THE COMBINED MATERIAL FLOW ANALYSIS AND LIFE CYCLE ASSESSMENT FOR INTEGRATED END-OF-LIFE OF MERCURY CONTAMINATED PETROLEUM WASTE MANAGEMENT

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ABSTRACT

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Putthita Chongchongprasert: The combined Material Flow Analysis and Life Cycle Assessment for integrated end-of-life of mercury contaminated petroleum waste management.

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Now a day, the waste management generated by offshore petroleum operation (including drilling and production) located in the Gulf of Thailand seem to be a great challenge. Because of their unique characteristic in terms of hazardous properties, petroleum waste requires particular treatments to reduce potential impacts to the environment and human life. This study, the petroleum waste by their disposal code, and waste code was sorted. The Hg-contaminated petroleum waste flow starting from waste generation towards to final disposal was conducted by Material Flow Analysis (STAN, 2.6.601) and Life Cycle Assessment (SimaPro 8.3.0.0) was conducted as tools for evaluating the environmental impacts. The treatment of Hg-contaminated waste was studied by SimaPro LCA software (SimaPro 8.3.0.0) using ReCiPe mid-point (H) method. The human toxicity (kg 1,4-DB eq) and climate change (kg CO_2 eq) impacts were selected because of human toxic damage and global warming concerns. The functional unit was one kg of Hg-contaminated waste. The treatment option was divided into four methods including storage, fuel blending, recovery unlisted material, and landfill. The combined result showed that Hg-contaminated waste disposed of Hg recovery indicated the benefit contributed to human toxicity (-1,344,704 t 1,4-DB eq) but high negative impact on climate change (34,785 t CO_2 eq). The landfill option indicated the high human toxicity impact (5.647 t 1,4-DB eq).

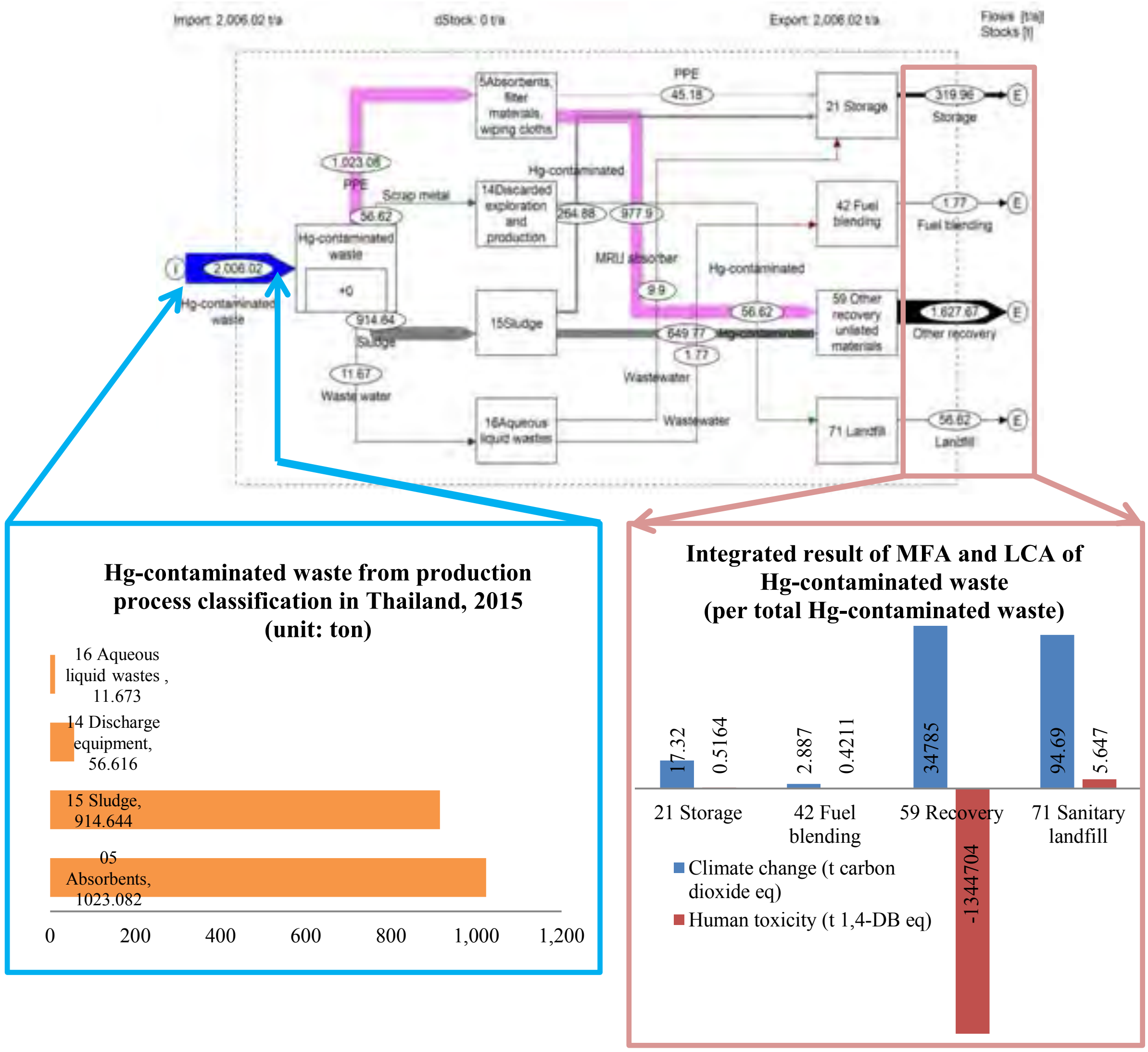
บทคัดย่อ

พุฒิตา จงจงประเสริฐ : การวิเคราะห์การไหลของวัสดุร่วมด้วยการประเมินวัฏจักรชีวิตในขั้นสุดท้ายของของเสียปนเปื้อนปรอทที่เกิดจากกิจกรรมปิโตรเลียม (The combined Material Flow Analysis and Life Cycle Assessment for integrated end-of-life of mercury contaminated petroleum waste management) อ. ที่ปรึกษา : ดร. อัมพิรา เจริญแสง 119 หน้า

ในปัจจุบันการจัดการของเสียที่เกิดขึ้นจากการดำเนินงานด้านปิโตรเลียมนอกชายฝั่ง (รวมถึงการขุดเจาะและการผลิตปิโตรเลียม) ที่ตั้งอยู่ในอ่าวไทยถือเป็นความท้าทายที่ยิ่งใหญ่เนื่องจากคุณสมบัติที่เฉพาะของของเสียในแง่ของคุณสมบัติที่เป็นอันตราย ดังนั้นของเสียปิโตรเลียมจึงต้องได้รับการบำบัดโดยวิธีเฉพาะเพื่อลดผลกระทบที่อาจเกิดขึ้นกับสิ่งแวดล้อมและชีวิตมนุษย์ได้ ในการศึกษาครั้งนี้ของเสียจากกระบวนการปิโตรเลียมจะถูกเรียงตามรหัสขยะและรหัสการกำจัด เครื่องมือที่ใช้สำหรับการประเมินสิ่งแวดล้อมในการศึกษาคือการไหลของของเสียปิโตรเลียมที่ปนเปื้อนปรอท เริ่มตั้งแต่การก่อกำเนิดของของเสียไปจนถึงการกำจัดในขั้นตอนสุดท้ายซึ่งดำเนินการโดยการวิเคราะห์การไหลของวัสดุ (สแตน 2.6.601) และการประเมินวัฏจักรชีวิต(8.3.0.0) ผลกระทบการรักษาของเสียที่ปนเปื้อนปรอทได้รับการศึกษาโดยซอฟต์แวร์ซิมาโปรโดยใช้วิธีการเรซิพี มิดพอยท์แบบเอช ความเป็นพิษของมนุษย์ (กิโลกรัมของ 1,4 ไดคลอโรเบนซีนสมมูล) และการเปลี่ยนแปลงสภาพภูมิอากาศ (กิโลกรัมของคาร์บอนไดออกไซด์สมมูล) ถูกเลือกเป็นผลกระทบที่ศึกษาเนื่องจากความเป็นพิษต่อมนุษย์ที่และปัญหาโลกร้อน โดยมีหน่วยหน้าที่คือหนึ่งกิโลกรัมของของเสียปนเปื้อนปรอท สำหรับวิธีการในการกำจัดของเสียแบ่งออกเป็นสี่วิธี ได้แก่ การเก็บรักษา การทำเชื้อเพลิงผสม การนำสิ่งปฏิกูลหรือวัสดุที่ไม่ใช้แล้วอื่นๆกลับคืนมาใหม่และการฝังกลบ จากผลการวิเคราะห์แสดงให้เห็นว่าของเสียที่ปนเปื้อนปรอทที่กำจัดโดยการนำปรอทกลับคืนมาใหม่ให้ประโยชน์ที่เป็นพิษต่อมนุษย์ (-1,344,704 ตันของ 1,4 ไดคลอโรเบนซีนสมมูล) แต่ให้ผลกระทบเชิงลบต่อการเปลี่ยนแปลงสภาพอากาศในปริมาณสูง (34,785 ตันของคาร์บอนไดออกไซด์สมมูล) สำหรับการฝังกลบระบุนั้นให้ค่าผลกระทบต่อความเป็นพิษของมนุษย์มากที่สุด (5.647 ตันของ 1,4 ไดคลอโรเบนซีนสมมูล)

GRAPHICAL ABSTRACT

Material Flow Analysis of Hg-contaminated



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CHAPTER I
INTRODUCTION

1.1 Introduction

The petroleum industry is the majority of manufacturing in Thailand. The high volume of petroleum demand causes more offshore waste generated. The waste generated in drilling and production with different portion and characteristics. The various wastes such as drill cuttings, oily wastewater, and Hg-contaminated waste are generated throughout a process. In addition, waste management from offshore petroleum operation becomes important in term of environmental regulation concern and human health protection. Therefore, waste disposal needs reasonable treatment for controlling and reducing environmental impacts. The Department of Industrial Works (DIW) and Department of Mineral Fuels (DMF), Thailand involved with responsibility for regulating the petroleum activities and its waste disposal methods. Because of the large amount of wastes disposed of from drilling and production, identifying appropriate waste treatment and disposal method become a challenge for those offshore industries. All of the offshore waste is identified and classified into categories based on two department database. Some of them are classified as a hazardous waste which needs extraordinary waste management such as waste with mercury (Hg)-contaminated. Wastes utilization technologies have been developed for reducing landfill disposal and convert into useful sources.

The reason to concentrate on Hg-contaminated waste was the high volume and its toxicity. In the Gulf of Thailand, the oil and gas reservoir contains a high concentration of mercury in gas and liquid form of petroleum. Mercury concentration is around 100-400 $\mu g/m^3$ in gas form and 400-1200 $\mu g/kg$ in liquid form (Sainal et al., 2017). Mercury is highly toxic that cause environmental and human impacts in daily life. According to mercury and health news topic, mercury is considered as a top-ten of chemicals of major public health concern by the World Health Organization (WHO) website. For the source of Hg released from petroleum production, they exist in hydrocarbons which are found in petroleum production, processing, transportation, and consumption systems. In the offshore production process, it can be released in the form of contamination in the petroleum wastes. Thus, mercury contaminated waste becomes the most concern in petroleum waste management. This study interested in Hg-contaminated waste management because of high contamination volume in Thailand offshore petroleum waste and its toxic release to the environment and human health.

There are environmental assessment tools for waste management. Material flow analysis or MFA is one of the primary tools for balancing the amount of waste flow in the boundary system (Huang *et al.*, 2012). MFA offers a linked waste flow in the system for strategic scheme development and design. The environmental impact of waste management activities can be a major concern issue for waste handling. Thus, life cycle assessment (LCA) is a tool for determining the potential environmental impacts thoroughly the entire product's life cycle. All of these two methods are applied as a tool for offshore petroleum waste and Hg-contaminated waste.

This study, the combined MFA and LCA are expected to provide the integrated relative result between the mass of waste and their environmental impacts. The waste in each disposal option and its environmental impacts are in the flow scheme represented the Hg-contaminated waste management and environmental assessment.

1.2 Objectives

The main objective of this study is to conduct the material flow analysis (MFA) and evaluate the environmental impacts of offshore petroleum waste (Hg-contaminated waste) disposal strategies.

- To identify and classify petroleum waste and conduct their waste flow regarding waste disposal options using MFA concept.
- To develop the waste treatment inventory of each disposal method for MFA and LCA study
- To evaluate the environmental impacts of petroleum waste disposal by conducting LCA at the end of life stage.

CHAPTER II
LITERATURE REVIEW

2.1 Petroleum Industry

Petroleum resource is a hydrocarbon occurred by natural sedimentation beneath the earth's surface. It exists in any state depending on temperature and pressure in the reservoir. Majority of the petroleum fractions are crude oils and natural gases which the utilization process governs by petroleum industries consisting of many operational processes which are divided into upstream, midstream and downstream. For the upstream mainly includes exploration and production so-called E&P of the crude oil and natural gas process. The midstream is deal with the transportation of products from upstream processes. Refineries are categorized into the downstream. Petroleum product is utilized for various products such as gasoline, pharmaceuticals, and solvent. During the operation, the wastes are generated through the whole processes. The waste must be handled with proper waste management technologies to reduce human and environmental impacts. According to environmentally concern, environmental impacts assessment or EIA become an important role in petroleum waste management (Jafarinejad, 2017).

2.2 Wastes from Exploration and Production

Wastes from the exploration and production (ESP) occur during such as drilling (i.e. drill cuttings), production (i.e. produced water), maintenance and decommissioning activities. In offshore exploration and production, base mud and cuttings from the drilling activity are the major waste. A large amount of base mud and cuttings wastes are re-injected into the well. General wastes generated are categorized into wastewater, air emission and solid waste (Jafarinejad, 2017).

2.2.1 Wastewater

Produced water, drilling fluid (base mud) and cuttings are the main sources of aqueous wastes in E&P.

2.2.2 Air Emission

In E&P process, several air pollutants such as volatile organic compounds (VOCs), hydrocarbons in the gas state, carbon dioxide and partially carbon monoxide. In addition, ozone-depleting gases (CFC) released in the drilling process.

2.2.3 Solid Waste

Solid wastes mainly from contaminated soils, oily base mud, etc. generated from the exploration and production. Some of the solid wastes generated in E&P are listed in Table 2.1.

Table 2.1 Example of solid wastes generated in E&P process (Jafarinejad, 2017)

Main Sources	Environmentally Significant Components
Tank/piping sludge, induced gas floatation unit/dissolved gas floatation unit (IGF/DGF) sludge, waxes	Inorganic salts, heavy metals, solids, organics, BOD, sulphides, corrosion inhibitors, biocides, demulsifiers, wax inhibitors, scale inhibitors, phenols, PAHs, hydrocarbons
Production chemicals	Demulsifiers, corrosions inhibitors, wax inhibitors, scale inhibitors, antifoaming agents, biocides, oxygen scavengers, flocculants
Industrial refuse	Heavy metals, metals, plastics, paints
Spent catalysts, e.g., catalyst beds, molecular sieve	Hydrocarbons, heavy metals, inorganic salts
Pigging sludges	Inorganic salts, hydrocarbons, heavy metals, solids, production chemicals, NORM, phenols, aromatics
Domestic refuse	Plastics, glass, organic waste

Typically, wastes from upstream process are mostly determined by solid waste and wastewater. The solid wastes can be classified into hazardous and non-hazardous waste. According to Thai’s law by type of wastes, petroleum industry is required to responsibility for handling a proper waste management system.

2.3 General Waste Management and Disposal Methods in Thailand

In Thailand, the Department of Mineral Fuel (DMF) and Department of Industrial Work (DIW) are the regulator to in charge with waste disposal. The waste generation code and disposal code provide systematic waste classification and their disposed method. Simply waste category distributes high efficiency of waste management. Therefore, they regulate their waste generation code and waste disposal code for waste management.

According to DMF, the principle of waste generation and waste disposal code has been announced in the waste management guideline from petroleum operations handbook since 2014. Waste codes also based on the data obtained from DIW. The waste generator must identify and quantify their waste generation followed by this announcement and write down in the waste disposal plan. The waste generator must report their waste disposal plan by monthly and annually. Waste generation codes are provided below in Table 2.2.

Table 2.2 Waste code mapping (Source: DMF disposal manual, 2014)

Waste code	Description
01 Produced water	
0101	Produced water containing dangerous substances
0102	Produced water other than those mentioned in 0101
02 Drilling muds	
0201	Water base mud
0202	Synthetic base mud containing dangerous substances
0203	Synthetic base mud other than those mentioned in 0202
0204	Oil base mud
03 Drill cutting	
0301	Drill cutting from water base mud
0302	Drill cutting from synthetic base mud
0303	Drill cutting from synthetic base mud other than those mentioned in 0302
0304	Drill cutting from oil base mud
04 Oil and liquid fuels	

Waste code	Description
0401	Waste hydraulic oils
0402	Waste engine, gear and lubricating oils
0403	Waste insulating and heat transmission oils
0404	Fuel oil and diesel
0405	Petrol
0406	Brake fluids
0407	Other fuels (including mixtures)
0408	Example analysed oil
0409	Oil wastes not otherwise specified
05 Absorbents, filter materials, wiping cloths and personal protective equipment	
0501	Absorbents, filter materials, wiping cloths and personal protective equipment contaminated by dangerous substances
0502	Absorbents, filter materials, wiping cloths and personal protective equipment other than those mentioned in 0501
0503	Absorbents, filter materials, wiping cloths and personal protective equipment contaminated by oil
06 Discarded chemicals	
0601	Discarded organic chemicals consisting of or containing dangerous substances
0602	Discarded inorganic chemicals consisting of or containing dangerous substances
0603	Discarded laboratory chemicals, consisting of or containing dangerous substances, including mixtures of laboratory chemicals
0604	Discarded chemicals other than those mentioned in 0601, 0602 or 0603
0605	Gas in pressure containers (including halons) containing dangerous substances
0606	Gas in pressure containers other than those mentioned in 0605
07 Off-specification, expired or unused chemicals	

Waste code	Description
0701	Off-specification, expired or unused chemicals consisting of or containing dangerous substances
0702	Off-specification, expired or unused chemicals other than those mentioned in 0701
0703	Off-specification, expired or unused gas in pressure containers (including halons) containing dangerous substances
0704	Off-specification, expired or unused gas in pressure containers other than those mentioned in 0703
08 Spent catalysis	
0801	Spent catalysts containing gold, silver, rhenium, rhodium, palladium, iridium or platinum (except 0804)
0802	Spent catalysts containing dangerous transition metals (transition metals are included scandium, vanadium, manganese, cobalt, copper, yttrium, niobium, hafnium, tungsten, titanium, chromium, iron, nickel, zinc, zirconium, molybdenum and tantalum) or dangerous transition metal compounds
0803	Spent catalysts containing transition metals or transition metal compounds not otherwise specified
0804	Spent catalysts contaminated with dangerous substances
09 Electrical and electronic equipment	
0901	Transformers and capacitors containing PCBs
0902	Discarded equipment containing or contaminated by PCBs
0903	Discarded equipment containing chlorofluorocarbons, HCFC, HFC
0904	Discarded equipment containing free asbestos
0905	Discarded equipment containing hazardous components (hazardous components from electrical and electronic equipment may include accumulators and batteries and marked as hazardous; mercury switches, glass from cathode ray tubes and other activated glass, and etc.) other than those mentioned in 0901 to 0904

Waste code	Description
0906	Discarded equipment other than those mentioned in 0901 to 0905
0907	Hazardous components removed from discarded equipment
0908	Components removed from discarded equipment other than those mentioned in 0907
10 Batteries and accumulators	
1001	Lead batteries
1002	Ni-Cd batteries
1003	Mercury containing batteries
1004	Alkaline batteries (except 1003)
1005	Other batteries and accumulators
1006	Separately collected electrolyte from batteries and accumulators
11 Packaging	
1101	Paper and cardboard packaging
1102	Plastic packaging
1103	Wooden packaging
1104	Metallic packaging
1105	Composite packaging
1106	Mixed packaging
1107	Glass packaging
1108	Textile packaging
1109	Packaging containing residues of or contaminated by dangerous substances
1110	Metallic packaging containing a dangerous solid porous matrix (for example asbestos), including empty pressure containers
1111	Packaging containing oil or liquid fuel
12 Linings, refractories and insulation materials	
1201	Linings and refractories containing dangerous substances
1202	Linings and refractories other than those mentioned in 1201
1203	Insulation materials containing asbestos

Waste code	Description
1204	Insulation materials consisting of or containing dangerous substances
1205	Insulation materials other than those mentioned in 1203 and 1204
13 Construction and demolition wasted	
1301	Mixtures of, or separate fractions of concrete, bricks, tiles and ceramics containing dangerous substances
1302	Mixtures of, or separate fractions of concrete, bricks, tiles and ceramics other than those mentioned in1301
1303	Glass, plastic and wood containing or contaminated with dangerous substances
1304	Wood
1305	Glass
1306	Plastic
1307	Metal waste contaminated with dangerous substances
1308	Metals including their alloys
1309	Cables containing oil, coal tar and other dangerous substances
1310	Cables other than those mentioned in 1309
1311	Construction and demolition waste containing mercury
1312	Construction and demolition waste containing PCB (for example PCB-containing sealants, PCB-containing resin-based floorings, PCB-containing sealed glazing units, PCB-containing capacitors)
1313	Construction and demolition waste (including mixed wastes) containing dangerous substances
1314	Construction and demolition waste other than those mentioned in 1311, 1312 and 1313
14 Discarded exploration and production equipment	
1401	Discarded casing or tubing from exploration and production wells
1402	Discarded drilling bits and drill pipes
1403	Discarded tubing or piping from production
1404	Discarded pressure gauge or temperature gauge or meters

Waste code	Description
1405	Discarded cables
1406	Discarded sling
1407	Discarded valves
1408	Discarded tanks or vessels
1409	Discarded exploration and production equipment containing oil
1410	Discarded exploration and production equipment containing dangerous substances
1411	Discarded exploration and production equipment other than those mentioned in 1401-1410
15 Sludge	
1501	Sludge waste from vessel, tank and barrel cleaning and pipe pigging containing oil
1502	Sludge from process equipment containing oil or dangerous substances
1503	Sludge from process equipment other than those mentioned in 1502
1504	Sludge from storm water pond
1505	Sludge from produced water pit containing dangerous substances
1506	Sludge from produced water pit other than those mentioned in 1505
1507	Sludge not otherwise specified
16 Aqueous liquid wastes (from domestic wastewater, treated process wastewater, untreated process wastewater, brine water, boiler blow-down and cooling tower blow down)	
1601	Aqueous liquid wastes containing dangerous substances
1602	Aqueous liquid wastes other than those mentioned in 1601
17 Wastes from human health care	
1701	Wastes whose collection and disposal is subject to special requirements in order to prevent infection

Waste code	Description
1702	Wastes whose collection and disposal is not subject to special requirements in order to prevent infection (for example dressings, plaster casts, linen, disposable clothing, diapers)
1703	Cytotoxic and cytostatic medicines
1704	Medicines other than those mentioned in 1703
1705	Chemicals consisting of or containing dangerous substances
1706	Chemicals other than those mentioned in 1705
18 Wastes from combustion	
1801	Bottom ash and slag containing dangerous substances
1802	Bottom ash and slag other than those mentioned in 1801
19 Wastes not otherwise specified in the list	
1901	Wastes not otherwise specified in the list containing oil or dangerous substances
1902	Wastes not otherwise specified in the list other than those mentioned in 1901

From DIW, the waste codes are categorized based on the European Waste Code system. The waste is classified into 19 code groups. The group of 1-12 defined as specific wastes from the main production. Group 13 to 19 defined as common wastes (not generated from the major production). In each waste code, it includes a 6 digits number to indicate where and type of waste generated.

In addition, treatment and disposal codes use a basis 3 digits number to indicate waste disposal method. Method of waste disposal generally classified into 8 groups.

In Thailand, DMF establishes the waste disposal code which comprises of 3-digit numbers. The first two digits are the main disposal code. In addition, the last digit is a specific definition of disposal method.

Table 2.3 Waste treatment and disposal methods

Disposal code	Method	Disposal code	Method
01	Sorting	05	Recovery
02	Storage	06	Treatment
03	Reuse	07	Disposal
04	Recycle	08	Other method

As a consequence, the fine-tuned details of waste treatment and disposal method are shown with the last digit of disposal codes as shown in Table 2.4.

Table 2.4 Disposal methods in brief

Disposal code	Method
011	Sorting
021	Storage
031	Use as raw material substitution
032	Return to original producer for disposal
033	Reuse container; to be refilled
039	Other reuse methods
041	Use as fuel substitution or burn for energy recovery
042	Fuel blending
043	Burn for energy recovery
044	Use as co-material in cement kiln or rotary kiln
049	Other recycle methods
051	Solvent reclamation/regeneration
052	Reclamation/regeneration of metal and metal compounds
053	Acid/base regeneration
054	Catalyst regeneration
059	Other recovery unlisted materials
061	Biological treatment

Disposal code	Method
062	Chemical treatment
063	Physical treatment
064	Physico-chemical treatment
065	Physico-chemical treatment of wastewater
066	Direct discharge to central wastewater treatment plant
067	Chemical stabilization
068	Chemical fixation using cementitious and/or pozzolanic material
069	Other detoxification methods
071	Sanitary landfill
072	Secure landfill
073	Secure landfill of stabilized and/or solidified wastes
074	Burn for destruction
075	Burn for destruction in hazardous waste incinerator
076	Co-incineration in cement kiln
077	Deep well or underground injection; sea-bed insertion
079	Other disposal methods
081	Collect and export
082	Land reclamation
083	Composting or soil conditioner
084	Animal feed

2.4 Solid Waste Management in the Petroleum Industry

Disposal method is one of the waste management methods. Generally, disposal methods consist of surface discharge, underground storage, or underground injection, oxidation, incineration, stabilization/encapsulation/solidification, secure landfill, and biodegradation or biotreatment. The waste disposal of E&P process can be both on offshore and onshore. Waste disposal methods in the petroleum industry are listed below (Jafarinejad, 2017).

2.4.1 Surface Discharge

For surface discharge, this method is available for aqueous or solid waste streams. Otherwise, waste must meet a regulation standard before discharge. In some locations, treated solids (such as drill cuttings) are allowed to discharge from the offshore. On the other hand, the solid wastes, which contain hydrocarbons, salts or heavy metals reaching to standard content, are permitted to discharge onshore.

2.4.2 Underground Injection

The underground injection provides the way to transport waste to underground reservoirs. The injection volume must consider based on the geological formation. The disposal well also should locate far from usable water to prevent contaminated. Before waste injection into the underground reservoir, pretreatment is required e.g., oil removal, coagulation, and sedimentation, filtration, aeration, oxygen exclusion, bacteria and mineral-scale treatment, and solids grinding to inject them as slurry. In addition, downhole disposal of oil base mud, water base mud and cuttings wastes may be successful in both onshore and offshore drilling operations. By the way, drill cutting cannot inject directly because of the large particle size. Drill cutting should be broken down into smaller pieces and mud/water slurry mixed before injection.

2.4.3 Burial

Burial of waste in pits is the simple and common disposal method in the past. The problem of burial method is the pollutant migration into usable underground water. Barrier is covered around pits to prevent solid pollutant waste vertically migration. The burial can be applied for the disposal of inert unrecyclable materials and stabilized wastes.

2.4.4 Secure Landfill

Landfilling is the waste deposition into the land and covering with soil. Secure landfill is the landfill constructed and operated with a special design for containing chemical waste that will leach or vaporize. Landfilling has a cheaper option for waste disposal in some country. However, the waste from refineries needs to be pretreatment before going to landfill. Liquid disposal waste is the most important key for design and monitoring in the landfill site. Thus, the underground can be contaminated with the leakage of liquid hazardous material waste.

2.4.5 Stabilization/Solidification/Encapsulation

Stabilization, solidification, and encapsulation are quick and cheap waste treatment processes. These processes generate dry solids. In the solid form, waste is easy to carry out and handle. Stabilization involves the conversion of waste to a chemically stable that resists leaching and encapsulation. Likewise, solidification is involved generation of a durable solid matrix to encapsulate contaminants. Stabilization is deal with transforming contaminants into a less toxic and/or less soluble form.

2.4.6 Incineration

Incineration is a combustion process that converts waste to a less bulky, less toxic, or less noxious material. Incineration system controls to get complete combustion and air-pollution control to minimize air pollution emission. Oily wastes operate complete combustion in excess air and auxiliary fuels condition. Critical parameters and factors that should be controlled during the incineration process are combustion condition, oxygen-to-air ratio, residence time, combustion temperature, waste-feed rates, feedstock quality, presence of auxiliary fuels, and gas emission. Parameters and factors in the incineration process need to be controlled because of complete combustion.

2.4.7 Oxidation Method

Oxidation can be chemical oxidation or other enhanced oxidation processes. The oxidation can be useful for soils and oily sludge treatment referred from research studies. Chemical oxidation occurred by adding reactive chemicals into oily wastes. Reactive chemicals oxidize organic compounds into carbon dioxide and water. Moreover, organic compounds are oxidized and converted into non-hazardous substances.

2.4.8 Biodegradation or Bioremediation

Biodegradation is a conversion of organic molecules into other substances such as water and carbon dioxide by a microorganism. Likewise, bioremediation is an action of materials adding to polluted environments to accelerate the natural biodegradation process. Bioremediation can be influenced by the type of microorganisms, nutrients, bio-surfactants, oxygen, water activity or moisture content, temperature, pH, salinity, time, and the concentration and characteristics of oily waste.

2.5 Hazardous Waste and Characterization

Hazardous waste referred to any waste which has a level of physical, chemical, biological, or infectious properties cause irreparable damage and illness to human health and/or the environment. The important characteristics of hazardous waste are ignitability, corrosivity, reactivity, and toxicity. The waste management of hazardous waste starts with waste generator until waste disposal. Generally, hazardous waste disposal is secured landfill and incineration (Rao et al., 2017).

2.5.1 Ignitability

Hazardous wastes which categorized as an ignitability substance are

• A liquid, other than an aqueous solution, containing, 24% alcohol by volume, and it has a flash point, 60°C;

• A liquid and is capable, under standard temperature and pressure, of causing fire through friction, absorption of moisture, or spontaneous chemical changes and when ignited, burns so vigorously and persistently that it creates a hazard;

• An ignitable compressed gas;

• An oxidizer that yields oxygen readily to stimulate the combustion of organic matter (e.g., chlorate, permanganate, inorganic peroxide, or nitrate)

2.5.2 Corrosivity

Hazardous wastes with a corrosive property are defined as

• Aqueous and has a pH less than or equal to 2 or greater than or equal to 12.5.

• A liquid and corrodes steel at the rate of 6.35 mm/year at a test temperature of 55°C.

2.5.3 Reactivity

• It is normally unstable and readily undergoes violent change.

• It reacts violently with water.

• It forms potentially explosive mixtures with water.

• When mixed with water it generates toxic gases, vapors or fumes in a quantity sufficient to present a danger to human health or to the environment.

• It is a cyanide- or sulfide-bearing waste that when exposed to pH conditions between 2 and 12.5, can generate toxic gases, vapors, or fumes in a quantity sufficient to present a danger to human health or environment.

• It is capable of detonation or explosive reaction if it is subjected to a strong initiating source or if heated under confinement.

• It is readily capable of detonation or explosive decomposition or reaction at standard temperature and pressure.

• It is a forbidden explosive.

• A solid waste that exhibits the characteristic of reactivity, but is not listed as a hazardous waste.

2.5.4 Toxicity

Toxicity is characterized by leaching procedures (TCLP). TCLP is applicable to mobility determination of metals and semivolatile organic compounds in soils. The complete evaluation of this would require two extractions, one for volatile and semivolatile compounds, and the other for metals. The TCLP test consists of five steps, namely separation procedure, particle-size reduction, extraction of solid material, the final separation of the extraction from the remaining solid, and testing/analysis of TCLP extract. Apparatus required for TCLP test is the agitation apparatus and extraction apparatus.

• The agitation apparatus must be capable of rotating the extraction vessel in an end-over-end fashion at 30, 62 rpm. The criteria are to prevent stratification of the sample and extraction fluid ensuring that all sample surfaces are continuously brought into contact with well-mixed extraction fluid.

• The extraction apparatus is a zero head-space extraction vessel. This is for use when the waste is being tested for the mobility of volatile analyses. The zero head extraction allows for liquid/solid separation within the device and allows for initial liquid/solid separation, extraction, and final extract filtration without opening the vessel with an internal volume of 500, 600 ml and accommodate a 90, 100 mm filter.

2.6 Tools for Waste Assessment and Management

2.6.1 Material Flow Analysis (MFA)

Material Flow Analysis or MFA is an engineering analysis tools based on flow quantities. MFA used to analyze including transformation, transportation, or storage of materials within a studied system (Allesch and Brunner, 2015). The principal of MFA is mass balance basis which helps to determine the capacity of waste treatment process dealing with amount of waste generation in each type. MFA is widely used in process design involving (1) defining a system boundary, (2) capturing the system structure and flows, (3) investigating database and calculation, and (4) analyzing material system processes and performing system balances (Huang *et al.*, 2012).

Astrid and Paul (2017) studied a tool to improve waste management systems in Austria. Mass flow analysis (MFA) was used as a waste management tool in this study. STAN was the main software performing MFA. Systems orientation and linked flow process by MFA method were helped the waste management. The key to performing MFA was a mass balance scoped with the interested-boundary system. The main point of MFA was the inputs must equal to outputs plus the change in stock. In this study, the waste management was improved by concentrate on goods level and substance levels such as carbon, cadmium and zinc. In a comprehensive way, the material flow began with waste input into boundary system. The material flow balance followed by collection, transportation, treatment, and recycling process. Also, landfill and their emissions should be linked to goods and substances assessment level. Austria conducted MFA to achieve 5-aims for waste management. The aims consisted of protection of living, reduction of greenhouse gases and air pollution, resources conservation, recycled material production which provide higher risk than generally, and waste storage without dangerous cases. Waste management was held to fulfill those aims. First of all, the scope and system boundary need to be established. The study focuses on all of the processes from collection to the landfill or etc. The relevant data in the year 2012 was chosen basically on its availability. The data were collected from official statistics, stakeholder and literature reviews. After that, collecting data was performed using STAN for waste management evaluation. All of the wastes were grouped by substance concentration basis. The major amount of waste was from construction and demolition in Austria. Composting plant is the most popular for waste treatment. In substance level, carbon is the most discharge in the form of carbon dioxide. The scenario had been assumed dealing with analysis data from MFA and statistics. The target of scenario analysis was to study the change in the waste management system and their impacts. Based case and assumption scenario were compared. In summary, collection and recycling were the best for Austria according to the scenario analysis. MFA performing had several benefits, for example, ensuring the consistency data, data set can use as a basis for subsequent assessment methods.

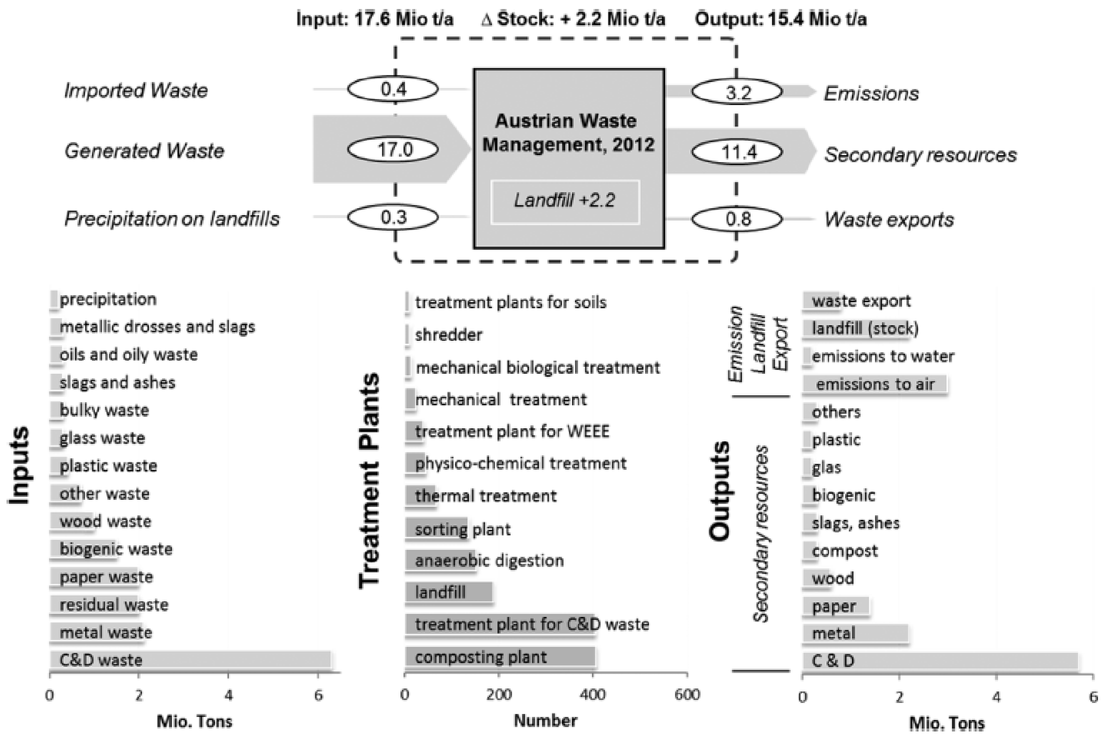


Figure 2.1 Material Flow Analysis (MFA) represented the waste management of Austria in the year 2012.

Nemanja and Paul (2014) studied the combination of material flow and substance flow in waste management. Both of material flow analysis (MFA) and substance flow analysis (SFA) were based on the mass balance principle. SFA was concentrated more on waste transformation during waste treatment operation. Generally, the MFA and SFA performed in a level of goods and substance for waste management. This study selected a region in the Republic of Serbia as a representative country. The objective of this study was to analyse the impact of different waste management. First of all, the obligations of this country for the environment and waste disposal must concern before setting up the scenarios. The scenarios were developed for 1 status quo of waste management and 3 new scenarios deal with total material flows and selected indicators substance. MFA and SFA performed using STAN software. In SFA, data required because of many substances in each good. All new scenarios were developed basis on assumptions to overcome the shortcomings. The base case of research called the status quo. The shortcomings consisted of resources conservation, landfill minimization, no negative impact on landfill emission, energy utilization to reduce fossil fuel consumption and no negative impact of waste treatment emission on livings. According to all criteria on shortcomings, 3 scenarios were developed. The assumptions for 3 new scenarios were provided as follow:

Scenario I: cement kiln and sanitary landfilling

Scenario II: waste-to-energy, sanitary landfill and hazardous waste landfill

Scenario III: waste-to-energy, sanitary landfill and hazardous waste landfill, Incineration without pre-treatment

Carbon, nitrogen, chlorine, cadmium, lead and mercury were selected as an interested substance in this study. As a consequence, the study of waste management by the MFA and SFA combination resulted in simply understandable. MFA was important for planning and designing of waste management. On the other hand, MFA/SFA still had some limitations. MFA/SFA combination needed to be evaluated by individual methods. In addition, information required good quality and abundant data. The data for MFA was efficient while scarcely in MFA. By the way, the combination showed good performance for indicating the comparison between the status quo and new scenarios.

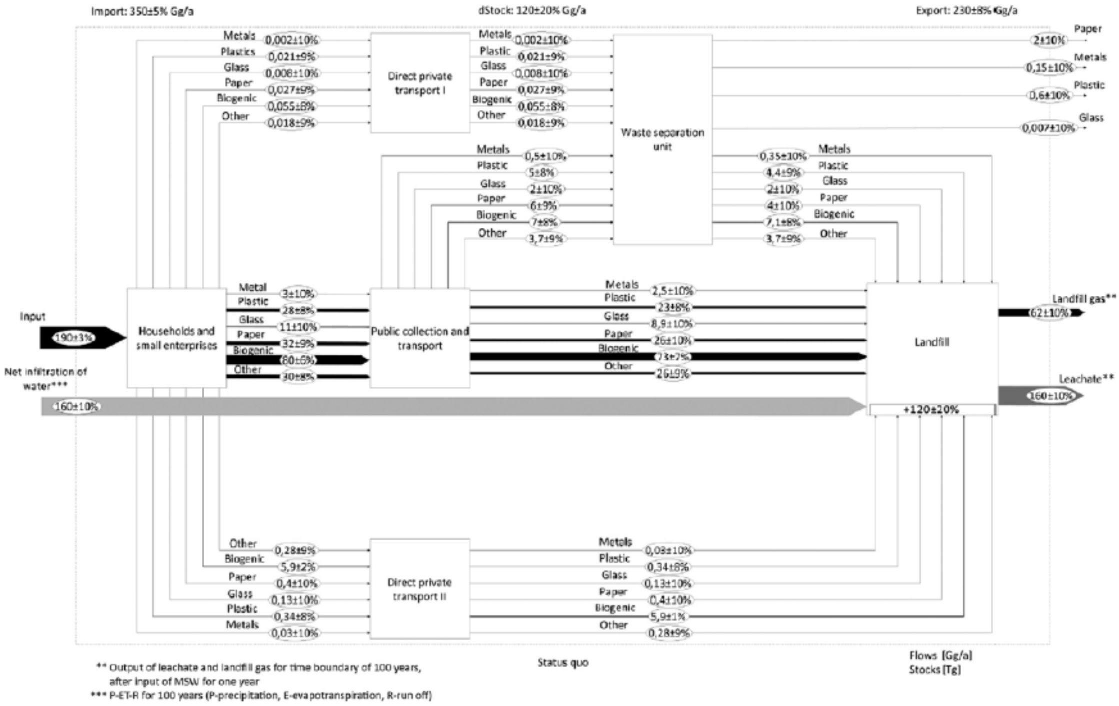


Figure 2.2 MFA of base case scenario (Nemanja and Paul, 2014).

2.6.2 Life Cycle Assessment (LCA)

From Scientific Applications International Corporation (2006), Life Cycle Assessment or known as LCA is a tool for environmental impacts assessment. LCA assesses the environmental impacts generated through whole process or human activities from raw material to end of life.

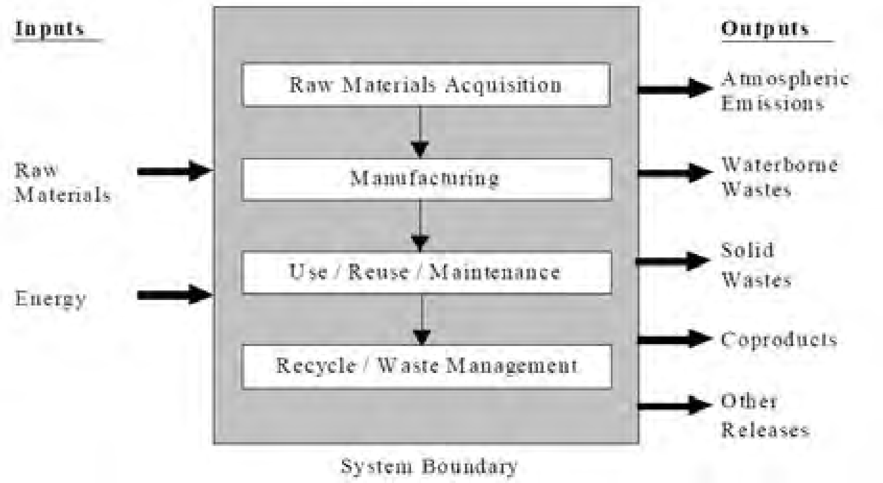


Figure 2.3 Life cycle stage

LCA tool can be assess the impacts by compiling an inventory of relevant energy, materials inputs and also waste releases to the environment. After that, the potential impacts are evaluated regarding inputs and outputs data. Result interpretation is the last process for decision making.

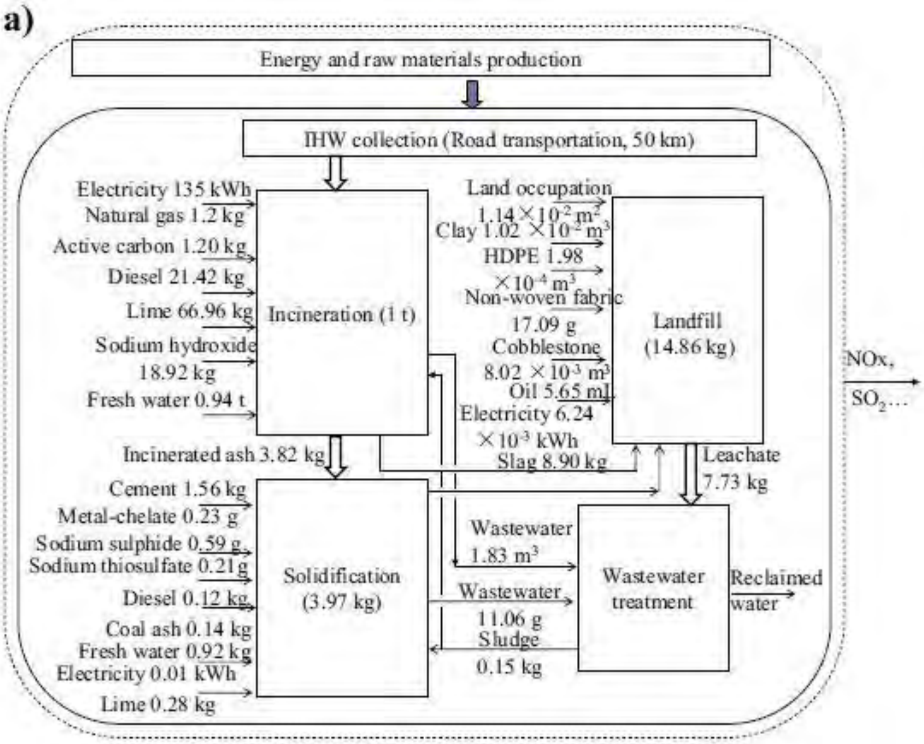
Figure 2.4 Life Cycle Assessment framework (Scholten, 2019).

LCA has 4 steps to access environmental impacts including goal and scope definition, inventory analysis, impact assessment and interpretation. First, goal and scope definition are to identify the boundary of the environmental effects in the assessment context. Second, inventory analysis is an identification and quantification of energy and materials usage, and environmental releases. Third, impact assessment is the potential human and ecological effects defined in the inventory analysis. Last, the interpretation step is the result evaluation and impact assessment to offer a clear solution under uncertain assumptions.

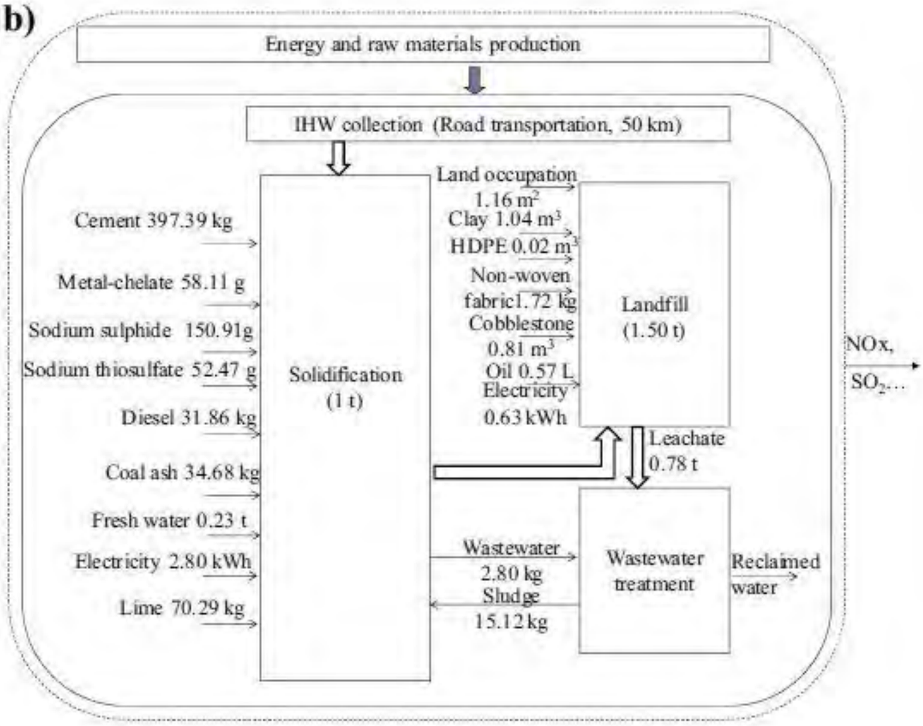
Samuel *et al.* (2012) studied the indicators for the assessment of sustainable production using petrochemical industry in Malaysia as a case study. Petrochemical industries were selected because they produced non-renewable fossil fuels and high energy consumption for operation. The Lowell Centre for Sustainable Production (LCSP) 5 tiers frameworks was utilized. The 5 tiers consisted of level 1: conformance indicators, level 2: performances indicators, level 3: effect indicators, level 4: supply chain and product life cycle indicators, level 5: sustainable systems indicators. Indicators were identified by the Global Reporting Initiative (GRI). For GRI guidelines, performance indicators were divided into 6 groups including environment, economic, society, human rights, labor practices and decent work, and product responsibility. LCSP represented the progressive of sustainability operating in the organization. The data was collected by questionnaire survey method and supplemented with semi-structured in-depth interviews. The results showed that the indicators were monitored mainly in the level of facilities compliance/conformance. Some indicators were in the level of performance and environmental impacts. The indicators on supply chain and product life cycle were insufficient monitored.

Jinglan *et al.* (2016) studied the industrial hazardous waste (IHW) incineration and landfilling by life cycle assessment in China. The LCA was performed by ReCiPe model. The waste disposal treatment was divided into three cases. The cases included incineration, landfill, and waste oil recovered from industrial hazardous waste. The incineration system included incineration unit, solidification, landfill, and wastewater treatment (see Figure 2.5a). The IHW landfill includes solidification, landfill, and wastewater treatment (see Figure 2.5b). The waste oil recovery system included distillation, incineration, incinerated ash solidification, landfill, etc. (see Figure 2.5c). The waste disposed of by each IHW disposal system was different in waste type and characteristics. The functional unit of this study was 1 ton of mixed IHW. They conducted twelve mid-point categories of environmental impacts. The human toxicity in this study was divided into carcinogen and non-carcinogens. As a result, the incineration exhibited the most environmental burden and in all impacts categories. On the other hand, the waste oil recovery indicated the lowest potential impacts except for non-carcinogens, climate change, and ozone depletion. The researchers also performed the sensitivity analysis and uncertainty analysis. The decrease of 5% direct emissions led to an increase in the benefit for carcinogens, climate change, and fossil depletion for the incineration system scenario. The uncertainty analysis method was Monte-Carlo simulation. For conclusion, carcinogen was the major impact category because of the direct emissions of mercury and arsenic from the incineration activities. The improvement can be attained by enhancing the use of recycling technology which can be reduced the environmental impacts from IHW disposal.

a)


Energy and raw materials production
IHW collection (Road transportation, 50 km)
Electricity 135 kWh
Natural gas 1.2 kg
Active carbon 1.20 kg
Diesel 21.42 kg
Lime 66.96 kg
Sodium hydroxide 18.92 kg
Fresh water 0.94 t
Incineration (1 t)
Incinerated ash 3.82 kg
Land occupation 1.14×10-2 m2
Clay 1.02 ×10-2 m3
HDPE 1.98 ×10-4 m3
Non-woven fabric 17.09 g
Cobblestone 8.02 ×10-3 m3
Oil 5.65 ml
Electricity 6.24 ×10-3 kWh
Slag 8.90 kg
Landfill (14.86 kg)
Leachate 7.73 kg
NOx, SO2…
Cement 1.56 kg
Metal-chelate 0.23 g
Sodium sulphide 0.59 g
Sodium thiosulfate 0.21 g
Diesel 0.12 kg
Coal ash 0.14 kg
Fresh water 0.92 kg
Electricity 0.01 kWh
Lime 0.28 kg
Solidification (3.97 kg)
Wastewater 1.83 m3
Wastewater 11.06 g
Sludge 0.15 kg
Wastewater treatment
Reclaimed water

b)


Energy and raw materials production
IHW collection (Road transportation, 50 km)
Cement 397.39 kg
Metal-chelate 58.11 g
Sodium sulphide 150.91g
Sodium thiosulfate 52.47 g
Diesel 31.86 kg
Coal ash 34.68 kg
Fresh water 0.23 t
Electricity 2.80 kWh
Lime 70.29 kg
Solidification (1 t)
Land occupation 1.16 m2
Clay 1.04 m3
HDPE 0.02 m3
Non-woven fabric1.72 kg
Cobblestone 0.81 m3
Oil 0.57 L
Electricity 0.63 kWh
Landfill (1.50 t)
Leachate 0.78 t
NOx, SO2…
Wastewater 2.80 kg
Sludge 15.12 kg
Wastewater treatment
Reclaimed water

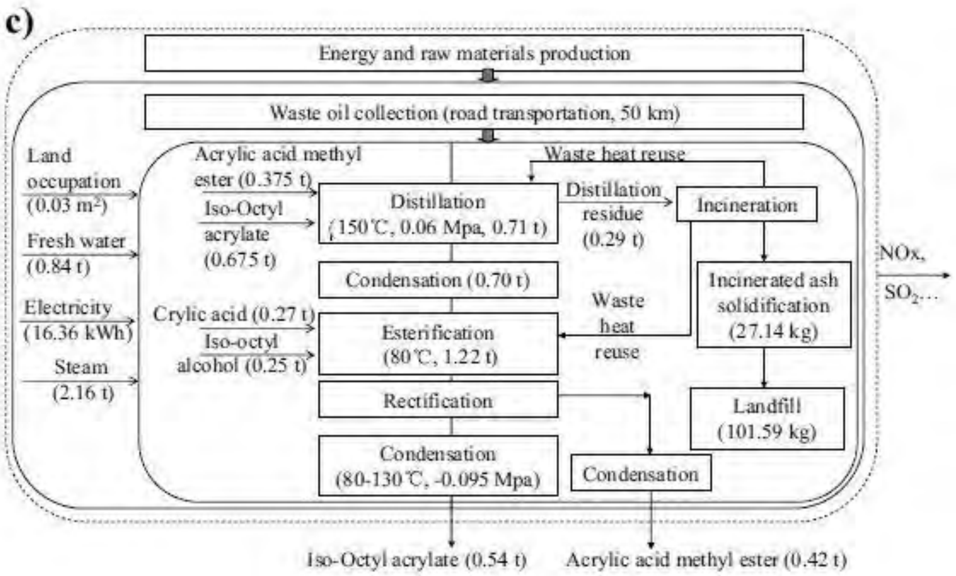


Figure 2.5 System boundary and mass flow of IHW a) incineration, b) landfilling, c) waste oil recovered (Jinglan *et al.*, 2016).

Congcong *et al.* (2017) studied on the life cycle assessment of recycling industrial mercury-containing waste. The environmental impacts were evaluated by ReCiPe H method. The functional unit was equal to the disposal of 10,000 tonnes of Hg-containing waste contained 110.28 tonnes of Hg. The Hg-containing wastes consisted of Hg-added products and Hg from industrial sources. The system boundary included the recycling without and with end-of-life. They performed LCA by SimaPro software. The recovery of Hg was distillation technology which consisted of the pretreatment, distillation, condensation, cleaning, and activated carbon absorption of tail gas. The hydrometallurgical was used for metal extraction. As a result, the Hg recycling was a contributor of Hg release to the air. Both scenarios dominated impacts to carcinogens and non-carcinogens. In addition, the Hg recycling without end-of-life disposal indicated higher impact than Hg with end-of-life disposal.

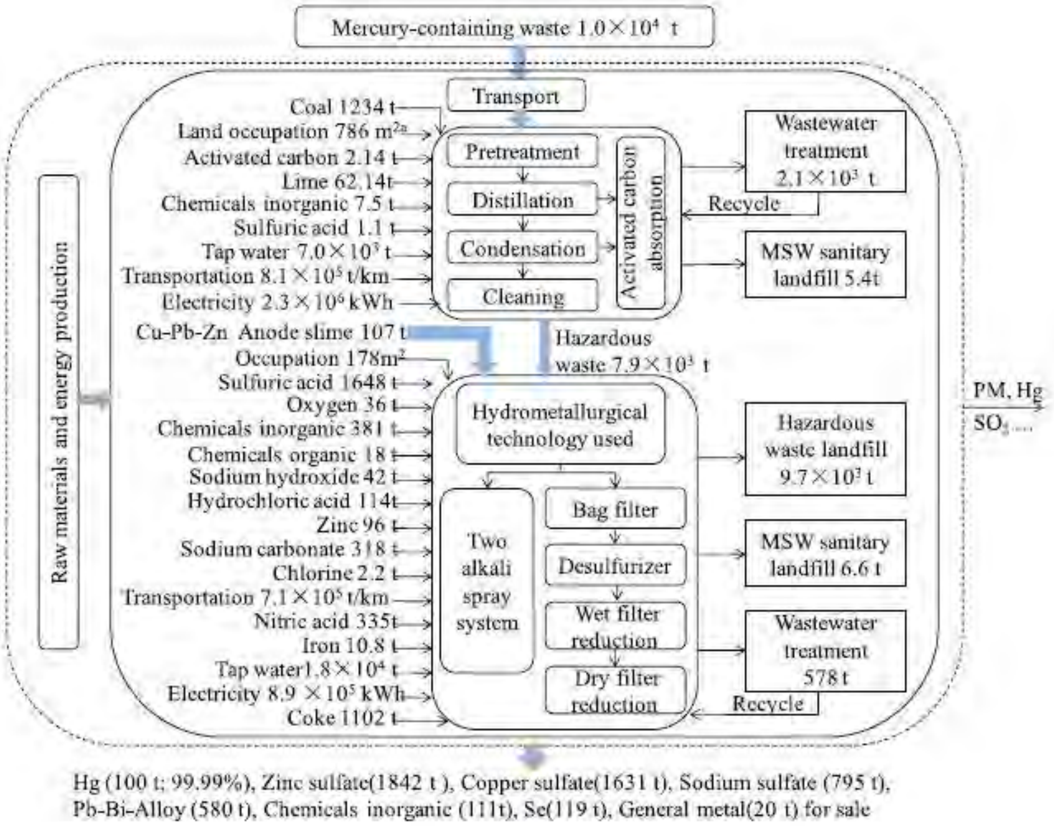


Figure 2.6 System boundary and mass flow of recycling Hg containing waste with end-of-life stage (Congcong *et al.*, 2017).

LCA performing has some limitations on environmental impact assessment. The main problems depend on resource and time intensive. In the gathering data process, the amount of available quality data related to final result accuracy. In addition, time and available data are related together. Quality and reliable data collection need more time to gather. Time-consuming for collecting the data reflects high cost on LCA projects.

Goals, criteria and indicator substances are needed for scenario development. Scenario is developed because to overcome the shortcoming of the system. Each scenario must combine the different treatment method (Scientific Applications International Corporation, 2006).

2.6.2.1 LCA by SimaPro (ReCiPe Evaluation Method)

According to SimaPro database manual-methods library (PRe, 2018), SimaPro consists of different assessment methods which are used to calculate impact assessment results. The SimaPro has a basic structure of impact assessment method including characterization, damage assessment, normalization, weighting, and addition (optional step). First, characterization is the substances which contribute to the impact multiplied by characterization factor. Second, damage assessment is a new step to make use of end-point methods. This assessment combines impact categories into damage categories. Third, normalization is the method to compare the impact category indicator by reference value. After normalization, all the impact category indicators are in the same unit. Lastly, weighting is to weight across the impact categories. Weighting can be applied to the normalization and non-normalization scored.

In addition, SimaPro comprises of a number of impact assessment methods. ReCiPe is one of those methods for impact assessment. ReCiPe consist of both mid-point and end-point impact categories. Mid-point is the categories basis on problem-oriented. While, end-point level is set based on the damage-oriented. End-point is calculated by multiplied mid-point impact with damage factor. In addition, the mid-point level consists of 18 impact categories;

1. Climate change
2. Stratospheric ozone depletion
3. Ionizing radiation
4. Ozone formation, human health
5. Fine particulate matter formation
6. Ozone formation, terrestrial ecosystems
7. Terrestrial acidification
8. Freshwater eutrophication
9. Marine eutrophication
10. Terrestrial ecotoxicity
11. Freshwater ecotoxicity
12. Marine ecotoxicity
13. Human carcinogenic toxicity
14. Human non-carcinogenic toxicity
15. Land use
16. Mineral resource scarcity

17. Fossil resource scarcity
18. Water use

The characterization at the mid-point level is composed of 18 categories, as mentioned. For example, climate change is the global warming potential. The unit is yr/kg CO_2 eq. Human toxicity and ecotoxicity is the factor for environmental persistence and accumulation in the human food chain.

For the end-point level, the impacts are multiplied with damage factors result in 3 end-point categories. They are human health, ecosystems, and resource scarcity.

In ReCiPe, there are 3 perspectives, including individualist (I), hierarchist (H), and egalitarian (E). These used to group similar types of assumptions and choices. The definition for each perspective is followed:

1. Individualist perspective (I) is based on the interested study in short-term, impact types that are undisputed, technological optimism as regards human adaptation.
2. Hierarchist perspective (H) is based on the most common policy principles with regards to time-frame and other issues.
3. Egalitarian perspective (E) is the most precautionary perspective, taking into account the longest time-frame, impact types that are not yet fully established but for which some indication is available.

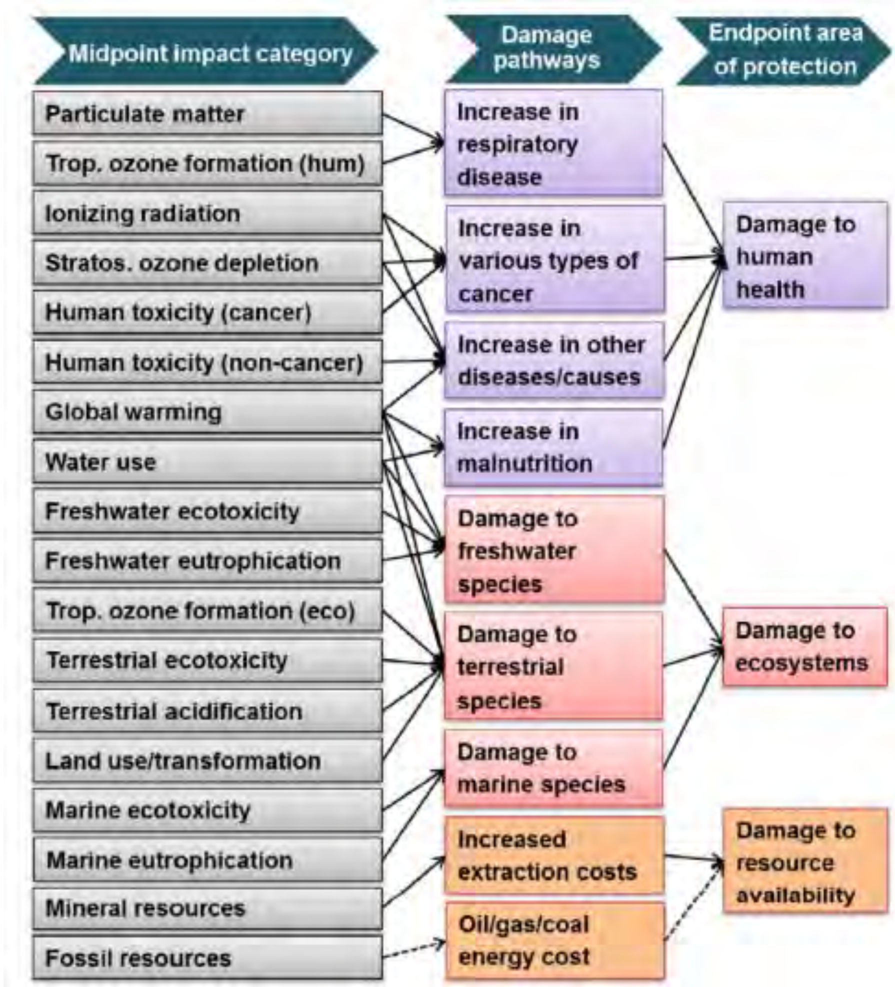


Figure 2.7 The relationship between mid-point and end-point impact categories (Huijbregts *et al.*, 2017).

CHAPTER III
EXPERIMENTAL

3.1 Scopes of the Research

The scopes of this research covered the following:

1. The secondary data of waste generation and waste disposal were gathered from 6 upstream offshore petroleum representatives in Thailand and in the calendar year 2015.
2. The end-of-life of waste management specified by disposal method and waste treatment was scoped for the study boundary.
3. The waste classification is based on database from the waste disposal guideline DIW (2005), the Ministry of Industry and Waste Management from Petroleum Operations Handbook, Department of Mineral Fuels (DMF, 2014).
    a. The waste treatment option and disposal method were divided into 8 main groups; sorting (01), storage (02), reuse (03), recycle (04), recovery (05), treatment (06), disposal (07), and other disposal methods (08).
    b. The waste disposal code (DMF) was divided into 19 groups (Waste Management from Petroleum Operations Handbook, DMF); 1 - Produced water, 2 - Drilling muds, 3 - Drill cuttings, 4 - Oil and liquid fuels, 5 - Absorbents, filter and PPE, 6 - Discarded chemicals, 7 – Off-specification, expired or unused chemicals, 8 - Spent catalysis, 9 – WEEE, 10 - Batteries and accumulators, 11 – Packaging, 12 - Linings, refractories and insulation materials, 13 - Construction and demolition wasted, 14 - Discarded exploration and production equipment, 15 – Sludge, 16 - Aqueous liquid wastes, 17 - Wastes from human health care, 18 - Wastes from combustion, 19 – Others.
    c. According to the data set, the waste was classified into 3 categories based on hazardous properties consist of hazardous waste (not include Hg), non-hazardous waste, and Hg-contaminated waste.

4. MFA was performed by STAN 2.6.601 software.
    a. The offshore wastes disposed of from the drilling and production process was identified.
    b. No stock was assumed in each process thus, mass in must equal to mass out in MFA.
5. The environmental impacts were evaluated using SimaPro 8.3.0.0 software. The specific scopes were defined in this analysis including:
    a. Evaluation for the waste was focused on mercury (Hg)-contaminated.
    b. ReCiPe Mid-Point (H) was used as the evaluation method.
    c. Functional unit of this study was set to be 1 kg of offshore Hg-contaminated waste disposal.
    d. Climate change and human toxicity were selected for evaluating environmental impacts.
    e. LCA was performed within Thailand waste disposal boundary (outside country treatment not included); for storage case.
    f. LCA was performed under the assumptions of this study as presented in Table 3.1.

Table 3.1 The Hg-contaminated waste assumptions for LCA evaluation

Disposal method	Assumption
021 storage	- No physical or chemical treatment before transportation - Not consider the storage room facilities energy consumption - Count only the distance of transportation and fuel consumption to the storage destination (9,000 km from Thailand) - No waste utilities for storage included
042 fuel blending	- Assume to have similar treatment process as incineration of industrial hazardous waste - No transportation cost and emission - Utilities are included - No benefit products from the fuel blending method
059 other recovery unlisted material (Recovery)	- Assume to have similar treatment process as a Hg-containing waste recycling with end-of-life stage - The benefit from recycled waste is counted (recovered products such as Hg, and chemical inorganic) - Utilities are included - No transportation cost and emission counted
071 sanitary landfill	- Assume to have similar treatment and area as an industrial hazardous landfill process - Landfill facilities are included - No transportation cost and emission counted

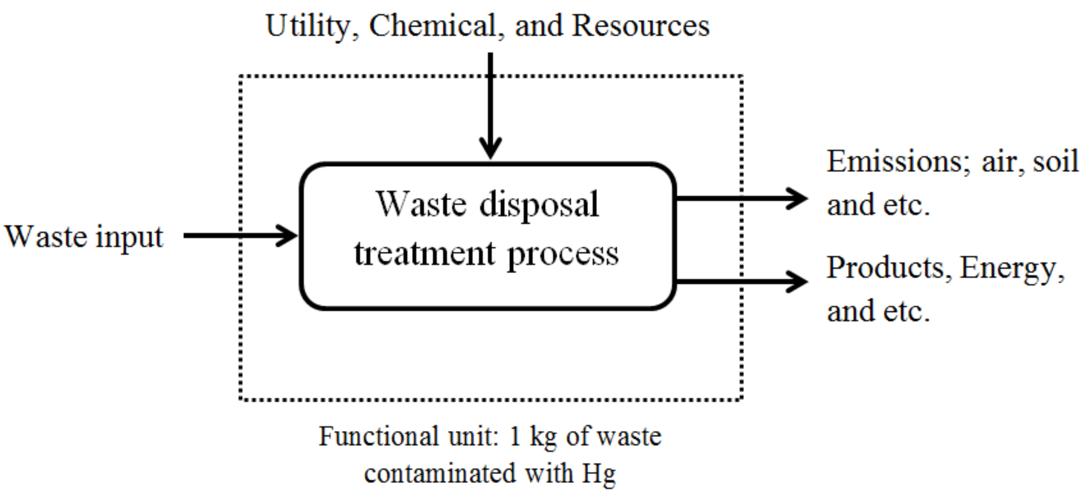


Figure 3.1 Boundary system study of end-of-life stage of waste management.

3.2 Materials and Equipment

Software:

1. STAN 2.6.601
2. SimaPro 8.3.0.0
3. Microsoft Office Excel 2010

3.3 Methodology

3.3.1 Data Collection and Scope Set Up

1. Set up the main scope of petroleum industrial wastes boundary at the end-of-life stage.
2. Gather the secondary data of wastes disposal based on the scope of work relying on such as mass flow in/out chemical, material, resources, electricity and the environmental releases.
3. Classify the wastes into target groups regarding the waste classification under the DIW and DMF.

3.3.2 Mass Flow Analysis (MFA) Using STAN Software

1. Input the grouped mass flow waste in/out data from step 1 scoped in the study boundary using STAN 2.6.601 software.
2. Calculate the mass waste in and mass out by weight through the boundary system.

3. Verify the mass flow balance in each process. The total mass flow in must be equal to mass out of process plus process stocks.

3.3.3 Life Cycle Inventory Assessment (LCIA) for Each End-of-Life Scenario of the Petroleum Waste Was Calculated Using SimaPro Software

1. Develop the scenarios based on study assumption.
2. Conduct the inventory analysis including the input and output, such as energy, materials usage, and environmental release for each case.
3. Assess the potential impacts focusing on human and ecological effects
4. Evaluate and compare the result obtained from the analysis.

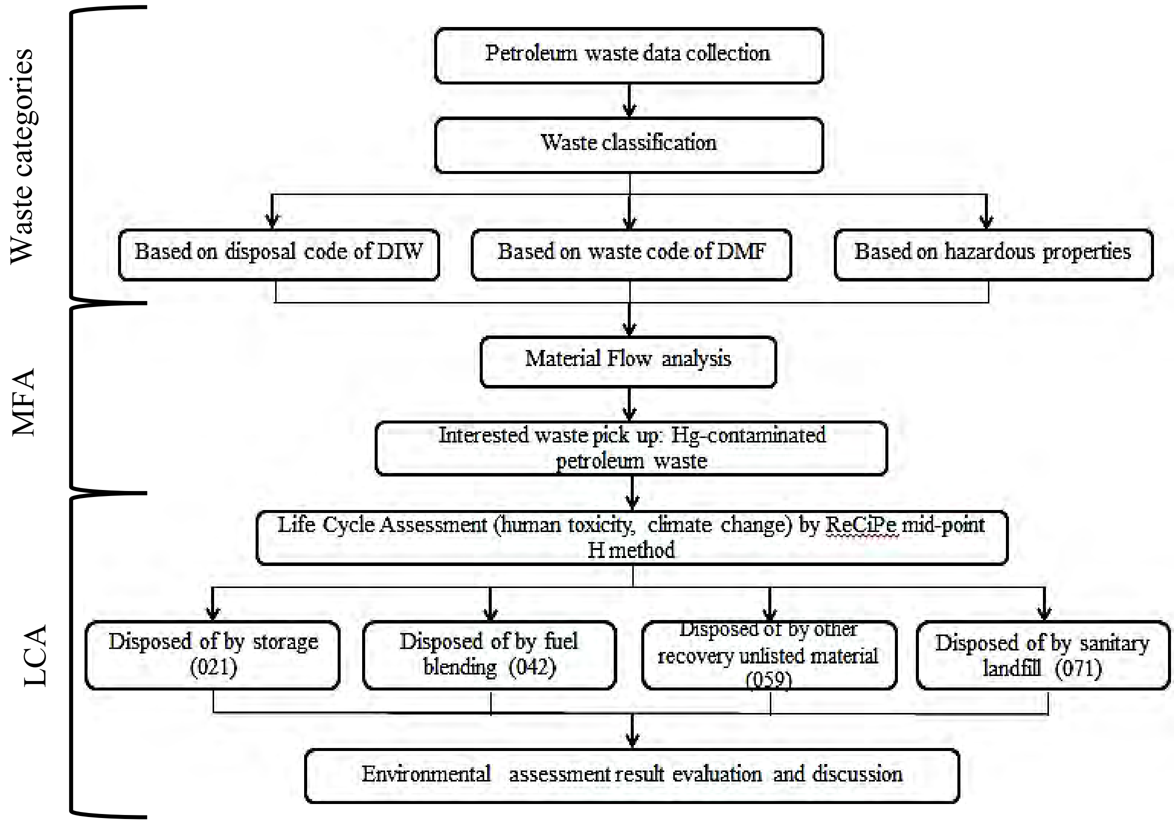


Figure 3.2 The methodology for the combined of MFA and LCA for petroleum waste management used in this work.

CHAPTER IV
RESULTS AND DISCUSSION

This study, the exploration and drilling session of the offshore operation was set to take place for around 6 years after the production of oil, and gas overcome for around 20 years until the decommissioning process. The waste data were collected from the 6 representatives in the year 2015. The waste was assumed to be disposed of year by year and no stock was taken into account. The total amount of offshore wastes was reported to be about 14 million tons. More than about 300 types of waste were analyzed. The offshore waste was accounted separately for the drilling and production process. The petroleum waste was characterized into the group based on waste type (waste code), disposal method (disposal code), and hazardous properties.

4.1 Petroleum Waste Categorization

4.1.1 Categorized by DMF Waste Code

First of all, the petroleum wastes are classified into 19 groups based on the waste code mapping regulated by DMF. All of the waste is categorized by its character. In this study, the waste was classified into 17 groups of waste code as listed below:

1 - Produced water
2 - Drilling muds
3 - Drill cuttings
4 - Oil and liquid fuels
5 - Absorbents, filter materials, wiping cloths and personal protective equipment (PPE)
6 - Discarded chemicals
7 - Off-specification, expired or unused chemicals
9 - Electrical and electronic equipment (WEEE)
10 - Batteries and accumulators

11 - Packaging

12 - Linings, refractories and insulation materials

13 - Construction and demolition waste

14 - Discarded exploration and production equipment

15 - Sludge

16 - Aqueous liquid wastes

17 - Wastes from human health care

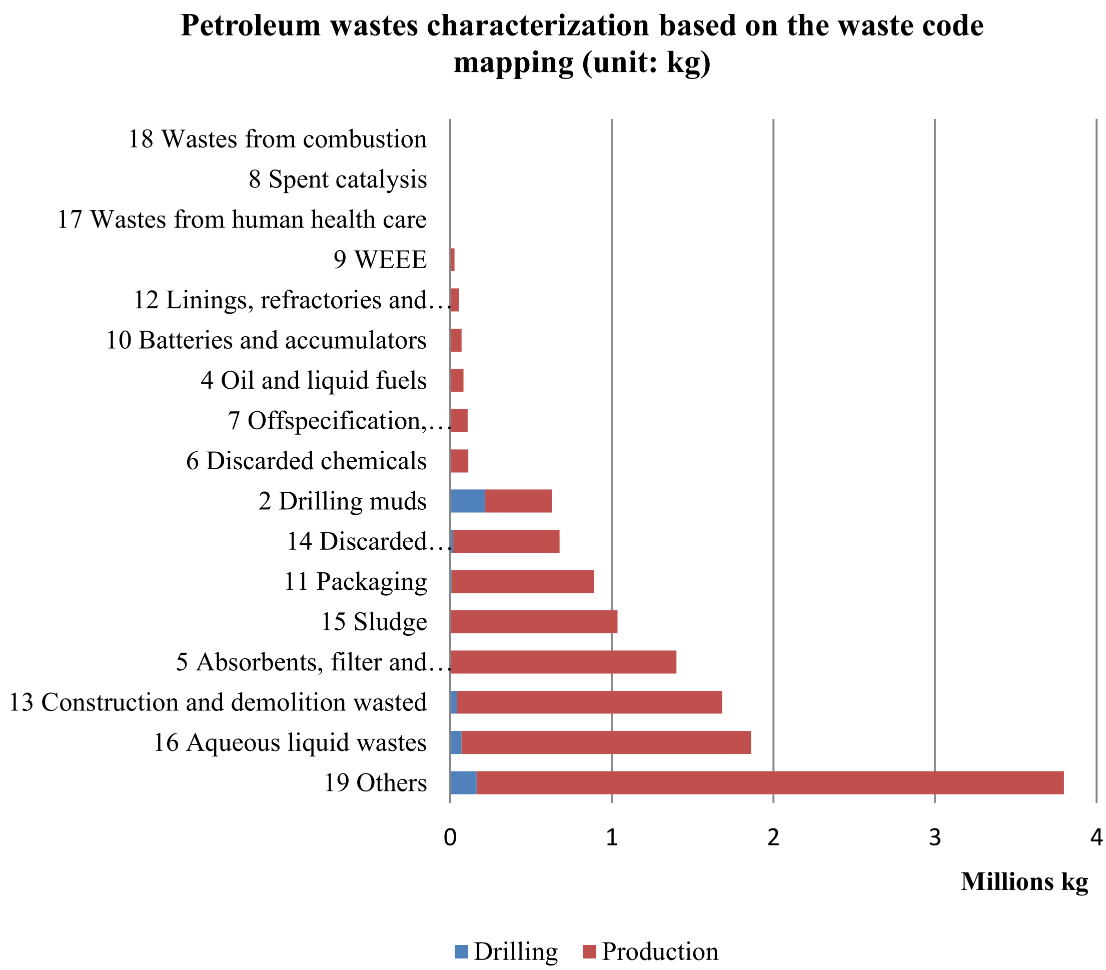
19 - Others

The spent catalyst (8) and waste from combustions (18) were absented in this study because of no waste can classify to those groups. Table 4.1 and Figure 4.1 show the amount of petroleum wastes disposed of from drilling and production processes in the year 2015.

Table 4.1 Top-ten wastes by weight basis categories from the drilling and production process classified base on the waste code

N0.	Drilling waste	Total waste (wt%)	Production waste	Total waste (wt%)
1	3 Drill cutting	1.0558%	1 Produced water	98.436%
2	2 Drilling muds	0.0015%	3 Drill cutting	0.4207%
3	19 Others	0.0012%	19 Others	0.0257%
4	16 Aqueous liquid wastes	0.0005%	16 Aqueous liquid wastes	0.0127%

N0.	Drilling waste	Total waste (wt%)	Production waste	Total waste (wt%)
5	13 Construction and demolition wasted	0.0003%	13 Construction and demolition wasted	0.0116%
6	11 Packaging	0.0001%	5 Absorbents, filter and PPE	0.0099%
7	15 Sludge	0.0000%	15 Sludge	0.0073%
8	5 Absorbents, filter and PPE	0.0000%	11 Packaging	0.0062%
9	4 Oil and liquid fuels	0.0000%	14 Discarded exploration and production equipment	0.0047%
10	10 Batteries and accumulators	0.0000%	2 Drilling muds	0.0029%



***Remark**: The data in Figure 4.1 did not include the waste group of produced water (1) and drill cuttings (3) in the drilling and production of the offshore petroleum

Figure 4.1 Petroleum waste characterization in the year 2015 based on DMF waste code mapping (unit: kg).

According to Figure 4.1, the waste generated from the production process (more than 99 wt%) is more than that of the drilling process (0.14 million tons). In addition, the produced water takes the first place of the most waste generated category in the production process, with around 98% of the total waste. Now, produced water is disposed of by deep well or underground injection. About 0.5% of the total waste is from the drill cuttings in the drilling process. The most of drill cuttings can be disposed of by land reclamation and some of them disposed of by co-incineration in a cement kiln. On the other hand, the waste disposal from the drilling process came from the drill cuttings (1%), drilling mud (0.002%), and the others (0.001%).

In addition, the petroleum waste was categorized based on the waste disposal codes. DIW had regulatory set the disposal codes for waste treatment. All of the wastes from drilling and production process of the offshore petroleum are disposed of as listed in Section 4.2.

4.1.2 Categorized by DIW Disposal Method

The petroleum waste can be classified based on their disposal and treatment methods. The DIW set up the code to define the waste disposal method, into 8 main groups and specific sub-group. The main group and its sub-group, which present in this study, including in the list below:

01 - Sorting (011 - storage)

02 - Storage (021 - storage)

04 - Recycle (041 - Use as fuel substitution or burn for energy recovery, 042 - fuel blending, 049 - other recovery methods)

05 - Recovery (059 - other recovery unlisted material) so-called recovery method

07 - Disposal (071 - sanitary landfill, 073 - secure landfill, 074 - burn for destruction, 075 - burn for destruction in hazardous waste incinerator, 076 - co-incineration in cement kiln, 077 - deep well/underground injection)

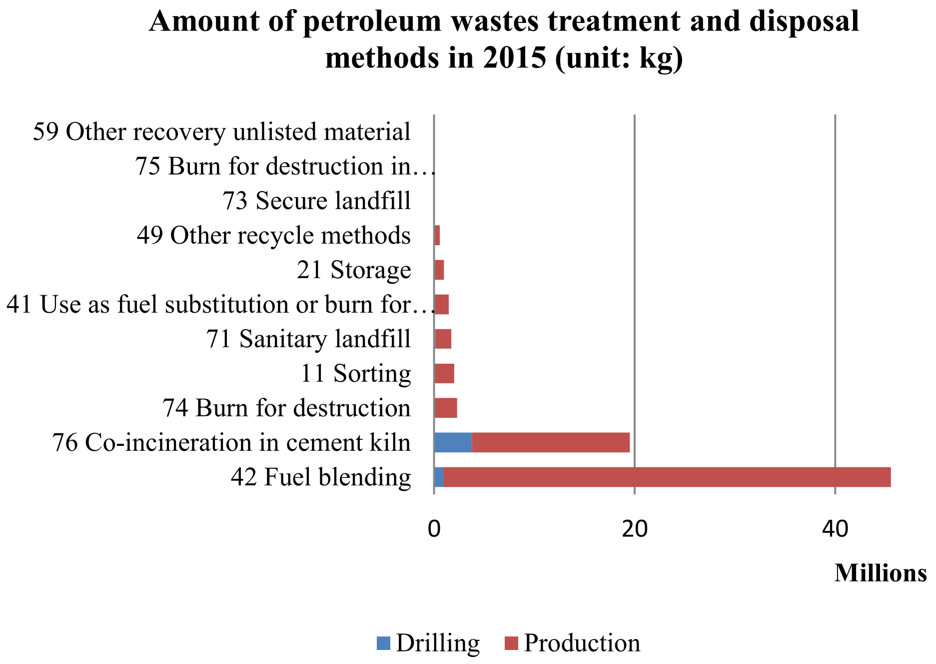
08 - Other methods (082 - land reclamation)

The weight amount of petroleum waste disposed of by several waste disposal methods is shown in Table 4.2 and Figure 4.2.

Table 4.2 Top-five of petroleum waste categorized by disposal methods

NO.	Drilling waste	Total waste (wt%)	Production waste	Total waste (wt%)
1	082 Land reclamation	1.0247%	077 Deep well or underground injection	98.450%
2	076 Co-incineration in cement kiln	0.0268%	042 Fuel blending	0.3161%
3	042 Fuel blending	0.0065%	076 Co-incineration in cement kiln	0.1115%
4	071 Sanitary landfill	0.0012%	074 Burn for destruction	0.0162%
5	011 Sorting	0.0004%	011 Sorting	0.0137%

*The waste showed in this table was accounted for more than 99% of the total petroleum waste generation (14 million tons)



*Remark: This is not include the waste from deep well/underground injection (077) (around 98 wt%) and land reclamation (082) (around 1 wt%).

Figure 4.2 Offshore petroleum waste characterized by waste disposal method.

According to Table 4.2 and Figure 4.2, most of the petroleum wastes were disposed of by deep well or underground injection (077) which is counted for around 98% of the total waste. As a result, the produced water is the largest fraction of the waste from petroleum production and it is disposed of by backfilling to the injection well. In addition, the produced water can be disposed of by the underground injection. Consequently, it is a typical disposal method for offshore operation in Thailand.

4.1.3 Categorized by Hazardous Properties

Thailand's oil and gas reservoirs have found a high level of mercury (Hg) content in the fraction (Sainal *et al.*, 2007). Thus, the production of oil and gas tend to have Hg-contaminated wastes in the whole operation (McDanial *et al.*, 1998). This study, petroleum wastes can be characterized into three categories based on hazardous substance classification. This study categories the waste into hazardous waste (exclude Hg-contaminated waste), non-hazardous waste, and Hg-contaminated waste. The hazardous waste is defined as toxic released substance waste contamination which has concentration beyond the DIW and DMF regulatory standard. Non-hazardous waste is a non-toxicity waste. Hg-contaminated waste is the waste contained more Hg content than a level which was announced in 2005 by DIW. As a result, the wastes are disposed of by the drilling process consists of hazardous and non-hazardous waste. While the wastes generated from the production process tend to have the additional of Hg-contaminated wastes.

4.2 Mass Flow Balances (by MFA) of Petroleum Waste

When focusing on the hazardous waste classification, the offshore waste can be classified into 19 groups of waste type and 8 main groups of disposal method mentioned in the previous sections (see Sections 4.1.1, 4.1.2, and 4.1.3). First of all, the amount of wastes from the drilling and production process were calculated based on the mass flow using STAN 2.6.601. The total mass in and mass out of the waste being treated must be equal, without including stock calculation. For more understanding, the waste flow was balanced for the drilling and production processes separately.

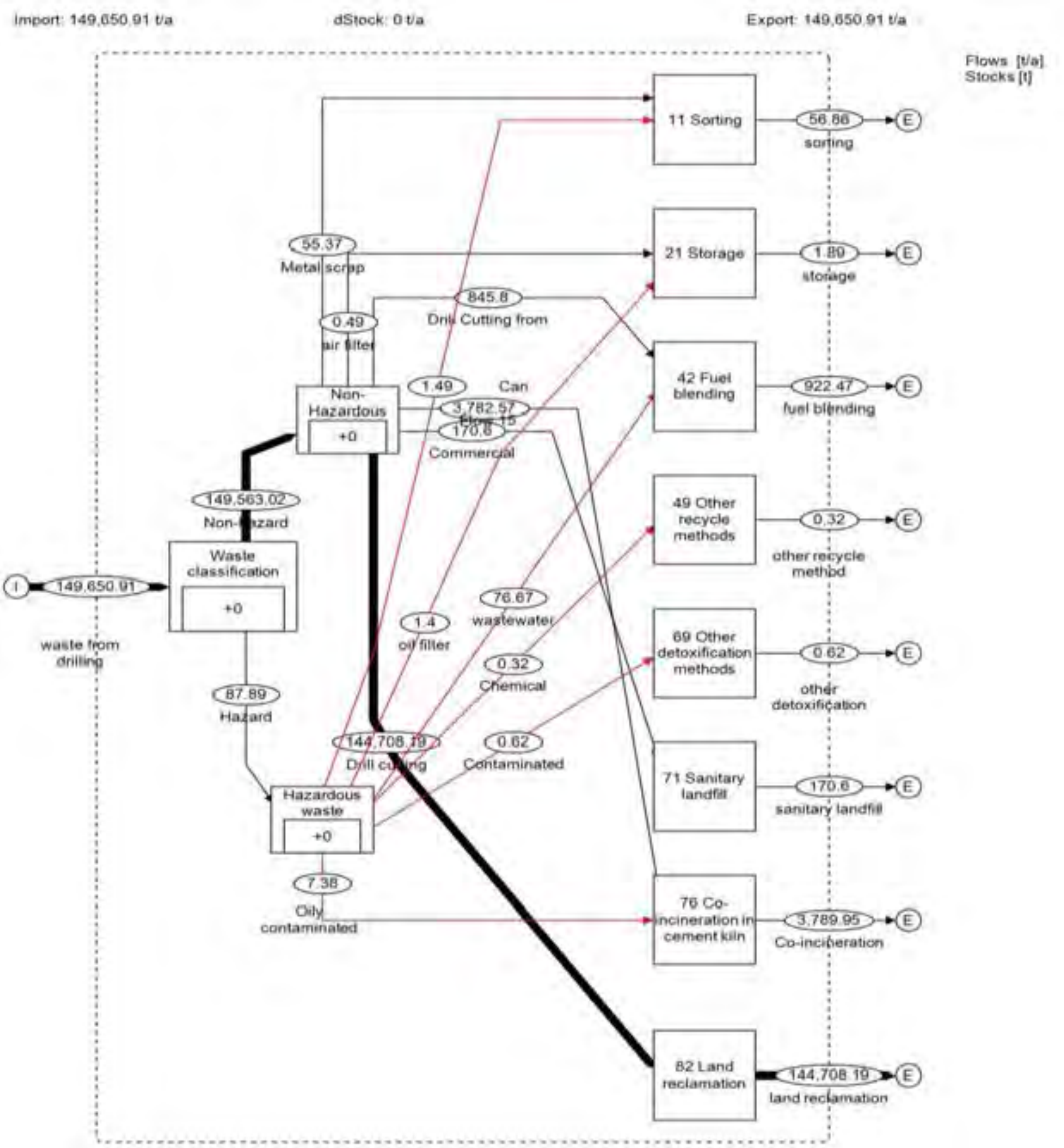


Figure 4.3 Waste flow balance diagram of the offshore wastes generated from the drilling process.

Figure 4.3 shows the waste flow at the end of life of offshore wastes from the drilling process. The total amount of waste generated during the drilling process was around 1 wt% compared with the total waste. The waste from the drilling waste can be divided into two groups, comprising of hazardous and non-hazardous wastes.

The non-hazardous waste is the largest fraction from the drilling process. The drill cuttings are the largest fraction of the non-hazardous waste, which is mainly disposed of by land reclamation method (082). On the other hand, the oil-contaminated materials are the highest amount of the hazardous waste from the drilling process which is disposed of by co-incineration in cement kilns.

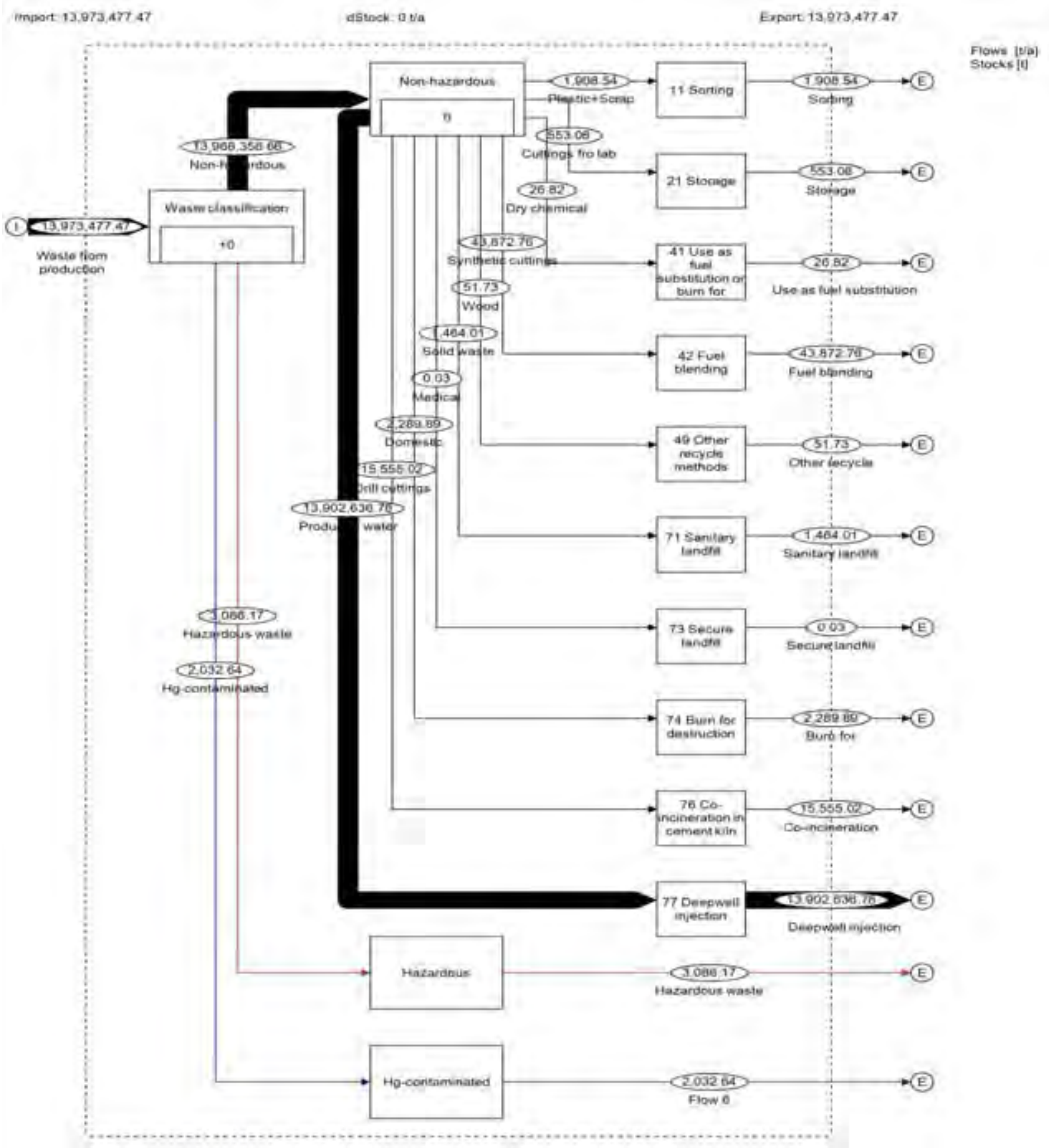


Figure 4.4 Waste flow balance of offshore petroleum production waste focus on non-hazardous waste disposal in Thailand.

Figure 4.4 shows the waste flow of the offshore from the production of petroleum which was focused only on the non-hazardous waste. The characteristic of waste generated from the production process is more varity than that of the drilling process. Around 98% of the offshore waste was generated from the production process. According to Figure 4.3, the waste from production was divided into three groups consisting of non-hazardous, hazardous, and mercury (Hg)-contaminated waste. The main waste stream from the production process is produced water, which is treated by the underground injection. As a consequence, the primary disposal method for non-hazardous waste in the production is deep well/underground injection.

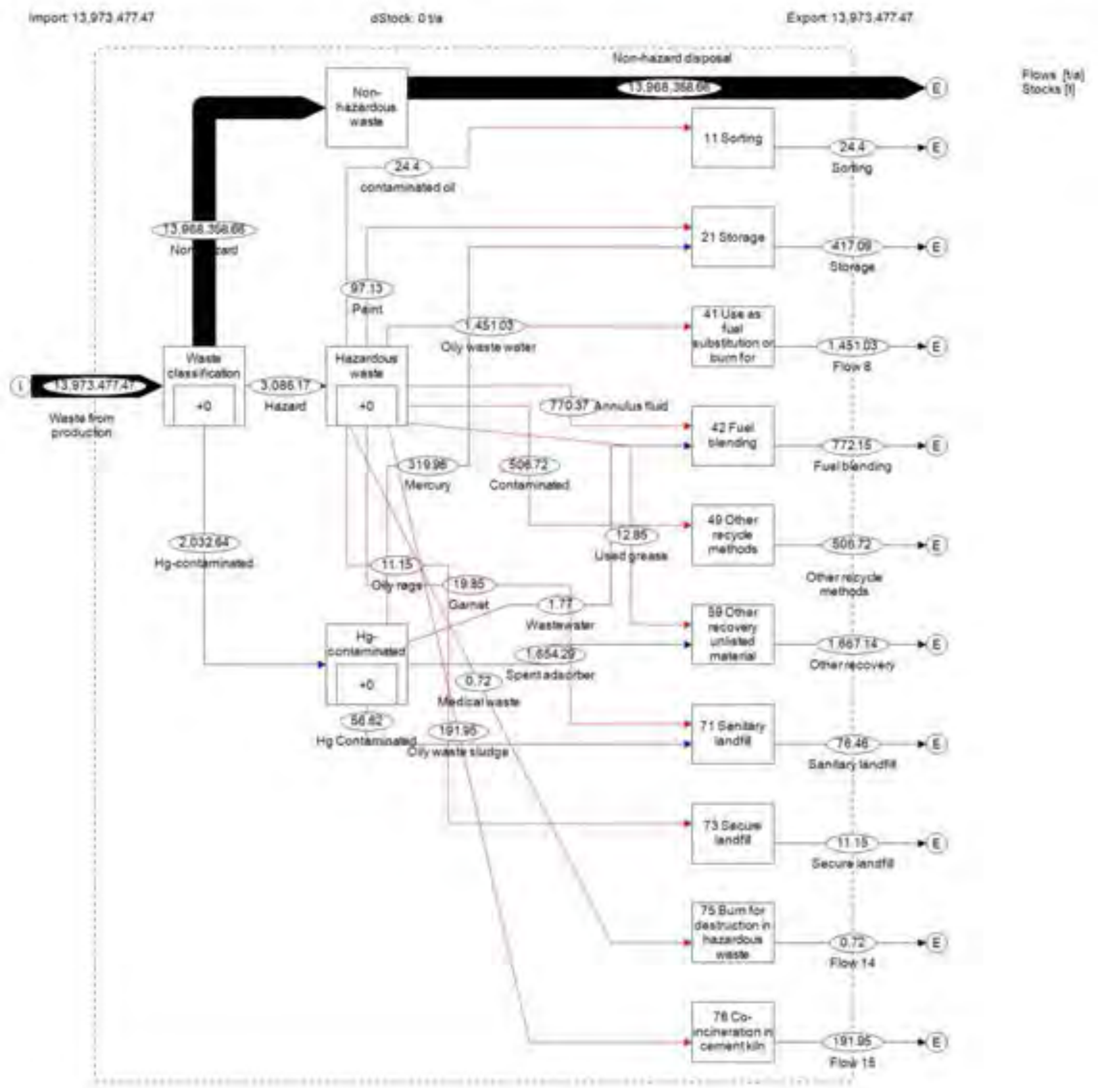


Figure 4.5 Waste flow balance of hazardous waste and Hg-contaminated waste from the offshore petroleum production in Thailand.

From Figure 4.5, Hg-contaminated waste was determined additionally from the waste classification in the drilling process. When considering only the hazardous and non-hazardous wastes, the waste flow distributed into each disposal method. The hazardous waste contained a high amount of oil-contaminated water which is disposed of by fuel substitution method (041). Otherwise, Hg-contaminated waste was favorably disposed of by other recovery method (059).

As a result of MFA analysis, the Hg-contaminated waste was counted at two-fifths of total hazardous waste in the production. As a fact, Hg is defined as a toxic substance to human and environment following by World Health Organization (WHO, 2017). From the hypothesis, the high amount of Hg contamination in the petroleum waste will result in high environmental impacts. Thus, Hg-contaminated waste is the interest to conduct waste in this study, which needs to evaluate the environmental impact because of their toxic release.

4.3 LCA and MFA of Petroleum Waste with Hg-Contaminated

The Hg-contaminated petroleum waste was classified into groups based on DMF waste code and DIW disposal code. Their waste types including absorbents filter materials (05), discarded exploration and production equipment (14), sludge (15), and aqueous liquid wastes (16). The disposal method of Hg-contaminated waste was divided into 4 methods including storage (021), fuel blending (042), other recovery unlisted materials (059), and sanitary landfill (071).

Table 4.3 Hg-contaminated waste classification

Disposal method	Waste type of Hg-contaminated (wt%)				Total (wt%)
	05 Absorbents, filter materials, wiping cloths and personal protective equipment	14 Discarded exploration and production equipment	15 Sludge	16 Aqueous liquid wastes	
021 Storage	2.25%	0.00%	13.20%	0.49%	15.95 %
042 Fuel blending	0.00%	0.00%	0.00%	0.09%	0.09%
059 Recovery	48.75%	0.00%	32.39%	0.00%	81.14 %
071 Sanitary landfill	0.00%	2.82%	0.00%	0.00%	2.82%
Total (wt%)	51.00%	2.82%	45.60%	0.58%	100.00 %

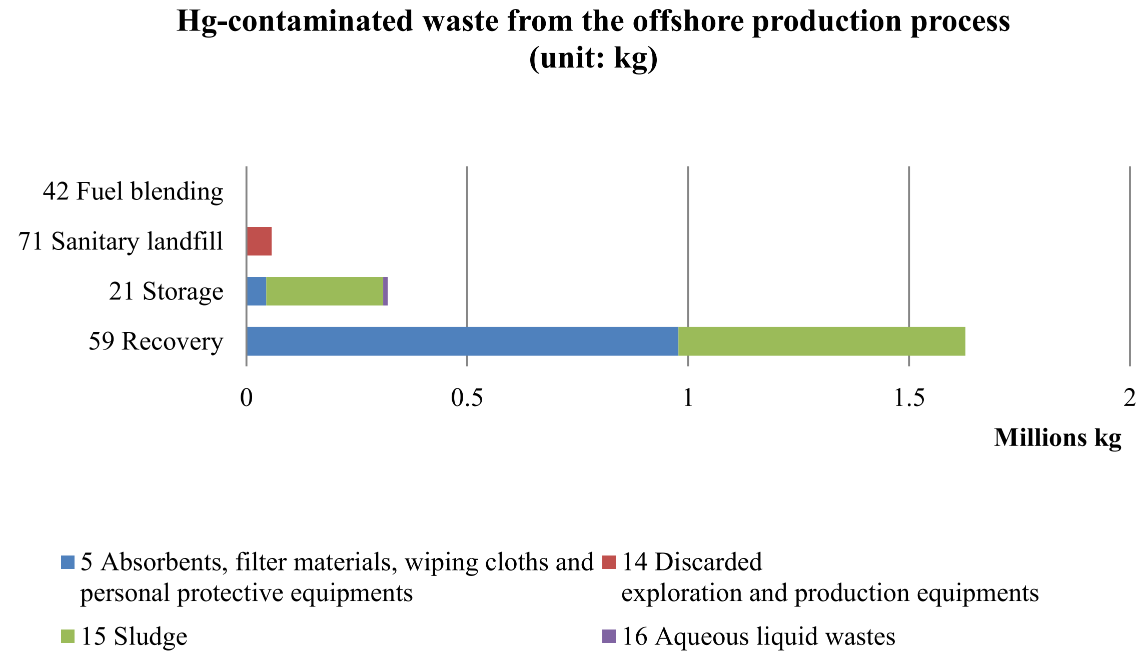


Figure 4.6 Hg-contaminated waste in different waste code and disposal method.

Hg-contaminated wastes from the offshore production in 2015 are shown in Figure 4.6 and Table 4.3. Hg-contaminated waste was composed of adsorbents (05) in the production process. The personal protective equipment (PPE), which is classified as group 05 wastes, is the most present of the Hg-contaminated waste from petroleum production.

4.3.1 MFA of Total Hg-Contaminated Petroleum Waste

MFA provides a simple mass flow pathway for petroleum waste. The Hg-contaminated waste with different types and disposal methods is presented in Figure 4.7.

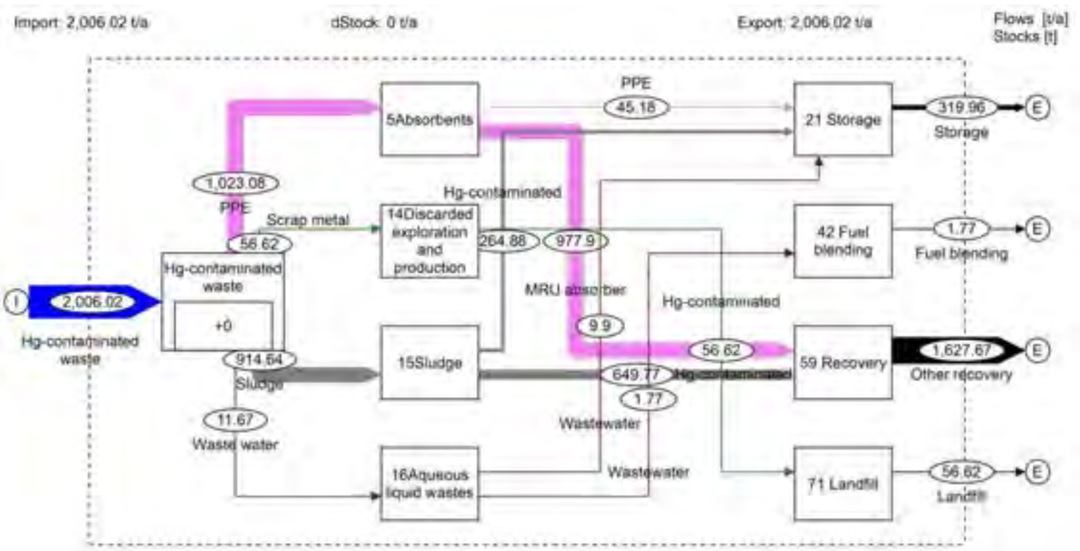
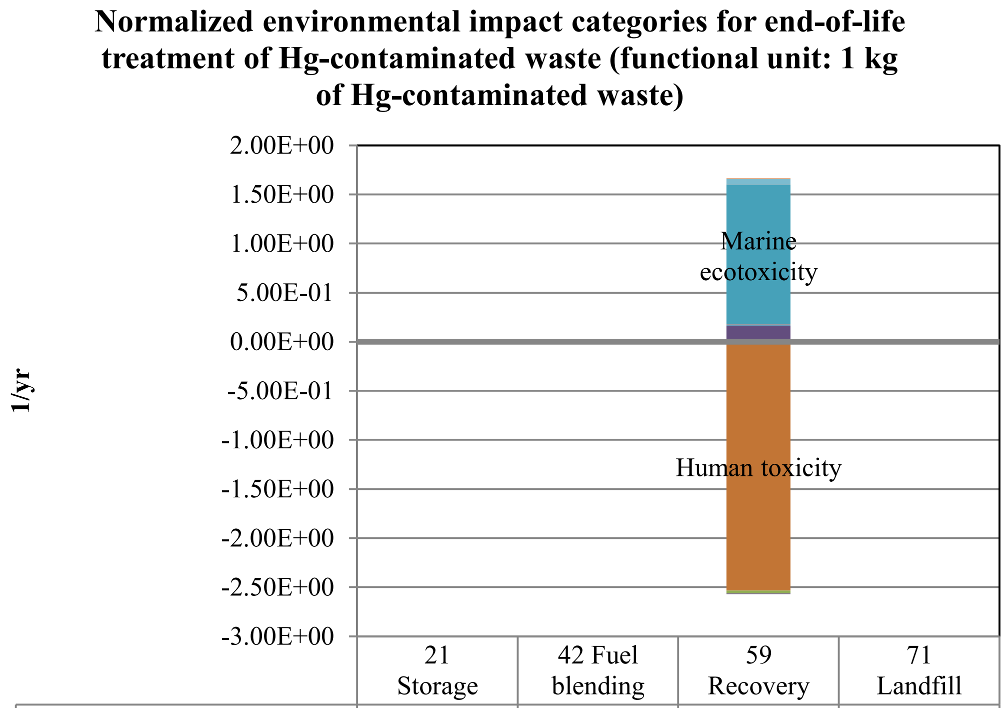


Figure 4.7 MFA of Hg-contaminated waste end-of-life stages (ton/annual).

The petroleum waste flow is shown in Figure 4.7 at the end-of-life stages. A large ton of the waste flow was from adsorbents (05) which were disposed of by other recovery unlisted material disposal methods (059). The second, the Hg-contaminated chemical sludge was generated at a high amount which was disposed of by other recovery methods (059). The less amount of the Hg-contaminated waste was disposed of by a fuel blending. The discharged exploration and production equipment disposed of by a sanitary landfill (071). Small amount of aqueous liquid waste was disposed of by a fuel blending method (042).

4.3.2 LCA Analysis

The LCA of Hg-contaminated waste was performed under the functional unit of 1 kg of Hg-contaminated waste. LCA was assessed by SimaPro 8.3.0.0. ReCiPe mid-point (H) method was selected as the main evaluation method. ReCiPe was selected as the assessment method because it can evaluate the impact in terms of human toxicity toxic, which essential for Hg-contaminated releases. The environmental impacts were evaluated for each Hg-contaminated waste disposal treatment methods. As mentioned in Section 4.3, the Hg-contaminated waste from the offshore production is divided into mainly 4 methods, including storage (021), fuel blending (042), other recovery unlisted material (059), and sanitary landfill (071) as shown below.



	21 Storage	42 Fuel blending	59 Recovery	71 Landfill
Fossil depletion	1.38E-05	9.33E-05	4.89E-03	3.42E-04
Metal depletion	3.53E-06	4.81E-04	6.24E-02	1.56E-04
Water depletion	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Natural land transformation	1.61E-06	5.38E-06	7.07E-04	2.50E-05
Urban land occupation	4.00E-07	2.91E-06	2.73E-03	1.60E-05
Agricultural land occupation	1.45E-07	6.36E-06	1.83E-04	1.43E-05
Ionising radiation	2.68E-06	1.72E-05	9.88E-04	6.24E-05
Marine ecotoxicity	9.73E-05	1.46E-04	1.42E+00	4.31E-04
Freshwater ecotoxicity	6.02E-06	3.44E-05	-6.14E-03	2.74E-04
Terrestrial ecotoxicity	3.79E-07	6.43E-06	-2.78E-02	9.31E-05
Particulate matter formation	2.29E-05	1.21E-04	6.27E-03	2.63E-03
Photochemical oxidant formation	7.96E-06	6.21E-05	3.37E-03	1.18E-04
Human toxicity	4.96E-06	7.30E-04	-2.54E+00	3.06E-04
Marine eutrophication	1.92E-06	1.82E-05	1.87E-03	3.64E-05
Freshwater eutrophication	3.46E-06	1.22E-04	1.55E-01	3.05E-04
Terrestrial acidification	2.90E-05	1.01E-04	4.44E-03	2.07E-04
Ozone depletion	2.31E-07	1.52E-06	5.51E-05	7.98E-06
Climate change	7.85E-06	2.36E-04	3.10E-03	2.43E-04

Figure 4.8 Normalized environmental impact categories of Hg-contaminated waste by disposal method.

According to Figure 4.8, the total normalized LCA evaluation of environmental impacts (18 categories) in each different waste disposal methods is shown. The recovery (059) significantly exhibited the human and environmental impacts when compared with the other methods. The Hg-contaminated disposed of by fuel blending (042) is lesser notably impacts than other recovery unlisted material methods. On the other hand, storage (021) and sanitary landfill (071) disposal method was the least impact. The least impact in storage method was because of no waste treatment assumption. Thus, direct emission by treatment was absence cause low environmental impacts. In addition, landfill had low direct emission. The environmental impacts came from landfill's material.

In addition, only the other recovery unlisted material of Hg-contaminated waste method presented the beneficial impacts, for example, human toxicity, terrestrial ecotoxicity, and freshwater ecotoxicity. Human toxicity is obvious contributed to environmental impact. The second adverse impact is marine ecotoxicity.

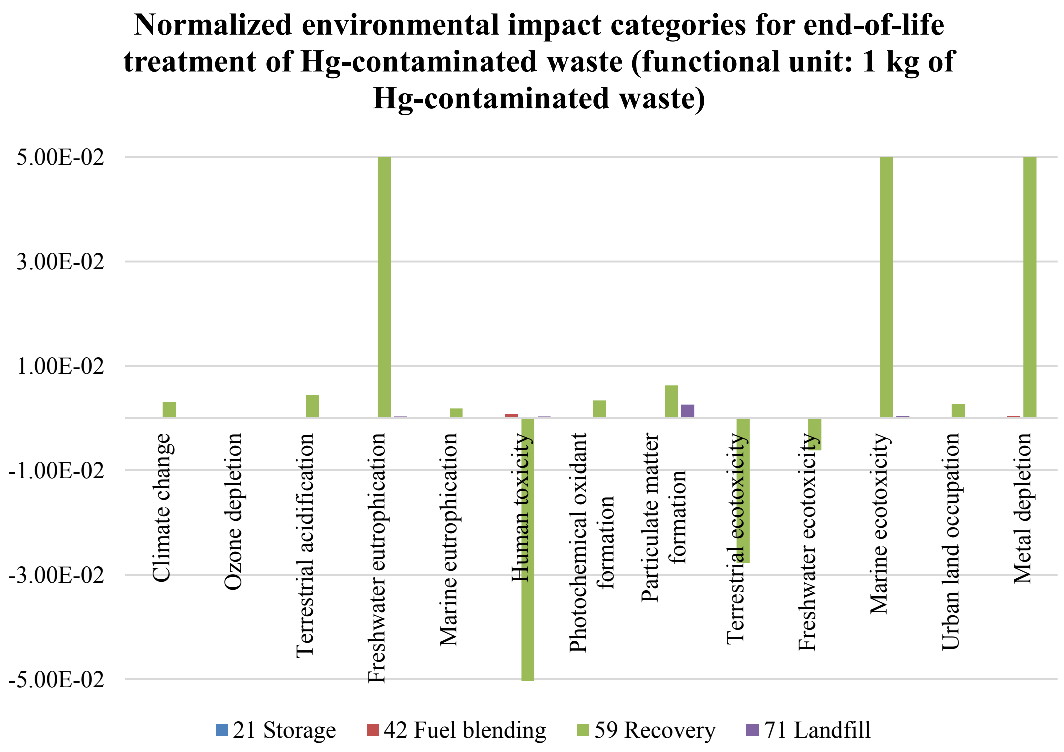


Figure 4.9 Normalization LCA of Hg-contaminated waste in each environmental impact categories.

From the graph shown in Figure 4.9, recovery disposal method contributed to various impacts categories. This treatment option showed high impacts on marine ecotoxicity, freshwater eutrophication, and metal depletion. On the contrary, recovery method also exhibited the beneficial impacts (negative value) on human toxicity, terrestrial ecotoxicity, and freshwater ecotoxicity.

According to DIW (2017), they allow the disposal method by fuel blending method into two ways. The first way is to blend with fuels for other fuel utilization which is applied for the case of high heating value (lower heating value/net calorific value more than or equal to 2,800 kcal/kg). On the other hand, the waste with low heating value (lower heating value/net calorific value less than 2,800 kcal/kg) will end up with incineration method which is defined as a second method for fuel blending. In this study, the input and output dataset for fuel blending were assumed to be similar to the incineration process of industrial hazardous wastes. Thus, when considering the fuel blending disposal method, the significant environmental impacts were photochemical oxidant formation, particulate matter formation, and terrestrial acidification.

The Hg-contaminated wastes disposed of by storage and landfill contributes less significant effects on the environment when compared with recovery method and fuel blending method. The recovery and fuel blending method consumed high amount of material and energy for their process. Hence, they would show higher than the others. The waste disposed of by the storage method had no any treatment or transform to the any stable form, compared with other option. The storage method was accounted for the waste stored in the tank/container. The direct emission by the waste treatment unit was assumed to be zero. Hence, the storage has less environmental impacts. In this study, the storage option is not compare with other treatment option.

Subsequently, the potential environmental impacts that are selected to be the most concern are human toxicity and climate change. Human toxicity is selected for further evaluation because the Hg-containing wastes release the toxic to the environment which can be harmful to all livings. In addition, global warming and greenhouse effects become a critical topic in the globalization era. The carbon dioxide (CO_2) is the major gas release cause the rising temperature around the world.

Thus, the climate change impact needs to be focused on in terms of the amount of CO_2 emission to nature.

4.3.3 The Human Toxicity Impact

4.3.3.1 Human Toxicity Impact From Storage Method (021)

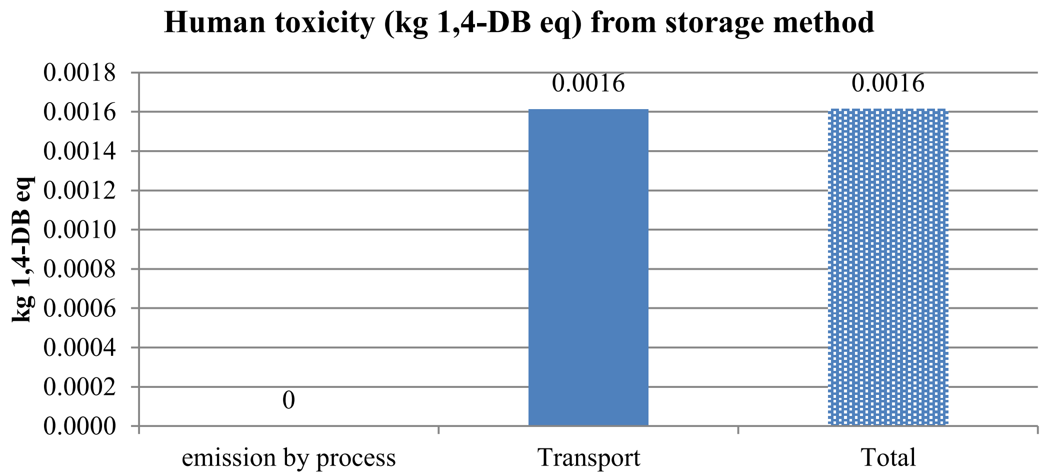


Figure 4.10 Human toxicity evaluation in storage (021) method.

The Hg-contaminated wastes disposed of by storage method are mainly included contaminated PPE, wastewater and, Hg-contaminated sand (adsorbents), which their classification is mentioned earlier in Figure 4.6.

The human toxicity impact by storage method is shown in Figure 4.10. According to the storage method assumption, the mass of the waste flow was not be treated by any methods (see Table 3.1). The waste was stored in the storage tank/container waiting for either storage or sent to abroad. The environmental impact assessment is counted only for waste transportation. The ocean transportation is selected and taken into account as an assumption for Hg-contaminated petroleum waste transport. Transportation starts with the production of one transoceanic tanker. The service of energy use and combustion emissions starts with the consumption of fuel for propelling (SimaPro 8.3.0.0 inventory description). In addition, all of the Hg-contaminated wastes have no treatment before transportation therefore, the emission by themselves and the treatment process are also not counted.

This study, it was assumed, the waste was transferred to the storage facilities abroad (considered for 9,000 km by distance). Thus, the transport of 1 kg of Hg-contaminated waste contributes to the human toxicity impact about 0.0016 kg 1,4-DB eq. The energy use (i.e., fuel) was estimated for the international data inventory for ocean transportation.

4.3.3.2 Human Toxicity Impact from Fuel Blending Method (042)

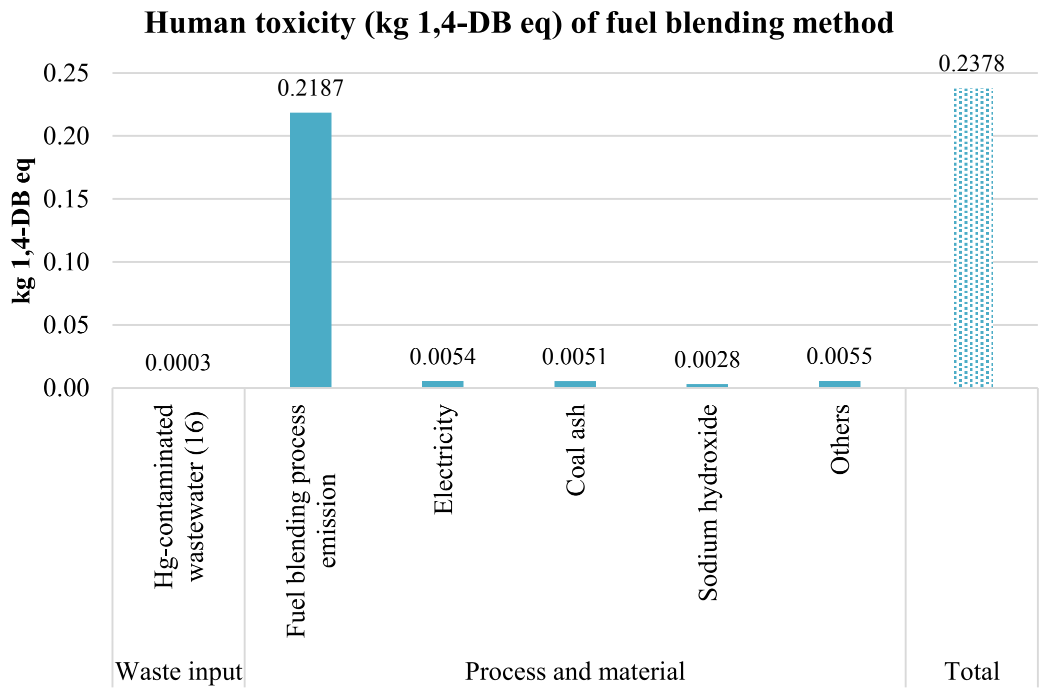


Figure 4.11 Human toxicity evaluation in fuel blending (042) method.

In this case, the fuel blending process assumed similarly to industrial hazardous waste incineration treatment process in China (Hong *et al.*, 2017) (based on the study's assumptions). The whole treatment process for fuel blending consisted of incineration, solidification for incinerated solids, landfill for solidified wastes and, wastewater treatment. The solidification in this incineration process was cement based. The waste stabilizing was needed before going to landfill for some incinerated wastes. The wastewater from each process went to the wastewater treatment (Hong *et al.*, 2016). In each sub-process, other materials and chemical substance are consumed for waste treatment. On the other hand, this study did not count the impact of waste transportation of the raw materials and Hg-contaminated wastes.

From Figure 4.11, the total human toxicity impact caused by fuel blending method is equal to 0.2378 kg 1,4-DB eq per 1 kg of Hg-contaminated waste. Referred to MFA in Figure 4.7, most of the waste disposed of by fuel blending is Hg-contaminated wastewater, which is classified as an aqueous liquid waste (16). The total human toxicity is the sum of the waste disposal input, fuel blending process, and material values.

From the result, the major impact on human toxicity came from the process emission. The emissions from fuel blending process lead to high human toxicity indicator because hazardous waste typically required more material for treating. The human toxicity impact also caused by the materials used for the secondary treatment process. Electricity and coal ash were the main used materials that lead to human toxicity impact. In addition, coal ash is the substance used as stabilizing agents for waste in solidification sub-process. The coal ash has fusibility characteristic depended on coal source (Dyk *et al.*, 2009). In addition, the coal ash mainly composes of mineral which might be the one source generated high human toxicity value. Even more, electricity used for operating the entire process also can cause human toxicity impact because of high energy consumption used for hazardous waste treating process.

Thus, the Hg-contaminated wastewater disposed of by fuel blending generates the high value of human toxicity impact from treatment operation process and material consumption.

4.3.3.3 Human Toxicity Impact from Recovery Method (059)

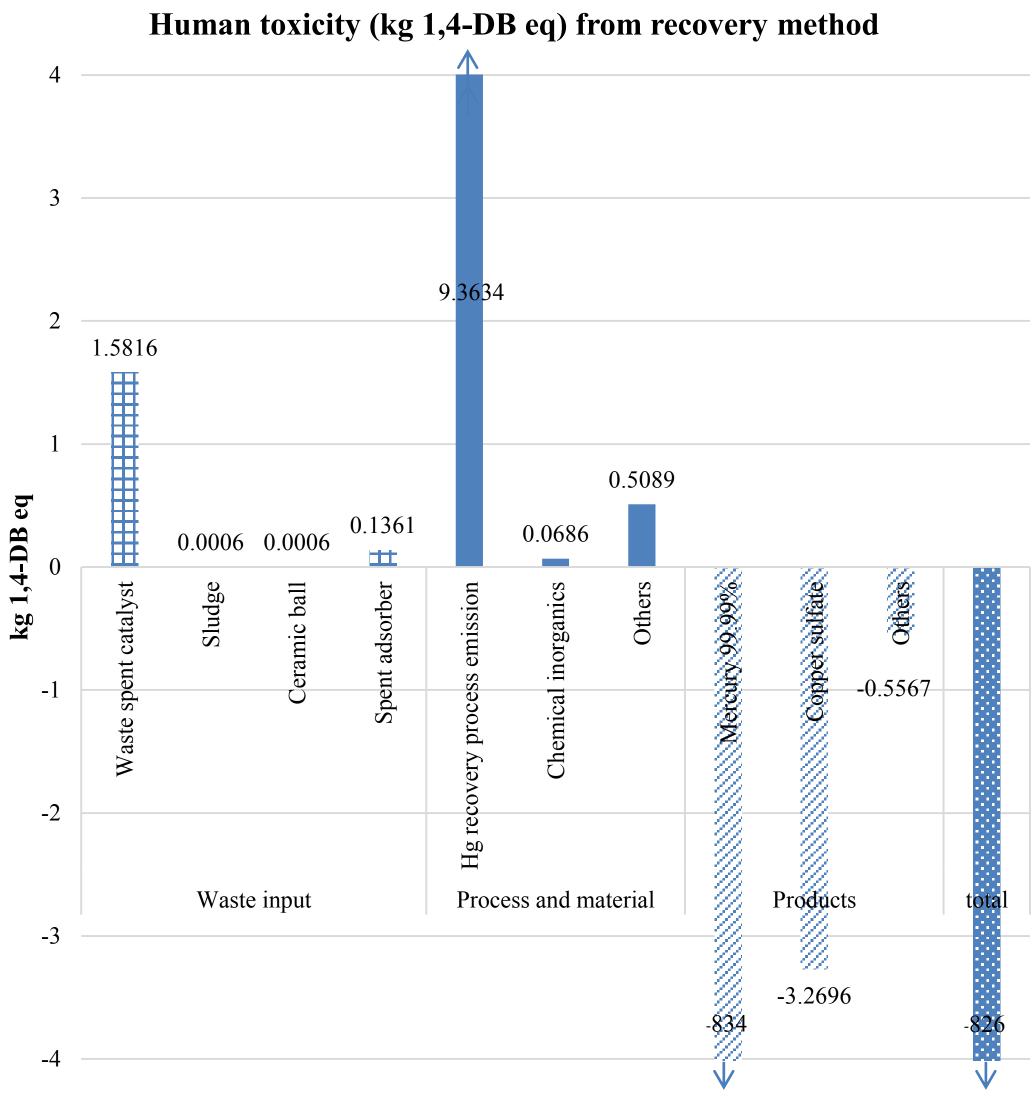


Figure 4.12 Human toxicity evaluation in recovery (059) method.

Figure 4.12, the recovery unlisted material method emitted the total value of human toxicity impact of -826 kg 1,4-DB eq. As noted, the negative value means a positive human toxicity impact. From the MFA analysis (see Figure 4.7), the waste disposal by the recovery method consisted of spent catalyst, sludge, ceramics ball and, spent adsorbers.

The Hg recovery process was assumed to have a similar process as Hg-containing waste recycling process (based on the study assumptions for other recovery unlisted material methods). The distillation technology is used for Hg-recovery and hydrometallurgical to extract the metals from industrial hazardous waste. All of the recovery treatment processes required raw material input for the waste treatment (Qi *et al.*, 2017).

For the recovery process (Hg recycling process), it is the only method that presents the benefits in terms of human toxicity impact. The products or recovered materials imposed a negative impact on human toxicity due to the fact that the new production can be substituted by the recovered products. Some of the wastes can be recovered to use again. Hence, the total impact can be reduced when Hg-recovery process is applied. According to Qi *et al.* (2017), Hg with 99.99% purified is the benefit product obtained from the Hg recovery process because it can be justified as a secondary raw material for Hg production. The benefit of Hg was calculated to be -833.9887 kg 1,4-DB eq.

On the other hand, the recovery process also releases some emissions to the environment. Hg-recovery process emissions omitted high value in human toxicity (9.3634 kg 1,4-DB eq).

4.3.3.4 Human Toxicity Impact from Landfill Method (071)

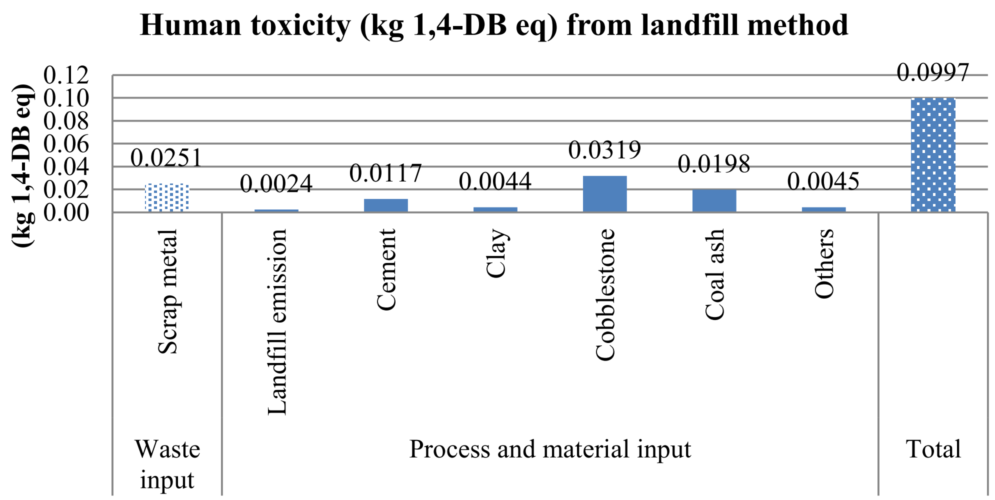


Figure 4.13 Human toxicity evaluation in landfill (071) method.

According to Figure 4.13, the disposal by landfill of Hg-contaminated metal scraps resulted in 0.0997 kg 1,4-DB eq of human toxicity. The main source of human toxicity impact came from the material input for the landfill operation. The impact also caused by the process itself and construction material.

The landfill was calculated for all materials used in constructing the facilities. The assumptions used in this assessment included solidification process, landfill and, wastewater treatment. The wastewater from the solidification process was treated. The others waste sent to the landfill after the solidification (Hong *et al.*, 2016). Cobblestone was the material used to construct the industrial hazardous waste landfill liner which contributed to a lot of human toxicity impact (about 0.0319 kg 1,4-DB eq). Clay is a building material for the landfill sites similar to cobblestone. Coal ash and cement were used as a stabilizer for the solidification unit of waste before going to landfill sites (Fan *et al.*, 2018). Both of them also caused a high value of human toxicity impact.

As a consequence, a high value of human toxicity impact generated by landfill method because of the emissions from Hg-contaminated metal scraps and the building materials used for landfilling. The majority materials used in the landfill which caused the impacts on human toxicity was cobblestone (landfill).

4.3.3.5 Comparison of Human Toxicity Impact in Each Disposal Method

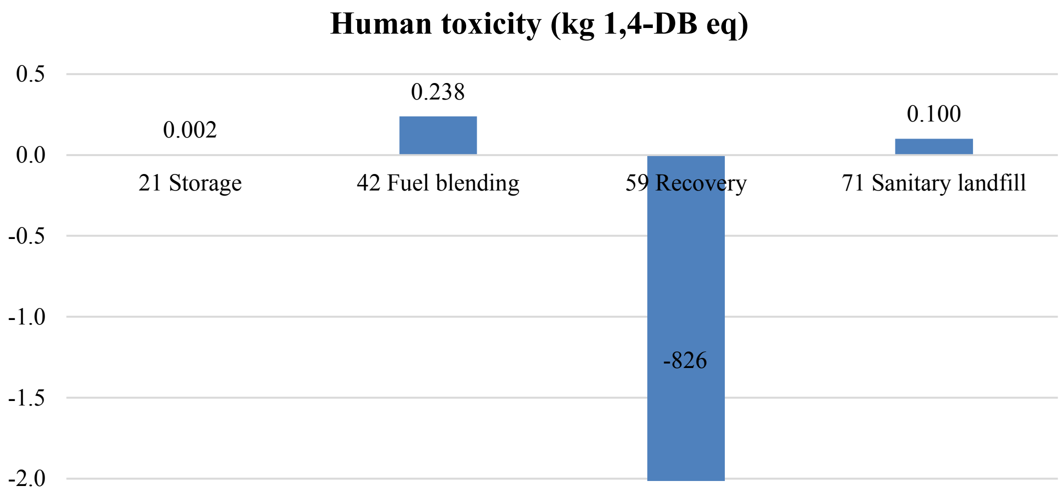


Figure 4.14 The comparison of human toxicity impact in each disposal method per functional unit.

As a conclusion, human toxicity impact reflex to the toxicity of chemical on livings. The emission of toxic substances, such as heavy metals, can lead to human health impacts (Durante *et al.*, 2015). When consider based on the same functional unit (1 kg of Hg-contaminated waste), human toxicity impact was mainly driven from the fuel blending method, of which was emitted from the process direct emission. While the waste disposed of by landfill was generated from landfill, the impact constructed materials, for example, cobblestone. On the other hand, recovery disposal method showed a positive benefit on human toxicity impact because of recovered product compensation. As, the recovered products can substitute the production of newly produced.

4.3.4 The Climate Change Impact

Climate change impact indicates global warming potential (Durante *et al.*, 2015). This impact is evaluated by the amount of carbon dioxide emissions and greenhouse gases that release into the atmosphere (Davis *et al.*, 2010). The impact assessment in this section was evaluated based on 1 kg of Hg-contaminated petroleum waste. Figure 4.15 shows the climate change impact evaluated by ReCiPe mid-point (H) method.

4.3.4.1 Climate Change Impact from Storage Method (021)

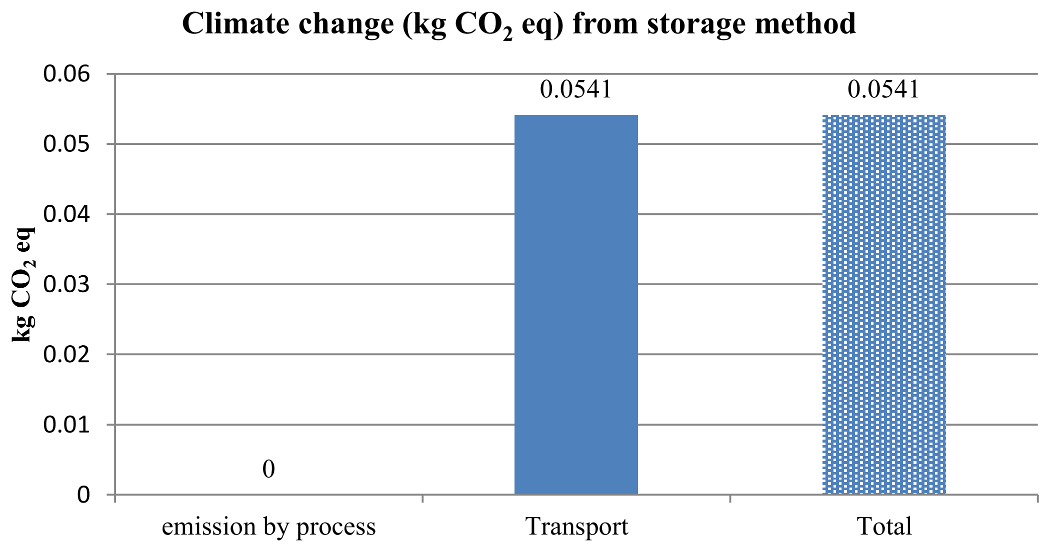


Figure 4.15 Climate change evaluation in storage (021) method.

The climate change impact is reported in the unit of kg CO_2 eq. The increasing of CO_2 and other greenhouse gases reflex the global temperature increase, as a consequence, leading to the climate change (Davis *et al.*, 2010). Thus, the climate change impact can be represented by kg of CO_2 eq generated from each waste disposal method.

From Figure 4.15, climate change impact of the storage method is equal to 0.0541 kg CO_2 eq. As mentioned in Section 4.3.3.1, there is no direct emission released by the process of this method due to none of waste treatment involved. The impact was counted within Thailand boundary only. Thus, the climate change impact came from the energy consumption by weight carried and by the tankship for waste transport.

4.3.4.2 Climate Change Impact from Fuel Blending Method (042)

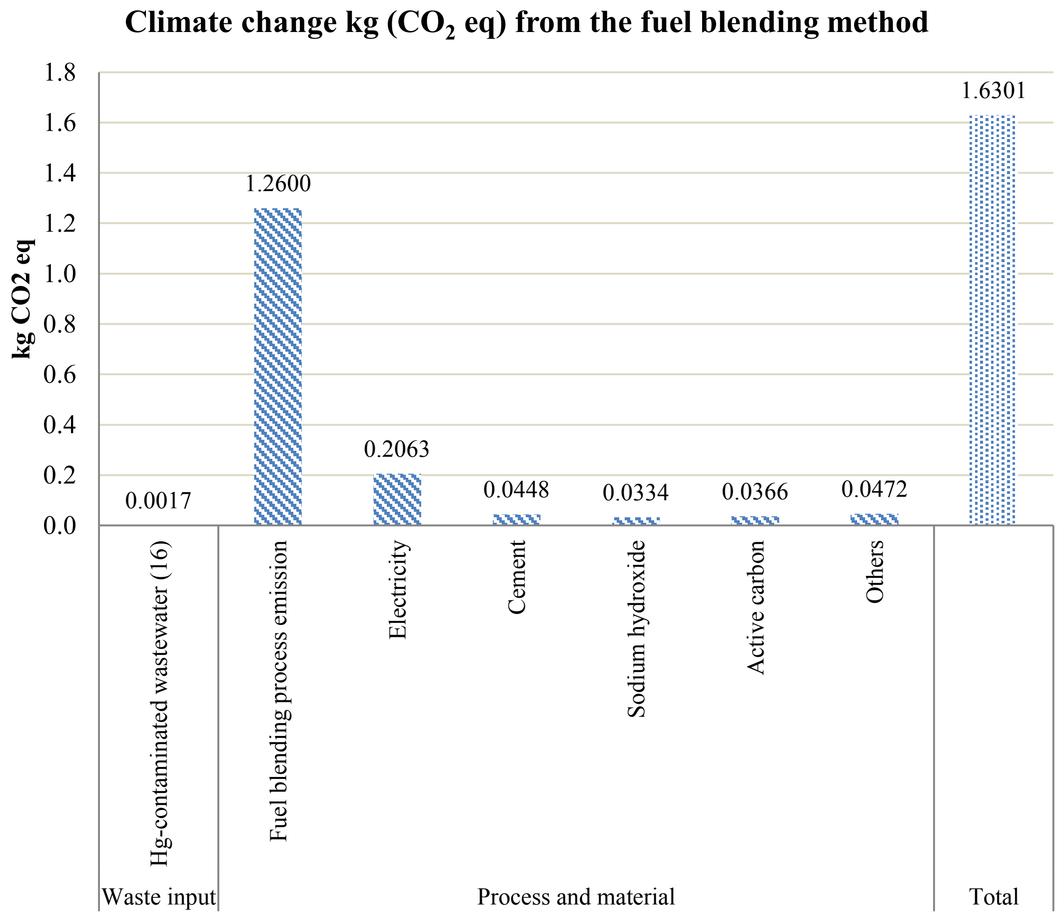


Figure 4.16 Climate change evaluation in fuel blending (042) method.

From Figure 4.16, the climate change impact contributed to fuel blending waste treatment method is equal to 1.6301 kg CO_2 eq. The Hg-contaminated waste disposed of by fuel blending method was mainly the wastewater. When focusing on the contaminated wastewater, the climate change impact is equal to 0.0017 kg CO_2 eq per functional unit. On the other hand, the main factors that cause the impact are from the process and material input for fuel blending treatment.

The process and material for fuel blending were assumed to be similar to the process of industrial hazardous waste incineration, as mentioned earlier in Section 4.3.3.2. The high value of climate change impact exhibits in the emission of total fuel blending process which is around 1.26 kg CO_2 eq. In addition, the electricity for fuel blending operation also contributed to the impact, representing about 0.2063 kg CO_2 eq. Cement was used for waste stabilization in the solidification process (Hong *et al.*, 2016). The process and materials tended to have a higher value of climate change impact than the waste that inputs in this process.

Consequently, the major of kg CO_2 emission was by fuel blending method came from the process emission. On the other hand, the Hg-contaminated wastewater exhibited less climate change impact.

4.3.4.3 Climate Change Impact from Recovery Method (059)

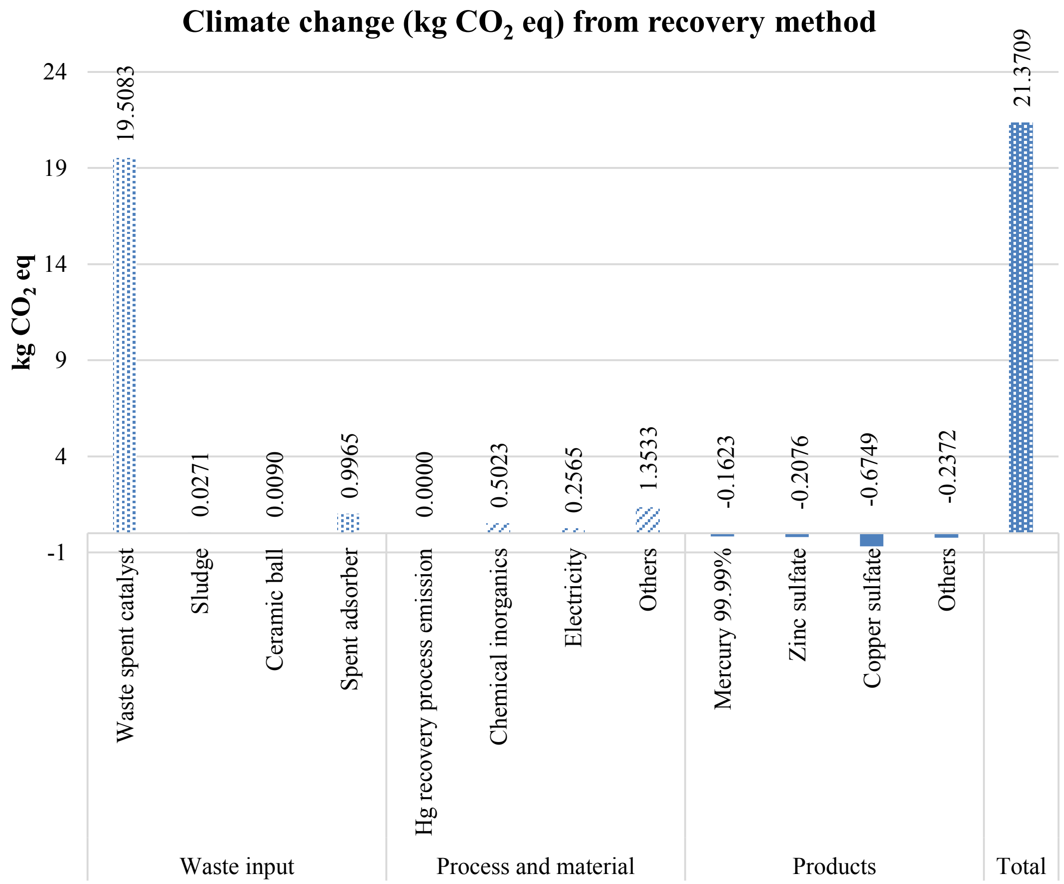


Figure 4.17 Climate change evaluation in recovery (059) method.

From Figure 4.17, the climate change for recovery method was about 21.37 kg CO_2 eq. The highest value of climate change impact was the spent catalyst input, which is classified as absorber group (05). From the net value of climate change impact, recovery method had a high CO_2 (Davis *et al.*, 2010).

From the process of Hg recovery the study of Qi *et al.* (2017), none of the climate change impact caused by the direct Hg recovery process emission. So, the material input in this study process did not contribute to the impact on climate change. The recovered products indicated a low benefit to climate change impact.

When considering the entire Hg recovery method for the end-of-life stage, CO_2 emission is emitted from mainly the waste disposal and less from the material input to the process. Thus, the Hg recovery method showed a high value of climate change impact.

4.3.4.4 Climate Change Impact from Landfill Method (071)

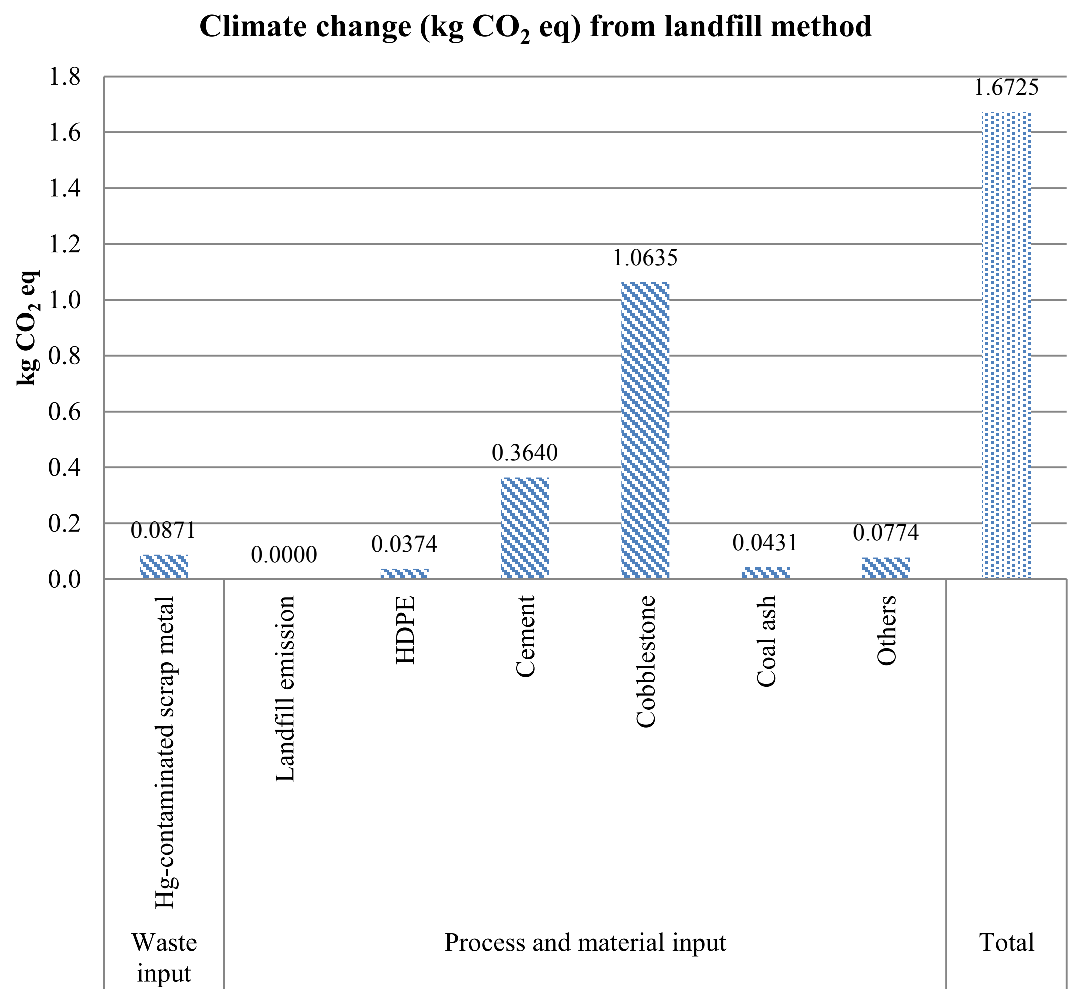


Figure 4.18 Climate change evaluation in landfill (071) method.

According to Figure 4.18, the net climate change impact is equal to 1.6725 kg CO_2 eq for the landfill method. The wastes disposed of by landfill method was

Hg-contaminated metal scraps which were exposed the value equal to 0.0871 kg CO_2 eq.

The climate change impact caused by the landfill came from the landfill building sites materials. As mentioned earlier (see Section 4.3.3.4), the dataset of process used in industrial hazardous waste landfill included solidification, landfill and, wastewater treatment. All of the processes also consumed the materials used for waste treatment, as mentioned in Section 2.6.2 (Hong *et al.*, 2016).

Cobblestone was the floor building material for industrial hazardous waste landfill sites. From Figure 4.18, the cobblestone shows the high value of climate change impact, which is equal to 1.0635 kg CO_2 eq followed by cement and coal ash. Cement (0.3640 kg CO_2 eq) and coal ash (0.0431 kg CO_2 eq) was the stabilizers for waste solidification.

As a result, the climate change impact is raised because of the building materials used for landfill sites construction. The impact of the Hg-contaminated metal scrap is not significant when comparing with the landfill facilities preparation.

4.3.4.5 Comparison of Climate Change Impact in Each Disposal Method

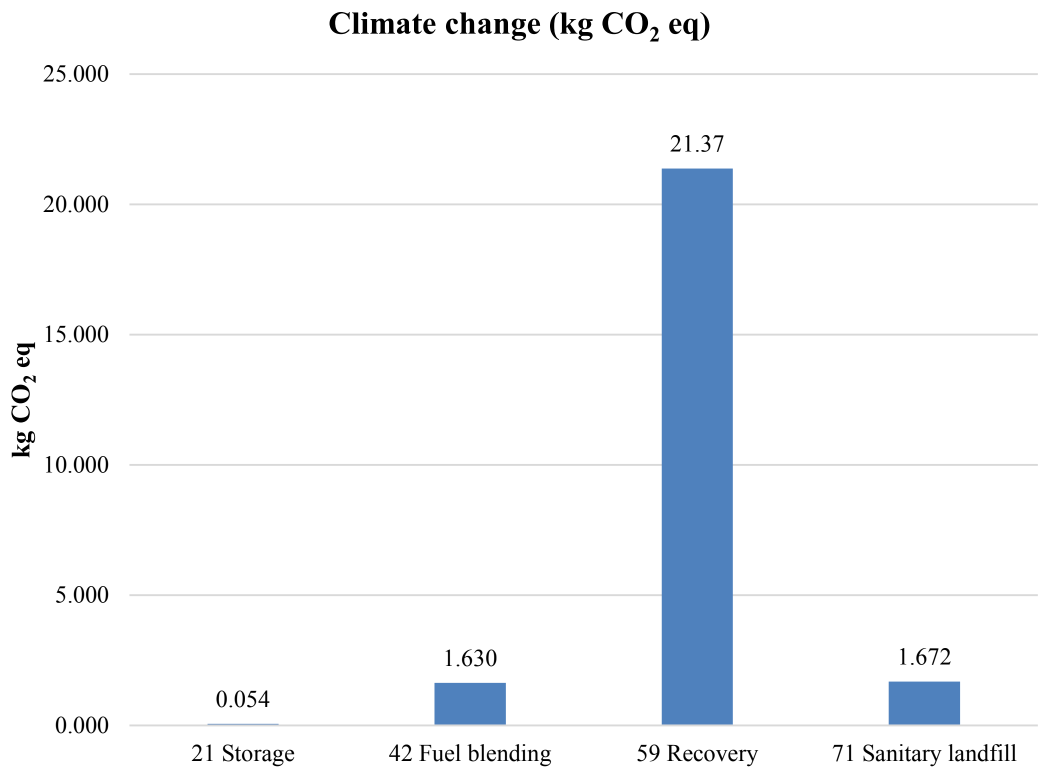


Figure 4.19 The overall LCA on climate change impact in each disposal method.

From Figure 4.19, the emission from storage method contributed to the climate change impact, which was generated from the waste transpotation only. Fuel blending method emitted the emission that contributes to the climate change impact. In addition, Hg recovery process shows high value of climate change impact. This is because of the Hg-contaminated waste input in the process. The landfill exhibited the climate change impact which was caused by landfill constructed materials.

4.3.5 Combined MFA and LCA Focused on Human toxicity and Climate Change Impacts for End-of-Life of Hg-Contaminated Waste Management

The Hg-contaminated waste was calculated based on amount of waste disposed of by each method referred to Figure 4.7. The MFA of the Hg-contaminated waste was allocated by the waste into waste type and disposal method. The MFA result as shown in Figure 4.7 also provides the mass flow from the waste classification until the end-of-life waste disposal. When MFA combined with LCA, it can help to integrate the result regarding environmental impact generated in terms of the waste flows.

Table 4.4 Integrated result in each disposal method

Disposal method	Amount of waste disposed of (ton)	Impact category	
		Human toxicity, HT (t1,4-DB eq)	Climate change, CC (t CO_2 eq)
Storage (021)	320.0	0.516	17.32
Fuel blending (042)	1.770	0.421	2.887
Recovery (059)	1,628	-1,344,704	34,785
Landfill (071)	56.62	5.647	94.69

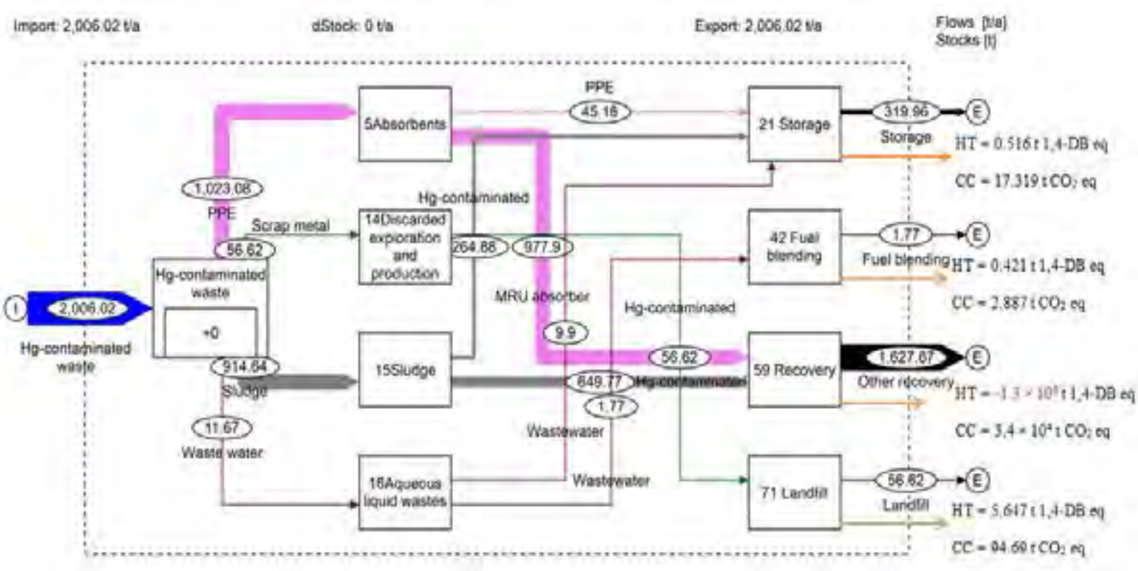


Figure 4.20 Combined MFA and LCA result in each disposal method (functional unit: total of Hg-contaminated waste).

From Table 4.4 and Figure 4.20, all of the mass flow in each disposal method is multiplied separately by both human toxicity impact and climate change impact.

Hg-contaminated waste is dominantly disposed of by Hg recovery method. Hence, the human toxicity impact by the recovery method is the highest because of a high amount of waste being disposed of (1,628 ton). On the other hand, the recovery method resulted in high benefit for human toxicity impact.

The landfill is the second waste disposal method based on the volume of the waste flow. It was high human toxicity impact when the amount of waste is considered. Also, the storage exhibits a higher human toxicity impact than the fuel blending.

The climate change impact is illustrated in Table 4.4 and Figure 4.20, the Hg recovery method has the highest climate change impact, which is equal to 34,784,713 kg CO_2 eq per the total waste flow. The waste spent catalyst (05), which is disposed of by the recovery method, is the major waste type that contributed to climate change impact. Landfill, storage and, fuel blending followed by for the integrated MFA and LCA result.

Hg recovery shows the positive impact in term of human toxicity but the highest negative impact on climate change. Landfill showed the high climate change impact. Storage showed the human toxicity impact and climate change impact because of amount of waste flow. Fuel blending showed less on both impacts because it was not favourable treatment method (low waste flow).

As a consequence, the combined assessment between MFA and LCA results in high benefit on human toxicity impact for the Hg recovery method. On the contrary, the highest human toxicity impact value is caused by the waste disposed of by landfill. The waste disposed of by landfill resulted in high human toxicity and climate change impacts. The waste treatment process and material used for building sites of landfill were a reason for the vast effects on the high environmental and human health impacts.

CHAPTER V
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The petroleum waste is classified into the group based on its waste code, disposal method and, hazardous properties. Material flow analysis (MFA) helps to create the boundary of waste flow by each category to their disposal method. The waste is identified and characterized through the MFA for further environmental impact analysis. The Hg-contaminated waste will be regulated under the Minamata convention (United Nations Environment Programme, 2019). So it was selected to analyse their end-of-life by Life Cycle Assessment (LCA).

The Hg-contaminated waste disposal method (Thailand, 2015) was divided into was included storage (021), fuel blending (042), recovery (059), and landfill (071). For the impact was analyzed based on designed functional unit (1 kg of Hg-contaminated waste), the waste disposed of by storage method contributed to human toxicity and climate change impacts are caused by the waste transportation only. For the fuel blending method, human toxicity and climate change impacts are caused by the process direct emissions. Recovery method (059) has a remarkable result on the benefit from human toxicity, but it generated high amount of CO_2 emission (climate change impact). The benefit of recovery method obtained from recovered products. Otherwise, the recovery method resulted in high climate change impact which was distributed by the waste input (waste spent catalyst). In addition, landfill method contributed to the human toxicity and climate change is caused by landfill constructed material (i.e. cobblestone). As integrated result of MFA and LCA, the high amount of waste disposed of by the recovery method (059) indicates a high adverse impact on climate change but also presents a benefit to human toxicity impact. In addition, the landfill method has the high impact on human toxicity, which was caused by their constructed material.

The combination of MFA and LCA exhibited the link between mass flow and the environmental assessment. The flow of waste in each method and environmental impact evaluation are corresponsed with their waste management. The high amount of waste flow multiplied the impacts to be higher than waste being generated. Thus, the wastes with the immense amount and high impacts indicators results in higher environmental impacts.

The integrated result showed the relative of waste flow and environmental impact assessment lead to a better understanding of the waste management system. The advantage and disadvantage in each method on environmental impacts can be exhibited by MFA and LCA.

5.2 Recommendations

For the performing of combined Life cycle assessment (LCA) and Material Flow Analysis (MFA), the recommendations would provide for improvement.

All of the impact categories in method of LCA have different calculation and database. The choice for selection any methods can be based on the focus topic. In addition, the either sensitivity or uncertainty analysis of LCA is needed for further study.

In addition, the others evaluation method can be applied for LCA at the end of life stage of waste depending on the environmental impact category of the interest. For example, USEtox method which would be another favourable for observing the impacts from mercury. This method has been developed and suitable to estimate human and ecotoxicological impacts of chemical emissions in LCA. Also includes the impact categories focusing on human toxicity (i.e., cancer, and non-cancer) and freshwater ecotoxicity.

In this study, the waste disposal by the different method considered only for the impacts on the environments and living life. For further study, the cost and economics comparative for each case would be an additional option for the benefit purpose.

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APPENDICES

Appendix A Raw Data of Petroleum Waste from the Unnamed Offshore Petroleum Company in Thailand 2015

The raw data of offshore waste disposal in the 2015 in Thailand was showed in the Table A.1.

The hazardous waste has a specific code for identifying. HM stand for hazardous waste – mirror entry and HA stand for hazardous waste – absolute entry. The waste with no HM or HA was defined as non-hazardous waste.

Table A.1 Raw data of the offshore drilling waste collection in Thailand 2015

No.	Waste category			Amount						DIW disposal code
	DMF waste code		Waste name	Unit	company 1	company 2	company 3	company 4	Total	
Waste from drilling										
1	0203		โคลนที่มีสารสังเคราะห์เป็นองค์ประกอบหลัก ที่ไม่ใช่ 0202	Ton	217.52	-	-	-	217.5	076
2	0301		เศษดินเศษหินจากการขุดเจาะช่วงบนโดยใช้น้ำทะเล	Metric ton	-	-	-	26,418	26,418.4	082
3	0301		เศษดินเศษหินจากการขุดเจาะช่วงที่ใช้โคลนที่มีน้ำเป็นองค์ประกอบหลัก	Metric ton	-	-	-	59,229	59,228.5	082
4	0303		เศษดินเศษหินจากการขุดเจาะโดยใช้โคลนที่มีสารสังเคราะห์เป็นองค์ประกอบหลัก	Metric ton	-	-	-	51,971	51,970.7	082
5	0303		เศษดินเศษหินจากการขุดเจาะโดยใช้โคลนที่มีสารสังเคราะห์เป็นองค์ประกอบหลัก ที่ไม่ใช่ 0302	Ton	3562.68	-	-	-	3,562.7	076
6	0303		เศษหินจากการขุดเจาะ	Ton	-	-	7,091		7,090.6	082
7	0409	HM	จารบีใช้งานแล้ว	kg	-	-	-	99	99.0	011, 042

No.	Waste category			Amount						DIW disposal code
	DMF waste code		Waste name	Unit	company 1	company 2	company 3	company 4	Total	
8	0303		Drill Cutting from Synthetic Based Mud	kg	-	845.80	-	-	845.8	042
9	0407		Used Oil	kg	-	300.00	-	-	300.0	042
10	0501		เศษผ้าปนเปื้อน (Contaminated Fabric/Rag)	kg	-	-	20	-	20.0	076
11	0501	HM	เศษผ้าปนเปื้อน/PPE	kg	-	-	420	-	420.0	076
12	0502		ไส้กรองอากาศ	kg	-	-	-	487	487.0	021
13	0503	HM	วัสดุดูดซับ วัสดุตัวกรองที่ปนเปื้อนน้ำมัน (Oil Filter)	kg	kg	-	115	-	115.0	076
14	0503	HM	ไส้กรองน้ำมัน	kg	207.50	91.50	-	972	1,271.0	021
15	0503	HM	เศษผ้าปนเปื้อน	kg	123.00	-	-	-	123.0	042
16	0503	HM	เศษผ้าที่ปนเปื้อนน้ำมัน (Contaminated Fabric)	kg	-	-	418	1,601	2,019.0	076
17	0602	HM	สารเคมีใช้แล้วที่เป็นสารอนินทรีย์	kg	-	-	-	2,920	2,920.0	
18	0701		สีหมดอายุ	kg	385.75	-	-	590	975.8	011, 042

No.	Waste category			Amount						DIW disposal code
	DMF waste code		Waste name	Unit	company 1	company 2	company 3	company 4	Total	
19	0905		ของเสียอิเล็คทรอนิกส์	kg	4.50	-	-	-	4.5	049
20	0905		หลอดไฟ	kg	-	-	2	20	21.7	049
21	0905		อุปกรณ์ไฟฟ้าที่ไม่ใช้งานแล้ว	kg	-	-	-	40	40.0	011
22	1001		แบตเตอรี่ประเภทใช้ตะกั่ว	kg	61.50	-	65	5	131.5	021
23	1101		บรรจุภัณฑ์ที่เป็นกระดาษ (Cardboard paper)	kg	-	-	108	-	108.2	011
24	1102		Plastic Scrap	kg	-	385.50	-	-	385.5	011
25	1102		ขวดน้ำดื่ม	kg	-	-	405	-	404.9	011
26	1102		ขวดพลาสติก	kg	-	-	-	202	202.0	011
27	1104		Steel Can/Aluminium Scrap	kg	-	26.60	-	-	26.6	011
28	1104		Steel can	kg	-	43.80	-	-	43.8	011
29	1104		Aluminum scrap	kg	-	39.90	-	-	39.9	071
30	1104		200 Ltr steel drum (cleaned)	kg	-	-	20	-	20.0	011
31	1104		ภาชนะโลหะ (ปี๊บ)	kg	23.00	-	-	-	23.0	011
32	1104		ถังโลหะ	kg	-	-	-	164	164.0	011

No.	Waste category			Amount						DIW disposal code
	DMF waste code		Waste name	Unit	company 1	company 2	company 3	company 4	Total	
33	1109		ถุงเคมีใช้แล้ว (Chemical sack)	kg	0.00	-	-	-	-	021
34	1109		ภาชนะปนเปื้อนสารเคมีขนาด 20-50 ลิตร (ถังพลาสติก)	kg	158.75	-	-	-	158.8	049
35	1109		กระป๋องสี	kg	77.50	62.10	-	-	139.6	049
36	1109		ถุงบรรจุสารเคมี	kg	5424.00	-	-	-	5,424.0	042
37	1109		บรรจุภัณฑ์ที่ปนเปื้อน (Paint can)	kg	-	-	132	-	131.9	069
38	1109		ภาชนะบรรจุปนเปื้อน (พลาสติก)	kg	-	-	-	488	488.0	069
39	1110		บรรจุภัณฑ์ที่ปนเปื้อนชนิดที่มีความดัน (Aerosol Cans / Spray can)	kg	-	-	5	-	5.0	069
40	1110		กระป๋องอัดแรงดัน	kg	-	-	-	222	222.0	011
41	1111		กระป๋องสีใช้แล้ว	kg	-	-	-	1,230	1,230.0	011
42	1304		เศษไม้	kg	-	-	2,093	-	2,093.0	071
43	1305		เศษแก้ว	kg	-	-	162	-	161.7	071
44	1306		เศษพลาสติก	kg	-	-	61	3,751	3,812.0	011, 071

No.	Waste category			Amount						DIW disposal code
	DMF waste code		Waste name	Unit	company 1	company 2	company 3	company 4	Total	
45	1308		เศษโลหะ	kg	2174.50	-	12,620	-	14,794.8	011
46	1308		สลิง	kg	4001.00	-	-	-	4,001.0	011
47	1308		เศษอลูมิเนียม (Aluminum Scrap)	kg	-	-	19	-	19.3	011
48	1308		โลหะและโลหะผสม	kg	-	-	-	18,333	18,333.0	011
49	1314		ท่อยาง	kg	-	-	1,442	2,749	4,191.0	071
50	1404		น้ำมันดีเซล (Diesel)	kg	-	-	2,370	-	2,370.0	076
51	1406		สายสลิงที่ไม่ใช้งานแล้ว	kg	-	-	-	16,486	16,486.0	011
52	1411		พลาสติกอุดท่อ	kg	51.50	-	-	-	51.5	011
53	1411		ท่อน้ำไม่ปนเปื้อน	kg	69.00	-	-	-	69.0	071
54	1411		ฝาปิดท่อขุดเจาะ (tubing protector)	kg	-	-	-	308	308.0	011
55	1501		Oily waste sludge	kg	-	-	4,805	-	4,805.0	076
56	1601		น้ำเสียปนเปื้อนน้ำมัน และ น้ำมันที่มีน้ำปนเปื้อนเกินกว่า 5%	kg	1727.50	-	69,094	-	70,821.5	042

No.	Waste category			Amount						DIW disposal code
	DMF waste code		Waste name	Unit	company 1	company 2	company 3	company 4	Total	
57	1601		น้ำปนเปื้อนน้ำมัน	kg	-	-	-	2,280	2,280.0	011, 042
58	1902		มูลฝอยทั่วไป และของเสียไม่อันตรายจากการคัดแยก	kg	22792.50	-	9,240	69,279	101,311.5	071
59	1902		Commercial Waste	kg	-	27091.30	-	-	27,091.3	071
60	1902		ของเสียอื่นๆ (ของเสียไม่อันตราย)	kg	-	-	35,644	-	35,644.0	071

Table A.2 Raw data of the offshore production waste collection in Thailand 2015

No.	Waste category			Amount								DIW disposal code
	DMF Waste code		Waste name	Unit	company 1	company 2	company 3	company 4	company 5	company 6	Total	
Petroleum production												
1	0102		น้ำจากกระบวนการผลิต ที่ไม่ใช่ 0101	bbl	38315 153	13440 843	-	-	49855 665	14982 072.64	11659 3733	077
2	0203		โคลนที่มีสารสังเคราะห์เป็นองค์ประกอบหลัก ที่ไม่ใช่ 0202	Ton	411.06 25	-	-	-	-	-	411.06 25	021
3	0301		เศษดินเศษหินจากการขุดเจาะโดยใช้โคลนที่มีน้ำเป็นองค์ประกอบหลักที่เหลือจากห้องปฏิบัติการ	Ton	-	-	-	42486	-	1380.0 0	43866	042
4	0303		เศษดินเศษหินจากการขุดเจาะโดยใช้โคลนที่มีสารสังเคราะห์เป็นองค์ประกอบหลัก ที่ไม่ใช่ 0302	Ton	15554. 84	-	-	-	-	-	15554. 84	076
5	0404	HA	Used oil (Used diesel)	kg	-	-	12734	-	-	-	0	021

No.	Waste category			Amount								DIW disposal code
	DMF Waste code		Waste name	Unit	company 1	company 2	company 3	company 4	company 5	company 6	Total	
6	0407	HM	น้ำมันใช้แล้ว	kg	31428	-	-	37890	-	3736.00	73054	042
7	0407	HM	Used Grease	kg	-	-	-	5868	-		5868	059
8	0409	HM	จารบีใช้แล้ว	kg	-	-	-	-	-	3320.00	3320	042
9	0501	HM	อุปกรณ์ป้องกันส่วนบุคคลที่ปนเปื้อนปรอท	kg	-	-	-	-	-	7659.00	7659	021,052
10	0501	HM	วัสดุดูดซับ (Absorbent)	kg	0	-	-	-	-		0	021
11	0501	HM	วัสดุตัวกรองที่ปนเปื้อนปรอท (filter)	kg	-	-	-	-	-	16267.00	16267	021,052
12	0501	HM	วัสดุดูดซับที่ปนเปื้อนสารอันตราย	kg	-	-	-	-	-	49212.00	49212	011,042
13	0501	HM	Glycol Filter	kg	-	-	-	5868	-	-	5868	059

No.	Waste category			Amount								DIW disposal code
	DMF Waste code		Waste name	Unit	company 1	company 2	company 3	company 4	company 5	company 6	Total	
14	05 01	HM	CO2 Filter	kg	-	-	-	403	-	-	403	059
15	0501	HM	Hg contaminated PPE and Solid waste	kg	-	-	-	45184	-	-	45184	021
16	0501	HM	Hg contaminated ceramic ball	kg	-	-	-	8549	-	-	8549	059
17	0501	HM	Spent MRU Adsorber	kg	-	-	-	920210	-	-	920210	059
18	0501	HM	Used Sorbead	kg	-	-	-	3240	-	-	3240	042
19	0501	HM	Waste Mercury Contaminated Sorbead	kg	-	-	-	50	-	-	50	059
20	0501	HM	Waste Spent MRU Catalyst	kg	-	-	-	49089	-	-	49089	059
21	0502		ไส้กรองน้ำ	kg	-	-	-		242	-	241.6	071

No.	Waste category			Amount								DIW disposal code
	DMF Waste code		Waste name	Unit	company 1	company 2	company 3	company 4	company 5	company 6	Total	
22	0502		ไส้กรองอากาศ	kg	2821.5	-	-	31541	-	8698.00	43060.5	071
23	0502		ถ่านกัมมันต์ใช้แล้ว	kg	-	-	-	-	-	1418.00	1418	011,071
24	0503	HA	Used oil filter	kg	-	-	796	-	-	-	796	076
					-	-	48	-	-	-	48	021
25	0503	HA	Fabric contaminated waste	kg	-	-	2691	-	-	-	2691	076
					-	-	455	-	-	-	455	021
26	0503	HA	Oily Rags/Filter Screens	kg	-	7768	-	-	-	-	7768	073
27	0503	HA	Oily Rags	kg	-	-	-	142261	-	-	142261	041
28	0503	HA	Lube Oil filter	kg	-	-	-	40623	-	-	40623	021
29	0503	HA	เศษผ้าปนเปื้อน	kg	10386.5	-	-		-	-	10386.5	042

No.	Waste category			Amount								DIW disposal code
	DMF Waste code		Waste name	Unit	company 1	company 2	company 3	company 4	company 5	company 6	Total	
30	0503	HA	เศษผ้าที่ปนเปื้อนน้ำมัน (Contaminated Fabric)	kg	-	-	-		256	19938.00	20194	076
31	0503	HA	วัสดุดูดซับ วัสดุตัวกรองที่ปนเปื้อนน้ำมัน (Oil Filter)	kg	-	-	-		2965		2964.7	076
32	0503	HA	ไส้กรองน้ำมัน	kg	8327.5	-	-		-	8298.00	16625.5	011,042
33	0503	HA	วัสดุดูดซับที่ปนเปื้อนน้ำมัน	kg	530	-	-		-	-	530	042
34	0503	HA	อุปกรณ์ป้องกันส่วนบุคคลที่สารอันตราย	kg	-	-	-		-	245.00	245	011,042
35	0601	HM	Used Thinner	kg	-	-	-	10552	-	-	10552	042
36	0601	HM	Waste Fluid Solvents	kg	-	-	-	365	-	-	365	021
37	0602	HM	สารเคมีใช้แล้วที่เป็นสารอนินทรีย์	kg	-	-	-	-	-	28925.00	28925	011,042

No.	Waste category			Amount								DIW disposal code
	DMF Waste code		Waste name	Unit	company 1	company 2	company 3	company 4	company 5	company 6	Total	
38	0602	HM	สารเคมีใช้แล้ว (Casing Fluid)	kg	-	-	-	-	-	70810.00	70810	011,042
39	0603	HM	Mix Hydrocarbons (Lab)	kg	-	-	-	1766	-	-	1766	021
40	0701	HM	Expired Chemical	kg	-	-	-	8940	-	-	8940	042
41	0701	HM	สีหมดอายุ	kg	5516	-	-	-	-	24019.00	29535	021
42	0701	HM	สารเคมีไม่ใช้แล้ว	kg	2850	-	-	-	-	-	2850	042
43	0701	HM	Used chemical waste	kg	-	-	1322	-	-	-	1322	021
44	0702		สารเคมีที่ยังไม่ได้ใช้งาน (ซีเมนต์และแบไรท์)	kg	6760	-	-	-	-	-	6760	042
45	0702		สารเคมีที่ไม่ได้คุณภาพ หมดอายุหรือยังไม่ได้ใช้งาน (Chemical Liquid Waste)	kg	-	-	-	-	180	-	180	076
46	0702		สารเคมีไม่ได้คุณภาพ	kg	-	-	-		-	4814.00	4814	011,042

No.	Waste category			Amount								DIW disposal code
	DMF Waste code		Waste name	Unit	company 1	company 2	company 3	company 4	company 5	company 6	Total	
47	0702		Expired Cement Powder	kg	-	-	-	40814	-	-	40814	021
48	0702		Dry Chemical Powder	kg	-	-	-	11830	-	-	11830	041
49	0702		Waste Fire Extinguishing foam (Corda)	kg	-	-	-	488	-	-	488	071
50	0804	HM	สารเร่งปฏิกิริยาใช้แล้ว	kg	-	-	-	-	-	0.00	0	021
51	'0905	HM	หลอดไฟฟลูออเรสเซน	kg	160	-	-	-	101	-	261.2	049
52	0905	HM	Broken used Fluorescent lamp	kg	-	-	-	20	-	-	20	021
53	0905	HM	Used Fluorescent Lamp	kg	-	-	-	1818	-	-	1818	049
54	0905	HM	หลอดไฟ	kg	-	-	-	-	-	888.00	888	011
55	0905	HM	Electronic equipment	kg	-	24	-	-	-	-	24.2	'073
56	0905	HM	ของเสียอิเล็คทรอนิกส์	kg	733.5	-	-	-	-	-	733.5	049
57	0905	HM	อุปกรณ์ไฟฟ้าที่ไม่ใช้งานแล้ว	kg	-	-	-	-	-	2476.00	2476	011

No.	Waste category			Amount								DIW disposal code
	DMF Waste code		Waste name	Unit	company 1	company 2	company 3	company 4	company 5	company 6	Total	
58	0906		Electronic waste	kg	-	-	186	-	-	-	186	021
				kg	-	-	20	-	-	-	20	049
59	0906		Used Electronic Appliance	kg	-	-	-	21334	-	-	21334	049
60	1001	HA	แบตเตอรี่ประเภทใช้ตะกั่ว	kg	1714.5	-	-		202	11745.00	13661	011,049
61	1001	HA	Used acid Battery	kg	-	-	-	57390	-	-	57390	049
62	1001	HA	Acid lead battery	kg	-	-	4210		-	-	4210	021
63	1002	HA	Used Acid Battery	kg	-	-	-	6407	-	-	6407	049
64	1004		Battery / Dry Cell	kg	-	5	-		-	-	5	073
65	1004		แบตเตอรี่ชนิดอัลคาไลน์	kg	-	-	-	2915	-	0.00	2915	021
66	1005		แบตเตอรี่ชนิดลิเที่ยม	kg	-	-	-		-	0.00	0	021
67	1101		บรรจุภัณฑ์ที่เป็นกระดาษ (Cardboard paper)	kg	-	439	-		703	176.00	1317.6	011

No.	Waste category			Amount								DIW disposal code
	DMF Waste code		Waste name	Unit	company 1	company 2	company 3	company 4	company 5	company 6	Total	
68	1101		Box	kg	-	20832	-		-	-	20832	071
69	1101		Paper and cardboard packaging	kg	-	-	-	2639	-	-	2639	011
70	1102		ขวดน้ำพลาสติก	kg	79	-	-		-	1634.00	1713	011
71	1102		ขวดน้ำดื่ม	kg	-	-	-	11720	4199	-	15919.35	011
72	1102		พลาสติก	kg	151	22976	-	-	-	-	23127	011
73	1102		Plastic/Plastic bottle	kg	-	4230	-	-	-	-	4230	'049
74	1102		Plastic tubing protector	kg	-	-	4542	-	-	-	4542	021
75	1102		Plastic container (Plastic waste)	kg	-	-	-	9321	-	-	9321	011
76	1102		Plastic scrap Tubing Protector	kg	-	-	-	1960	-	-	1960	011
77	1102		Plastic Container	kg	-	-	-	180	-	-	180	011

No.	Waste category			Amount								DIW disposal code
	DMF Waste code		Waste name	Unit	company 1	company 2	company 3	company 4	company 5	company 6	Total	
78	1103		Wood	kg	-	25714	-	-	-	-	25714	'049
79	1103		Pallets	kg	-	490	-	-	-	-	490	071
80	1104		200 Ltr steel drum (cleaned)	kg	-	-	-		8946	-	8946	011
81	1104		ถังโลหะ	kg	-	-	-	-	-	793.00	793	011
82	1104		ภาชนะโลหะ (ปี๊บ)	kg	222	-	-	-	-	-	222	'011
83	1104		Can/Metal/Aluminium	kg	-	8211	-	-	-	-	8211	071
84	1104		Food Can	kg	-	-	-	4839	-	-	4839	011
85	1104		Aerosol Can (Punctured)	kg	-	-	-	5070	-	-	5070	011
86	1104		Aluminium Can	kg	-	-	-	586	-	-	586	011
87	1104		Metal drums	kg	-	-	-	2012	-	-	2012	011
88	1104		Steel Band	kg	-	-	-	15176	-	-	15176	011
89	1107		Glass bottle	kg	-	5073	-	26133	-	-	31206	'071

No.	Waste category			Amount								DIW disposal code
	DMF Waste code		Waste name	Unit	company 1	company 2	company 3	company 4	company 5	company 6	Total	
90	1107		Glass	kg	-	453	-	-	-	-	453	'049
91	1109		บรรจุภัณฑ์ที่ปนเปื้อน (Paint can)	kg	-	-	-	-	610	-	609.9	069
92	1109	HM	ภาชนะบรรจุปนเปื้อน	kg	-	-	-	-	-	3679.00	3679	011,069
93	1109	HM	ภาชนะบรรจุปนเปื้อน (โลหะ)	kg	-	-	-	-	-	9396.00	9396	011,069
94	1109	HM	ภาชนะบรรจุปนเปื้อน (พลาสติก)	kg	-	-	-	-	-	2498.00	2498	011,069
95	1109	HM	ภาชนะบรรจุปนเปื้อนปรอท (พลาสติก)	kg	-	-	-	-	-	3730.00	3730	069,077
96	1109	HM	ตลับหมึก	kg	-	-	-	-	-	460.00	460	011,049
97	1109	HM	Contaminated packaging	kg	-		8431	-	-	-	8431	021
98	1109	HM	Empty paint can	kg	-	-	4352	-	-	-	4352	049
		HM			-	-	203	-	-	-	203	021

No.	Waste category			Amount								DIW disposal code
	DMF Waste code		Waste name	Unit	company 1	company 2	company 3	company 4	company 5	company 6	Total	
99	1109	HM	Small plastic drum	kg	-	-	461	-	-	-	461	049
100	1109	HM	Empty Hydrocarbon Contaminated Drums - Plastic drums 200 L	kg	-	-	-	19600	-	-	19600	049
101	1109	HM	Empty Contaminated Drums -Plasticl drums 150 L	kg	-	-	-	2312	-	-	2312	049
102	1109	HM	Empty contaminated drums - Plastic drums 25 L	kg	-	-	-	13016	-	-	13016	049
103	1109	HM	Empty contaminated drums - size 1000 L	kg	-	-	-	120780	-	-	120780	049
104	1109	HM	Empty contaminated drums - size > 1.5 m3	kg	-	-	-	51070	-	-	51070	049
105	1109	HM	Chemical sack	kg	-	-	-	194640	-	-	194640	041
106	1109	HM	Emptly contaminated bottles (Lab)	kg	-	-	-	120	-	-	120	021
107	1109	HM	ภาชนะปนเปื้อนสารเคมี ขนาด 150 -200 ลิตร (ถังโลหะ)	kg	1200	-	-	-	-	-	1200	049

No.	Waste category			Amount								DIW disposal code
	DMF Waste code		Waste name	Unit	company 1	company 2	company 3	company 4	company 5	company 6	Total	
108	1109	HM	ภาชนะปนเปื้อนสารเคมี ขนาด 150 -200 ลิตร (ถังพลาสติก)	kg	7793	-	-	-	-	-	7793	049
109	1109	HM	ภาชนะปนเปื้อนสารเคมี ขนาด 20 -50 ลิตร (ถังพลาสติก)	kg	1769	-	-	-	-	-	1769	049
110	1109	HM	ภาชนะปนเปื้อนน้ำมันและสารเคมีขนาดต่างๆ (ถังโลหะ)	kg	544	-	-	-	-	-	544	'049
111	1109	HM	ภาชนะปนเปื้อนน้ำมันและสารเคมีขนาดต่างๆ (ถังพลาสติก)	kg	286	-	-	-	-	-	286	049
112	1109	HM	ถุงเคมีใช้แล้ว Chemical sack	kg	3760	-	-	-	-	-	3760	021
113	1109	HM	กระป๋องสี	kg	2314.5	-	-	11234	-	-	13548.5	049
114	1109	HM	บรรจุภัณฑ์ที่ปนเปื้อนน้ำมันหรือมีเศษสารอันตรายตกค้าง	kg	360	-	-	-	-	-	360	049
115	1109	HM	ถุงบรรจุสารเคมี	kg	8347	-	-	-	-	-	8347	042
116	1110	HM	กระป๋องอัดแรงดัน	kg	-	-	-	-	-	1935.00	1935	011

No.	Waste category			Amount								DIW disposal code
	DMF Waste code		Waste name	Unit	company 1	company 2	company 3	company 4	company 5	company 6	Total	
117	1110	HM	Aerosol Can (Not drilled)	kg	-	-	-	132	-	-	132	042
118	1110	HM	Paint Cans	kg	-	1685	-	-	-	-	1685	'073
119	1110	HM	Empty spray can	kg	-	222	-	-	-	-	222	042
120	1110	HM	Empty cylinder / Bucket	kg	-	-	-	347	-	-	347	011
121	1110	HM	Empty aerosol can	kg	-	-	150	-	-	-	150	021
122	1111	HA	Oily Can	kg	-	992	-	-	-	-	992	073
123	1111	HA	Sample Glass Bottles	kg	-	1	-	-	-	-	1	042
124	1111	HA	Broken Glass Pen Holder	kg	-	10	-	-	-	-	10	042
125	1111	HA	Empty contaminated drums- Empty Metal drums 200 L	kg	-	-	-	96752	-	-	96752	049

No.	Waste category			Amount								DIW disposal code
	DMF Waste code		Waste name	Unit	company 1	company 2	company 3	company 4	company 5	company 6	Total	
126	1111	HA	Empty contaminated drums- Empty Metal drums 200 L (from used oil & oily waste pumped	kg	-	-	-	101863	-	-	101863	049
127	1111	HA	กระป๋องสีใช้แล้ว	kg	-	-	-		-	9803.00	9803	011,069
128	1111	HA	บรรจุภัณฑ์ที่ปนเปื้อนน้ำมันหรือเชื้อเพลิงเหลว	kg	320	-	-	-	-	-	320	049
129	1111	HA	ภาชนะปนเปื้อนน้ำมันขนาด 150 -200 ลิตร (ถังโลหะ)	kg	3300	-	-	-	-	-	3300	049
130	1111	HA	ภาชนะปนเปื้อนน้ำมันขนาด 150 -200 ลิตร (ถังพลาสติก)	kg	630	-	-	-	-	-	630	049
131	1111	HA	ภาชนะปนเปื้อนน้ำมันขนาด 20 -50 ลิตร (ถังพลาสติก)	kg	129	-	-	-	-	-	129	'049
132	1111	HA	ภาชนะปนเปื้อนน้ำมันขนาด 150-200 ลิตร (ถังเหล็ก)	kg	8	-	-	-	-	-	8	049

No.	Waste category			Amount								DIW disposal code
	DMF Waste code		Waste name	Unit	company 1	company 2	company 3	company 4	company 5	company 6	Total	
132	1111	HA	ภาชนะปนเปื้อนน้ำมันขนาด 150-200 ลิตร (ถังเหล็ก)	kg	8	-	-	-	-	-	8	049
133	1205		ฉนวนที่ไม่ใช่ 1203 และ 1204	kg	198	-	-	-	-	-	198	071
134	1205		ฉนวนกันความร้อน (Insulation)	kg	-	-	-	-	825	-	825	071
135	1205		ฉนวนใยแก้ว	kg	-	-	-	-	-	2262.00	2262	011,071
136	1205		Used Insulation Material	kg	-	-	-	50578	-	-	50578	071
137	1205		Empty Cylinders	kg	-	-	-	607	-	-	607	071
138	1302		Construction Waste	kg	-	-	-	2644	-	-	2644	071
139	1302		Non Hazardous wastes - Construction wastes	kg	-	-	-	291	-	-	291	071
140	1304		Wooden from deconstruction	kg	-	-	-	151204	-	-	151204	011
141	1304		เศษไม้	kg	-	-	-	-	7923	-	7923	071

No.	Waste category			Amount								DIW disposal code
	DMF Waste code		Waste name	Unit	company 1	company 2	company 3	company 4	company 5	company 6	Total	
142	1305		เศษแก้ว	kg	-	-	-	-	616	409.00	1024.6	071
143	1306		เศษพลาสติก	kg	-	-	-	-	1170	26121.00	27291.1	011
144	1307	HM	เศษโลหะที่ปนเปื้อนด้วยปรอท	kg	-	-	-	-	-	0.00	0	021
145	1307	HM	Steel	kg	-	365	-	-	-	-	365	'073
146	1308		Scrap Metal (construction)	kg	-	-	-	81175	-	-	81175	011
147	1308		Scrap Metal - (construction) project	kg	-	-	-	151000	-	-	151000	011
148	1308		Construction Waste	kg	-	-	-	3806	-	-	3806	011
149	1308		เศษโลหะ	kg	73710	-	-	-	226844	4500.00	305054	011
150	1308		เศษอลูมิเนียม (Aluminum Scrap)	kg	-	-	-	-	721	-	720.6	011
151	1308		สายเหล็กสำหรับรัดถัง(ลวดแบน)	kg	7243	-	-	-	-	-	7243	011

No.	Waste category			Amount								DIW disposal code
	DMF Waste code		Waste name	Unit	company 1	company 2	company 3	company 4	company 5	company 6	Total	
152	1308		สลิง	kg	2332	-	-	-	-	-	2332	011
153	1308		โลหะและโลหะผสม	kg	-	-	-	-	-	735966.00	735966	011
154	1308		Metal Scrap	kg	-	-	2204	-	-	-	2204	021
					-	-	1350	-	-	-	1350	011
155	1309	HM	เศษสแตนเลส (Stainless)	kg	-	-	-	-	8	-	8.4	011
156	1313	HM	Paint Residue	kg	-	-	-	2980	-	-	2980	042
156	1313	HM	Paint Sludge-(Expired Paint)	kg	-	-	-	45660	-	-	45660	042
156	1313	HM	Used Copper Slag	kg	-	-	-	2730	-	-	2730	041
156	1313	HM	Natural Garnet	kg	-	-	-	8700	-	-	8700	071
156	1313	HM	Used Garnet	kg	-	-	-	4650	-	-	4650	041

No.	Waste category			Amount								DIW disposal code
	DMF Waste code		Waste name	Unit	company 1	company 2	company 3	company 4	company 5	company 6	Total	
156	1314		Steel Sawdust	kg	-	-	-	6361	-	-	6361	041
156	1314		ท่อยาง	kg	-	-	-	-	2915	8667.00	11582	011
156	1314		เศษยาง	kg	-	-	-	-	-	1869.00	1869	074
156	1314		การ์เนตใช้แล้ว	kg	-	-	-	-	-	71958.00	71958	011,071
156	1314		ผงเหล็กขัดใช้แล้ว	kg	-	-	-	-	-	930.00	930	071
156	1314		Grating plastic mix steel	kg	-	-	1260	-	-		1260	021
156	1402		ก้านเจาะที่ไม่ใช้งานแล้ว	kg	-	-	-	-	-	13520.00	13520	011
156	1403		Rubber hose	kg	-	180	-	-	-	-	180	071
156	1403		Stainless scrap	kg	-	-	-	724	-	-	724	011
156	1404		น้ำมันดีเซล (Diesel)	kg	-	-	-		-	-	0	076

No.	Waste category			Amount								DIW disposal code
	DMF Waste code		Waste name	Unit	company 1	company 2	company 3	company 4	company 5	company 6	Total	
156	1405		Aluminum Scrap	kg	-	-	-	610	-	-	610	011
156	1405		สายไฟที่ไม่ใช้งานแล้ว	kg	-	-	-	17616	-	36.00	17652	011
156	1406		สายสลิงที่ไม่ใช้งานแล้ว	kg	-	-	-		-	23598.00	23598	011
156	1409	HA	Thread protector	kg	-	-	-	11148	-	-	11148	071
156	1410	HM	Hg Contaminated Scrap matals, material, pipes	kg	-	-	-	56616	-	-	56616	**071**
156	1411		Scrap metal (Process)	kg	-	-	-	269695	-	-	269695	011
156	1411		เชือก	kg	1170	-	895	-	1980	-	4045	011
156	1411		พลาสติกอุดท่อ	kg	7501	-	-	-	-	-	7501	011
156	1411		ท่อน้ำไม่ปนเปื้อน	kg	1480	-	-	-	-	-	1480	'071
156	1411		ฝาปิดท่อขุดเจาะ (tubing protector)	kg	-	-	-	-	-	140955.00	140955	011,071
156	1411		Rubber Hose	kg	-	-	648	52107	-	-	52755	021

No.	Waste category			Amount								DIW disposal code
	DMF Waste code		Waste name	Unit	company 1	company 2	company 3	company 4	company 5	company 6	Total	
156	1411		Plastic tubing protector	kg	-	-	4292		-	-	4292	021
					-	-	244		-	-	244	049
157	1411		Hg Contaminated Scrap matals,material,pipes	kg	-	-	-	26627	-	-	26627	059
158	1411		Hg Contaminated Scrap matals,material,pipes	kg	-	-	-	26627	-	-	26627	059
159	1501		Hg contaminated sludge	kg	-	-	-	649767	-	-	649767	059
160	1501		Oily waste sludge	kg	-	-	-		82944	-	82944	076
161	1501	HA	Mercury Contaminated Sand	kg	-	-	-	251967	-	-	251967	021
162	1501	HA	Pigging waste	kg	-	-	-	4339	-	-	4339	021
163	1501	HA	Glycol Sludge	kg	-	-	-	710	-	-	710	059
164	1501	HA	Printer Ink	kg	-	15	-	-	-	-	15	042
165	1502	HM	กากตะกอนน้ำมัน	kg	11445	-	-	-	-	-	11445	042

No.	Waste category			Amount								DIW disposal code
	DMF Waste code		Waste name	Unit	company 1	company 2	company 3	company 4	company 5	company 6	Total	
166	1502	HM	กากตะกอนปนเปื้อนปรอท	kg	-	-	-	-	-	0.00	0	021
167	1502	HM	โลหะปรอท (Elemental Mercury)	kg	-	-	-	12910	-	0.00	12910	021
168	1507		Contaminated Sand	kg	-	-	-	-	-	-	0	076
169	1507		Waste Sludge	kg	-	-	-	8360	-	-	8360	021
170	1507		Waste Sludge from ERTC drain	kg	-	-	-	8630	-	-	8630	041
171	1601		น้ำเสียปนเปื้อนน้ำมัน และน้ำมันที่มีน้ำปนเปื้อนเกินกว่า 5%	kg	42072	-	-	-	2233	-	44305	042
172	1601		Chemical Liquid wastewater	kg	-	-	-	-	427	-	427	076
173	1601	HM	Oily wastewater	kg	-	-	32642	-	49291	-	81933	076
		HM		kg	-	-	15960	-	-	-	15960	021

No.	Waste category			Amount								DIW disposal code
	DMF Waste code		Waste name	Unit	company 1	company 2	company 3	company 4	company 5	company 6	Total	
174	1601	HM	น้ำปนเปื้อนน้ำมัน	kg	-	-	-	-	-	18741.00	18741	011
175	1601	HM	น้ำเสียที่มีสารอันตราย	kg	-	-	-	-	-	19220.00	19220	042
176	1601	HM	Hg contaminated wastewater	kg	-	-	-	9902	-	-	9902	021
177	1601	HM	Oily waste water	kg	-	-	-	1099370	-	-	1099370	041
178	1601	HM	Annulus Fluids	kg	-	-	-	498729	-	-	498729	042
179	1601	HM	Hg contaminated wastewater	kg	-	-	-	1771	-	-	1771	042
180	1601	HM	Water contaminated oil	kg	-	320	-	-	-	-	320	'073
181	1701	HA	Used Medical wastes	kg	-	-	-	500	-	-	500	075
182	1701	HA	ของเสียติดเชื้อ	kg	80	-	-	-	80	57.85	217.85	075
183	1703	HA	ยาหมดอายุ	kg	-	-	-	-	-	29.22	29.22	-
184	1704		Non Hazardous wastes - Expired Medical wastes	kg	-	-	-	152	-	-	152	071

No.	Waste category			Amount								DIW disposal code
	DMF Waste code		Waste name	Unit	company 1	company 2	company 3	company 4	company 5	company 6	Total	
185	1704		Expired medicine	kg	-	24	-	-	-	-	24	'073
186	1901		ดินปนเปื้อนน้ำมัน	kg	514	-	-	-	-	-	514	021
187	1901		Contaminated Soil	kg	-	-	-	9116	-	-	9116	042
188	1901	HM	Oily Glass/Wood/Paper/Plastic	kg	-	17320	-	-	-	-	17320	042
189	1901	HA	Paint sludge (expired)	kg	-	-	1266	-	-	-	1266	021
190	1902		Domestic Garbage (combustible)	kg	-	-	-	2167127	-	-	2167127	074
191	1902		Domestic Garbage (incombustible)	kg	-	-	-	19899	-	-	19899	071
192	1902		Used Tire	kg	-	-	-	6534	-	-	6534	071
193	1902		Industrial non hazardoud wastes (others) - Wire Waste	kg	-	-	-	4123	-	-	4123	071
194	1902		Industrial non hazardoud-Scrap Rope	kg	-	-	-	29824	-	-	29824	071

No.	Waste category			Amount								DIW disposal code
	DMF Waste code		Waste name	Unit	company 1	company 2	company 3	company 4	company 5	company 6	Total	
195	1902		Scrap Rope	kg	-	-	-	27723	-	-	27723	071
196	1902		มูลฝอยทั่วไป และของเสียไม่อันตรายจากการคัดแยก	kg	357589	-	-	-	-	635175.00	992764	071
197	1902		ขยะมูลฝอย	kg	-	-	-	-	33265	-	33265	074
198	1902		ของเสียอื่นๆ (ของเสียไม่อันตราย)	kg	-	-	-	-	211786	-	211786.2	071
199	1902		Commercial Waste	kg	-	-	87627	-	-	-	87627	074
				kg	-	-	24689	-	-	-	24689	021

Appendix B Data for LCIA Inventory Input

For LCA, the data input in the inventory of SimaPro 8.3.0.0 are in the table below. The waste, process emission and material, and products in each Hg-contaminated (20 mg/kg) waste disposal method were different.

Table B.1 Data inventory for storage method (021)

	Name	SimaPro inventory	Unit	Amount
Transportation	Waste to storage	Transport, freight, sea, transoceanic tanker {GLO}| processing | Alloc Def, S	kgkm	2879667000

*The assumption of this method was the waste in storage is waiting for transport to storage room. The whole waste was counted as one mass. The distance to storage destination was assumed equal to 9000 km. The functional unit is the total waste disposed by storage method.

Table B.2 Data inventory for fuel blending method (042) waste disposed

	Name	SimaPro inventory	Unit	Amount
Waste input	Hg contaminated wastewater	Water, deionised, from tap water, at user {RoW}| production | Alloc Def, S	kg	1770.965
	Hg fraction	Mercury {GLO}| treatment of used fluorescent lamp | Alloc Def, S	kg	0.03542

*The assumption of this method was the waste treat by IHW incineration process. The incineration unit includes incineration, solidification, landfill, and wastewater treatment. The functional unit is equal to 1771 kg of waste.

Table B.3 Data inventory for waste incineration treatment unit for fuel blending disposal method

	Name	SimaPro inventory	Unit	Amount
Process, energy, and materials input	Land occupation	Land use II-III	m^2a	0.46
	Sodium sulfide	Sodium sulfide {GLO}| production | Alloc Def, S	g	0.59
	HDPE (landfill)	Polyethylene, high density, granulate {RoW}| production | Alloc Def, S	kg	0.19206
	Lime	Lime {GLO}| market for | Alloc Def, U	kg	48.95
	Diesel	Diesel {RoW}| petroleum refinery operation | Alloc Def, S	kg	29.05
	Cement (solidification)	Cement, Portland {RoW}| production | Alloc Def, S	kg	48.95
	Clay	Clay {RoW}| clay pit operation | Alloc Def, S	kg	17.8092
	Non-woven fabric	Textile, knit cotton {GLO}| textile production, knit cotton, batch dyed | Alloc Def, S	kg	0.0171
	Fresh water	Tap water {RoW}| tap water production, conventional treatment | Alloc Def, S	ton	2.39
	Cobblestone	Natural stone plate, cut {RoW}| production | Alloc Def, S	kg	20.1703
	Metal-chelate	Nickel, 99.5% {GLO}| smelting and refining of nickel ore | Alloc Def, S	g	0.23

	Name	SimaPro inventory	Unit	Amount
Process, energy, and materials input	Coal ash	Aluminium oxide {GLO}| production | Alloc Def, S	kg	0.14
	Wastewater	Water, decarbonised, at user {RoW}| water production and supply, decarbonised | Alloc Def, S	ton	1.01
	Sodium thiosulfate	Sodium sulfate, anhydrite {RoW}| sodium sulfate production, from natural sources | Alloc Def, S	g	0.21
	Sodium hydroxide	Sodium hydroxide, without water, in 50% solution state {RoW}| chlor-alkali electrolysis, membrane cell | Alloc Def, S	kg	26.61
	Natural gas	Natural gas, from high pressure network (1-5 bar), at service station {RoW}| processing | Alloc Def, S	kg	0.59
	Active carbon	Activated carbon, granular {RoW}| activated carbon production, granular from hard coal | Alloc Def, S	kg	4.1
	Incinerated ash	Ferrite {GLO}| production | Alloc Def, S	kg	3.82
	Incinerated slag	Aluminium oxide {GLO}| production | Alloc Def, S	kg	8.9
	Electricity	Electricity, high voltage {CENTREL}| production mix | Alloc Def, S	kWh	258.24
Direct air emission	Particulates	Particulates	kg	0.18

	Name	SimaPro inventory	Unit	Amount
Direct air emission	Sulfur dioxide	Sulfur dioxide	kg	0.65
	Carbon dioxide	Carbon dioxide	ton	1.26
	Nitrogen oxides	Nitrogen oxides	kg	2.52
	Carbon monoxide	Carbon monoxide	kg	0.26
	Hydrogen fluoride	Hydrogen fluoride	g	1.6
	Hydrogen chloride	Hydrogen chloride	g	42.89
	Mercury	Mercury	g	0.15
	Arsenic	Arsenic	g	2.32
	Nickel	Nickel	g	0.32
	Lead	Lead	g	1.32
	Chromium	Chromium	g	0.17
	Tin	Tin	g	0.15
	Antimony	Antimony	mg	4.7
	Copper	Copper	mg	58.17
	Manganese	Manganese	g	0.15
	Dioxins	Dioxins (TEQ)	µg	2.7
Direct soil emission	Fluorine	Fluorine	g	9.25
	Arsenic	Arsenic	mg	0.11
	Nickel	Nickel	mg	3.59
	Barium	Barium	mg	3.67

	Name	SimaPro inventory	Unit	Amount
Direct soil emission	Zinc	Zinc	mg	2.16
	Copper	Copper	mg	0.34
	Mercury	Mercury	mg	7.5
	Cadmium	Cadmium	mg	0.12
	Lead	Lead	mg	1.54
	Chromium	Chromium	mg	0.61

*This table was based on functional unit of 1 ton of mixed IHW

Table B.4 Data inventory for other recovery unlisted material (059) waste disposed

	Name	SimaPro inventory	Unit	Amount
Waste	Hg fraction	Mercury {GLO}| treatment of used fluorescent lamp | Alloc Def, S	kg	32.5533
	Waste Spent MRU Catalyst	Silver {RoW}| silver-gold mine operation with refinery | Alloc Def, S	kg	49088.01822
	Hg contaminated sludge	Petroleum {RoW}| petroleum and gas production, off-shore | Alloc Def, S	kg	649754.0047
	Hg contaminated ceramic ball	Sanitary ceramics {RoW}| production | Alloc Def, S	kg	8548.82902
	Spent MRU Adsorber + Sorbead	Activated silica {GLO}| production | Alloc Def, S	kg	920241.5948

Table B.5 Data inventory for recycling of Hg-containing waste treatment unit for other recovery unlisted material method

	Name	SimaPro inventory	Unit	Amount
Process, energy, and materials input	Land occupation	Land use II-III	m^2a	963.89
	Coal	Coal, hard	ton	1230
	Zinc	Zinc	ton	96.1
	Iron	Iron	ton	10.77
	Oxygen	Oxygen	ton	35.71
	Coke	Petroleum coke {RoW}| petroleum refinery operation | Alloc Def, S	ton	1100
	Tap water	Tap water {RoW}| market for | Alloc Def, S	ton	25700
	Activated carbon	Activated carbon, granular {GLO}| market for activated carbon, granular | Alloc Def, S	ton	2.32
	Lime	Lime {GLO}| market for | Alloc Def, S	ton	62.25
	Cu-Pb-Zn anode slime	Anode slime, silver and tellurium containing stockpiling {RoW}| anode slime, silver and tellurium containing stockpiling | Alloc Def, S	ton	107.14
	Wastewater	Water, deionised, from tap water, at user {RoW}| production | Alloc Def, S	ton	2650
	Chemical inorganic	Activated silica {GLO}| production | Alloc Def, S	ton	2850

	Name	SimaPro inventory	Unit	Amount
Process, energy, and materials input	Chemical organic	Chemical, organic {GLO}| market for | Alloc Def, S	ton	18.41
	Solid waste	Iron scrap, sorted, pressed {RoW}| treatment of municipal solid waste, incineration | Alloc Def, S	ton	12
	Hazardous waste	Chlorine, gaseous {RoW}| chlor-alkali electrolysis, mercury cell | Alloc Def, S	ton	9720
	Electricity	Electricity, high voltage {CENTREL}| production mix | Alloc Def, S	kWh	3210000
Direct air emission	Particulates	Particulates	ton	3.69
	Mercury	Mercury	ton	0.18
	Sulfur dioxide	Sulfur dioxide	ton	1.36
	Nitrogen dioxide	Nitrogen dioxide	ton	0.13
	Sulfuric acid	Sulfuric acid	ton	0.015
	Mercury compounds	Mercury compounds	kg	24.2
	Chloride	Chloride	kg	9.09
	Hydrogen chloride	Hydrogen chloride	kg	2.27
	Arsenic	Arsenic	kg	4.09
	Antimony	Antimony	kg	8.18
	Lead	Lead	kg	8.18

	Name	SimaPro inventory	Unit	Amount
Recovered products	Mercury	Mercury {GLO}| production | Alloc Def, S	ton	100
	Zinc sulfate	Zinc monosulfate {RoW}| production | Alloc Def, S	ton	1842
	Copper sulfate	Copper sulfate {GLO}| production | Alloc Def, S	ton	1631
	Sodium sulfate	Sodium sulfate, anhydrite {RoW}| sodium sulfate production, from natural sources | Alloc Def, S	ton	795
	Pb-Bi-alloy	Activated silica {GLO}| production | Alloc Def, S	ton	111
	Chemical inorganic	Cast iron {RoW}| production | Alloc Def, S	ton	20
	General metal	Aluminium alloy, AlLi {RoW}| production | Alloc Def, S	ton	580
	Serenium	Selenium {RoW}| production | Alloc Def, S	ton	119

*The recycling of Hg-containing waste treatment unit using functional unit equal to 10,000 tonnes of Hg-containing waste that contained 110.28 tonnes of Hg

Table B.6 Data inventory for other landfill (071) waste disposed

	Name	SimaPro inventory	Unit	Amount
Waste input	Hg contaminated scrap metal	Iron scrap, sorted, pressed {RoW}| sorting and pressing of iron scrap | Alloc Def, S	kg	56614.8677
	Hg content	Mercury {GLO}| treatment of used fluorescent lamp | Alloc Def, S	kg	1.1323

Table B.7 Data inventory for IHW landfill of Hg-contaminated waste treatment unit

	Name	SimaPro inventory	Unit	Amount
Process, energy, and materials input	Land occupation	Land use II-III	m^2a	1.16
	Sodium sulfide	Sodium sulfide {GLO}| production | Alloc Def, S	g	150.91
	HDPE	Polyethylene, high density, granulate {RoW}| production | Alloc Def, S	kg	19.4
	Lime	Lime {GLO}| market for | Alloc Def, U	kg	70.29
	Diesel	Diesel {RoW}| petroleum refinery operation | Alloc Def, S	kg	32.34
	Cement	Cement, Portland {RoW}| production | Alloc Def, S	kg	397.93
	Clay	Clay {RoW}| clay pit operation | Alloc Def, S	kg	1815.84
	Non-woven fabric	Textile, knit cotton {GLO}| textile production, knit cotton, batch dyed | Alloc Def, S	kg	1.72
	Fresh water	Tap water {RoW}| tap water production, conventional treatment | Alloc Def, S	ton	0.23
	Cobblestone	Natural stone plate, cut {RoW}| production | Alloc Def, S	kg	2037.15
	Metal-chelate	Nickel, 99.5% {GLO}| smelting and refining of nickel ore | Alloc Def, S	g	58.11

	Name	SimaPro inventory	Unit	Amount
Process, energy, and materials input	Coal ash	Aluminium oxide {GLO}| production | Alloc Def, S	kg	34.68
	Wastewater	Water, decarbonised, at user {RoW}| water production and supply, decarbonised | Alloc Def, S	ton	2.8
	Sodium thiosulfate	Sodium sulfate, anhydrite {RoW}| sodium sulfate production, from natural sources | Alloc Def, S	g	52.47
	Electricity	Electricity, high voltage {CENTREL}| production mix | Alloc Def, S	kWh	3.43
Direct soil emission	Fluorine	Fluorine	g	1800
	Arsenic	Arsenic	mg	399.33
	Nickel	Nickel	mg	392.58
	Barium	Barium	mg	718.53
	Zinc	Zinc	mg	35.93
	Copper	Copper	mg	18.3
	Mercury	Mercury	µg	1.2
	Cadmium	Cadmium	mg	12.11

	Name	SimaPro inventory	Unit	Amount
Direct soil emission	Lead	Lead	mg	59.72
	Chromium	Chromium	mg	95.18

*This table was based on functional unit of 1 ton of mixed IHW

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