgCO_2e/ Mt CPO

2) $E_{\text{stabilization pond}}$ = $Q_{ww,,y}$ x $COD_{removed,\ y}$ x $MCF_{ww,treatment,BL}$ x $Bo_{,ww}$ x UF_{BL} x GWP_{CH4}

= (75,929 m^3/year) x [(25,559 – 4,694mg/L) /1000] x 0.8 x 0.25 kg CH_4/kg COD x 0.89 x 25

= 7,049,951 kgCO_2e/year

= 225.26 kgCO_2e/ Mt CPO

Total GHG emission = 1,603,868 kgCO_2e + 7,049,951 kgCO_2e

= 8,653,819 kgCO_2e/year

= 276.51 kgCO_2e/ Mt CPO

4. Changing the stabilization pond to be the aerated lagoon

For the normal practice, the influent COD and effluent of the stabilization pond was 14,605 and 4,694 mg/L.

$E_{\text{Stabilization pond'}}$ = $Q_{ww,,y}$ x $COD_{\text{removed, y}}$ x $MCF_{ww,\text{treatment},BL}$ x $Bo_{,ww}$ x UF_{BL} x GWP_{CH4}

= (75,929 m^3/year) x [(14,605 – 4,694mg/L) /1000] x 0.8 x 0.25 kg CH_4/kg COD x 0.89 x 25

= 3,348,769 kg CO_2e/year

= 107 kg CO_2e/ Mt CPO

Calculation of electricity used

Oxygen requirement = 1.5 * BOD_5 removed

COD/BOD = 1.56

Influent BOD_5 = (14,605 mg/L) / 1.56

= 9,362 mg/L

Effluent BOD_5 = (4,694 mg/L) / 1.56

= 3,009 mg/L

BOD_5 Removed = 9,362 mg/L – 3,009 mg/L

= 6,353 mg/L

= 6.353 kg/m^3

Oxygen requirement = 1.5 * 6.353 kg O_2/m^3

= 9.53 kg O_2/m^3 * 8.7 m^3/hour

= 83 kg O_2/hour

For the theatrical and practical oxygen applied

Oxygen requirement = 83/0.5 kg O_2/hour

= 166 kg O_2/hour

Determine the surface aerator power requirement, assuming that the aerators to be used at are rated 1.2 kg O_2/kWh

Energy = (166 kg O_2/hour)/ (1.2 kg O_2/kWh)

= 140 kW

Assuming the energy for mixing is 5W per cubic meter of the aerated lagoon basin, and detention time is 7 days

The volume of aeration basin

= 7 days x 225 m^3/day

= 1,575 m^3

The energy for mixing requirement is

= 5 W/m^3 x 1,575 m^3

= 8 kW

Energy = 150 kW

Electricity used = 150 kW x 24 hour/day x 365 days/year

= 1,314,000 kWh/year

GHG emission = 0.561 kgCO_2 /kWh x 1,314,000 kWh/year

= 737,154 kg CO_2e/year

= 23.55 kg CO_2 / Mt CPO

The GHG emission reduction

= 107 - 23.55 kg CO_2 / Mt CPO

= 83.45 kg CO_2 / Mt CPO

VITAE

Name Miss Roihatai Kaewmai

Student ID 5210120032

Educational Attainment

Degree	Name of Institution	Year of Graduation
Bachelor of Engineering in Environmental Engineering	Prince of Songkla University, Songkhla, Thailand	2009

Scholarship Awards during Enrolment

Research assistant scholarship, Faculty of Engineering, Prince of Songkla University, Songkhla, Thailand (2009-2011)

List of Publication and Proceeding

Suksaroj, C., Banchapattanasakda, W., Kaewmai, R., Piwdeang, N., Wattanachira, S., and Musikavong1, C. (2009). Rejection of Dissolved Organic Matter in Raw Water Supply by Different Membrane Pore Size. *The 7th International Symposium on Southeast Asian Water Environment.* October 28-30, Bangkok, Thailand.

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