Original Paper

Life Cycle Assessment of a Petroleum-Contaminated Soils Thermal Desorption Unit

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Abstract

Environmental issues involving the oil and gas industry have been growing in awareness; therefore high priority is given to waste handling and disposal. Although thermal desorption unit (TDU) is meant to reduce the environmental damage of the waste from oil industries, it may also contribute to the damage. A way of putting this to check is by taking the life cycle assessment of the operation. This study presents the environmental impact assessment using a gate-to-gate approach of a thermal desorption unit in Nigeria, analyzed following ISO 14040 standards. GaBi software obtained from PE international was used to carry out the analysis with the management of 46,541,880 kg of the waste mix for a period of 365 days considering worst case scenario as the functional unit. The results showed the fossil depletion is about 2,516,253 kg of oil equivalent, water depletion is 0.883 m^3 and particles to air is close to 35% of the particles generated. Weak point analysis to show the unit with the greatest impact on the environment was also estimated by GaBi. This study proves that operation of a TDU can be certified eco-friendly.

Keywords: Thermal desorption unit, Life cycle assessment, Global warming potential, Contaminated soil

INTRODUCTION

Remediation of contaminated site reduces risks to human health, enhances ecosystem sustainability, and often brings beneficial reuse of the site (Hou *et al.*, 2016). There are lots of onshore and offshore projects where disposal of drilling solid waste, like oil-based mud, is a major problem as it needs appropriate end-point disposal (Doyle *et al.*, 2008). Thermal desorption (TD) is a method of removing organic compounds from solid materials such as soil, sludge, filter cake, or drilling cuttings without thermally destroying them. It is fundamentally a thermal physical separation process that should not be mistaken with incineration as it does not destroy the components (Cheng *et al.*, 2006). The volatilized contaminants are either collected or thermally destroyed in other treatment units. Two major components make a thermal desorption unit; the desorber itself and the off-gas treatment system (Okeke and Obi, 2013).

Thermal desorption unit (TDU) helps in the management of the waste being discharged to our environment, thereby reducing the effect to lives of people, other living things and also reduces the environmental impact of such contaminants (Jørgensen *et al.*, 2000). One of the major wastes gotten from gas and exploration companies is mud contaminated with drill cuttings. The presence of mud during drilling is essential for drilling bits lubrication, subsurface pressures maintenance and carrying of cuttings to the surface. It is a complex system of fluids which are either oil-based or water-based with several chemical and mineral additives (Clarens *et al.*, 2008).

There are many methods of treating drill cuttings, but thermal desorption method has several advantages over others. This method has proved to be the most economical, effective and environmentally friendly method. The recovery of the products and subsequent recycling and usage help reduce stress on the environment and avoidable economic loss (Okeke and Obi, 2013). Thermal desorption is faster and provides better clean up than other methods, particularly at sites that have high concentrations of contaminants (Inoue and Katayama, 2007). Some factors alter the effectiveness of a thermal desorption process and can also imply a short lifespan for the process. It is important to ensure that the facility is designed and operated in a way that maximises the process efficiency, in terms of raw materials and energy use, in order to minimise carbon footprint and promote the sustainable use of resources whilst maintaining safe and effective standards of operation (Hou et al., 2016).

Life cycle assessment (LCA) is a technique for analyzing how processes or services affect the environment throughout their lifespan. LCA analyses the greenhouse gas (GHG) emissions of a product or service from; cradle to gate, cradle to grave or gate to gate as the case may be. The LCA system is a powerful decision support methodology that is especially valuable for identifying, assessing, and comparing material disposition alternatives and for selecting and documenting a preferred alternative (Frischknecht *et al.*, 2005). LCA of thermal desorption unit is used to analyze the emissions of gases which are detrimental to the environment from the several units of a TDU during the operation and obtain the best method of reducing it to as low as reasonably practicable (ALARP). The LCA is important because during this process the emissions of hydrocarbons and several toxic substances will directly impact soils and groundwater (Clarens *et al.*, 2008). In the study to consider the risk by environmental burden due to the implementation of remediation, LCA was introduced to estimate the amount of CO_2 emission as an index of environmental burden (Inoue and Katayama, 2007). Several companies have researched ways by which waste product can be treated before final disposal and the environmental impact of the process. Most of these companies deal with waste that has a strong environmental impact and also mixed with soil matter. For instance, Ashtabula Environmental Management Project (AEMP) used LCA to conduct research and analysis of the most economical and environmental friendly method of treating polychlorinated biphenyl (PCB) contaminated soil (Gao, 2010). In a similar manner, Fernald Environmental Management Project (FEMP) used LCA to evaluate alternatives for the PCB low-level RCRA sludge (29,000 lb) and the non-PCB low-level RCRA sludge (an additional 200,000 lb). The environmental exchanges during the life-cycle of the thermal desorption unit (use of finite resources, emissions to air, soil and water) are translated into a number of environmental impacts including global warming, ozone formation, acidification, eutrophication, respiratory impacts, human- and Eco-toxicity and resource use (Lemming *et al.*, 2012). Some of the available simulation tools for conducting LCA are SimaPro, GaBi, OpenLCA, and Umberto.

In this study, the goal of the life cycle assessment is to analyse the environmental impact of a thermal desorption unit that treats contaminated drill-cuttings. The primary data was obtained from the basis of waste treatment facility design of Montego Upstream services thermal desorption unit. GaBi 4.4, an LCA computer program, was used to perform the assessment because it is equipped with its database. The category of LCA used in this study was the Stand-alone LCA; estimating the part of the life cycle of the thermal desorption unit with the highest environmental impact. Some estimations where also made, like equipment fuel consumption rate and electricity consumption rates.

MATERIALS AND METHODS

This study used Montego Upstream services waste treatment facility in Amupke area of Sapele in Delta State, Nigeria as the case study. Montego Upstream services is a new facility that was recently set up in order to deal with the waste product gotten from oil drilling points, as they are more in the southern part of the country. Reasonable estimations and calculation on emission from utilities were done using the eco-invent library. Thereafter, LCA was conducted using GaBi simulation software (version 4.4). GaBi was used because it is equipped with its own database, which implies ease of work and it is also user-friendly.

Thermal Desorption Unit Operation Method

Thermal desorption consists fundamentally of two processes, separation process in which heat is applied to a contaminated material, such as sediment, soil, sludge, or filter cake, to vaporize the contaminants into a gas stream. This is followed by the treatment process to meet regulatory requirements prior to discharge (Feeney *et al.*, 1998). A thermal desorption unit typical consists; grizzly, feed hopper, feed screw conveyor, rotary dryer, hot product screw conveyor, pug mill, cyclone, pre-scrubber, wet scrubber, condenser, gravity decanter, hot air generator, cold product conveyor, plate heat exchanger, chiller unit, cooling tower, water collection tank, oil collection tank, and burner. The feed hopper receives the contaminated material after the grizzly must have filtered off the large rocks and metal materials, at a rate of 5313 kg/hr. The contaminated materials are dropped on the screw conveyor and transferred to the rotary dryer. The weight of the material dropped on the screw conveyor was recorded in the control room. Hot air from the hot air generator was used to heat the rotary dryer. The drying process in the rotary dryer enables the contaminant to vaporise, leaving the solid material clean and contaminant free. The hot solid material was sent to the pug mill with a screw conveyor for treatment and cooling with water. It was passed through the screw conveyor so that record of the weight of exit material was taken. From the pug mill, the cool dried material was sent to another screw conveyor from which the final weight was recorded and the product was then collected. The gases evolved, which apparently contain dirt, during the separation in the rotary dryer were sent to the cyclone where the dirt was filtered out and the cleaner gas was sent to the pre-scrubber and wet-scrubber for further cleaning, in the case of any dry powder or dirt escaping the cyclone. The separation in the scrubbers was done by entrapping the particles in liquid droplets produced by the water spray in the scrubber. Finally, the obtained gas was condensed and sent to the decanter where it was separated into oil or water. The water used in the wet scrubber was recycled using a plate heat exchanger to avoid heat loss and water wastage. The plate heat exchanger supplies cool water to the wet scrubber and sends heated water to the cooling tower. Make-up water was sent to the cooling water to replace water loss in the process due to evaporation.

Functional Unit

The functional unit is the mathematically quantified definition of the function of a product system. The functional unit in this study is the management of 46,541,880 kg of waste mix and 42,048,000 kg of contaminated soil for a period of 365 days considering the worst case scenario.

System Boundaries

The scope of this study is from gate to gate, which starts from the input of contaminated material to the rotary dryer to getting the required products. The qualitative and quantitative data for inclusion in the inventory was collected for each unit process that was included within the system boundary. The process plan of the Thermal desorption unit is shown in Figure 1.

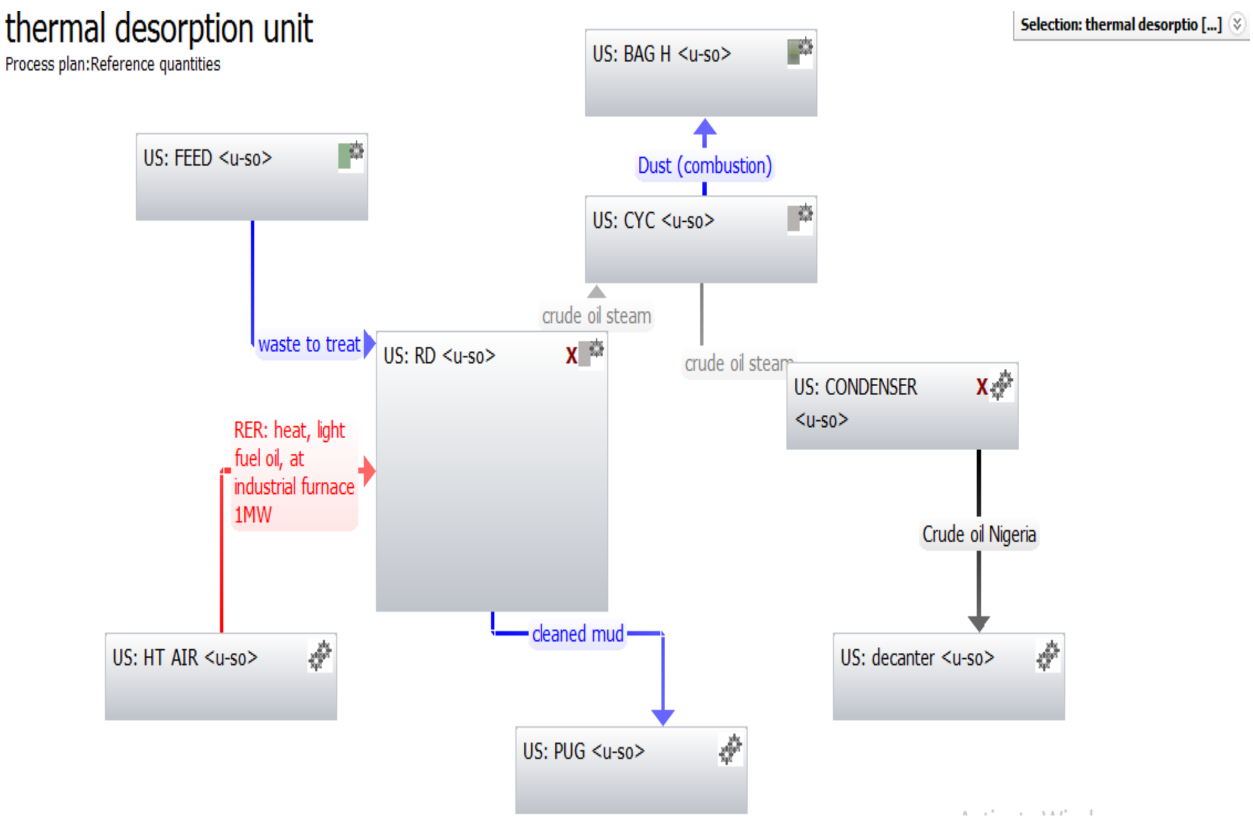

Figure 1: Process plan for the thermal desorption unit

Data Collection

The primary data was obtained on the basis of the design of Montego Upstream services thermal desorption unit. The data about energy and raw materials consumption, treatment process, treatment efficiency and pollutant input and output flows are characterized as shown in Table 1. Some estimations where also made, like equipment fuel consumption rate and electricity consumption rates as shown in Table 2.

Site conditions: Ambient temperature (Min: 10 ^{o}C Max: 40 ^{o}C Avg.: 35^{o}C), Installation: Indoor, **Area:** Non Hazardous, Non Explosive, Non Flameproof.

Design Temperature of burner: 950^{o}F

Operating temperature of cyclone: 500^{o}F

Table 1: Major Inputs and Outputs

Input / Unit	Value	Output / Unit	Value
Total Feed-rate (kg/hr)	46,541,880	Total Feed-rate (kg/hr)	438,000,000
Moisture: Oil rate (kg/hr)	2,628,000	Moisture: Oil rate (kg/hr)	26,200,000
Water rate (kg/hr)	113,880	Water rate (kg/hr)	112,580
Power: Voltage (V)	415	Power: Voltage (V)	415
Frequency (Hz)	50	Frequency (Hz)	50
Connected load (hp)	97	Consumed load (hp)	77.6

Table 2: Utilities Used

Category / Unit	Quantity
Generator –diesel powered	1
Diesel (liter/year)	245280
Electricity (kWh)	525600

RESULTS AND DISCUSSION

This section presents the environmental impact distribution of the entire process. The data used in this study was obtained from two sources; primary data from Montego Upstream and secondary data through reasonable estimations. Due to the incompleteness of the data from the TDU contractors, estimations from assumptions and calculations had to be incorporated to get a realistic process model. Graphs of various emissions and environmental impacts are automatically calculated and plotted for ease of analysis. This process accounts for global warming potential (GWP), fossil depletion, particles to air and water depletion and the graphs obtained are presented in Figures 2, 3, 4 and 5, respectively. The weak point analysis is also properly indicated on Table 3.

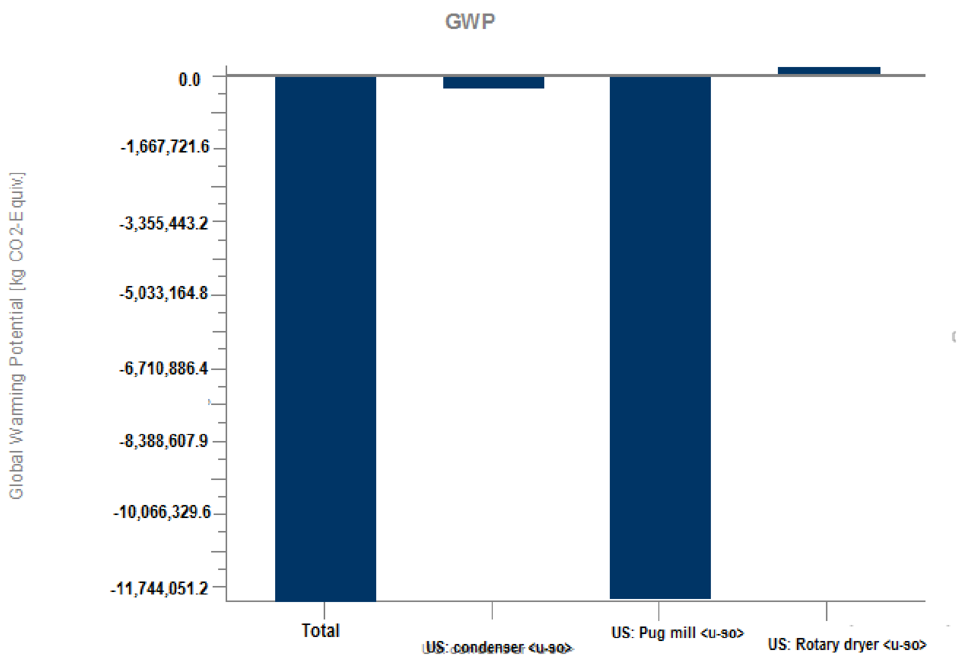

Figure 2: Plot of Global Warming Potential [kg CO2- Equiv.]

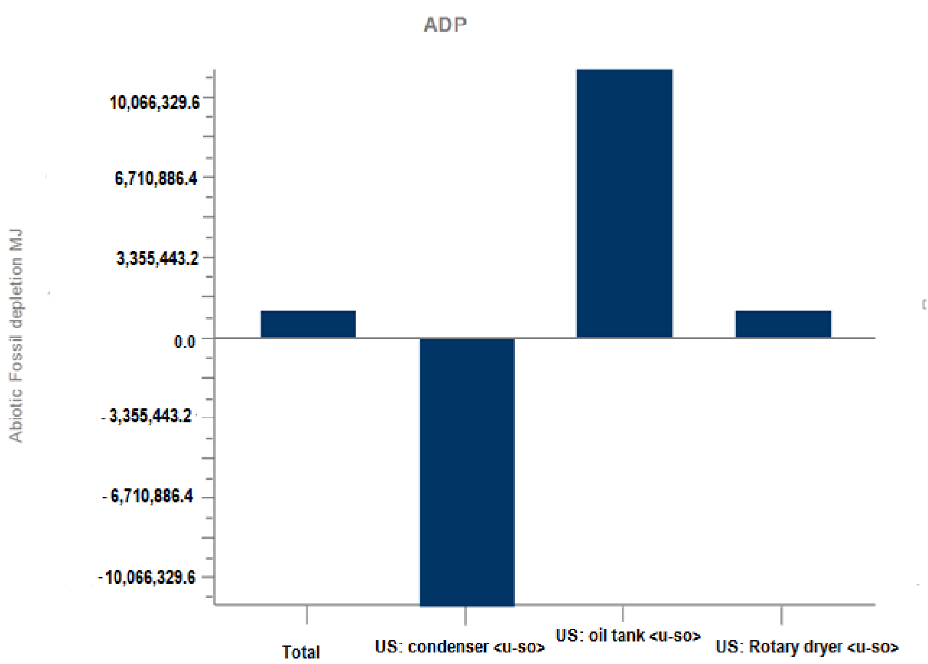

Figure 3: Plot of Fossil Depletion

The life cycle assessment was calculated for an operation with a period of one year, taking 365 days for worst case scenario. Taking into consideration the kg CO_2e of the material, before and after treatment, the total for the GWP is -11,744,051.2 kg CO_2e. This negative value indicates that the process has a positive impact on the environment (Figure 2).

The abiotic depletion potential (ADP) covers some selected natural resources as metal-containing ores, crude oil, and mineral raw materials. Abiotic resources include raw materials from non-living resources that are non-renewable. This impact category describes the reduction of the global amount of non-renewable raw materials. Non-renewable in this case means a time frame of at least 500 years. The abiotic depletion potential is split into two sub-categories, elements and fossil. Fossil includes the fossil energy carriers (crude oil, natural gas, coal resources) all listed in MJ of lower calorific value.

Generally, in Nigeria, much emphasis is on the use of crude oil products for power generation which is leading to fast deterioration of the non-renewable resource. Figure 3 shows that the contribution to fossil depletion can be regarded manageable due to the recovery of crude oil in the condenser. Notwithstanding, an alternative source of fuel, which will not have an impact on non-renewable resources and negative environmental impact should be employed.

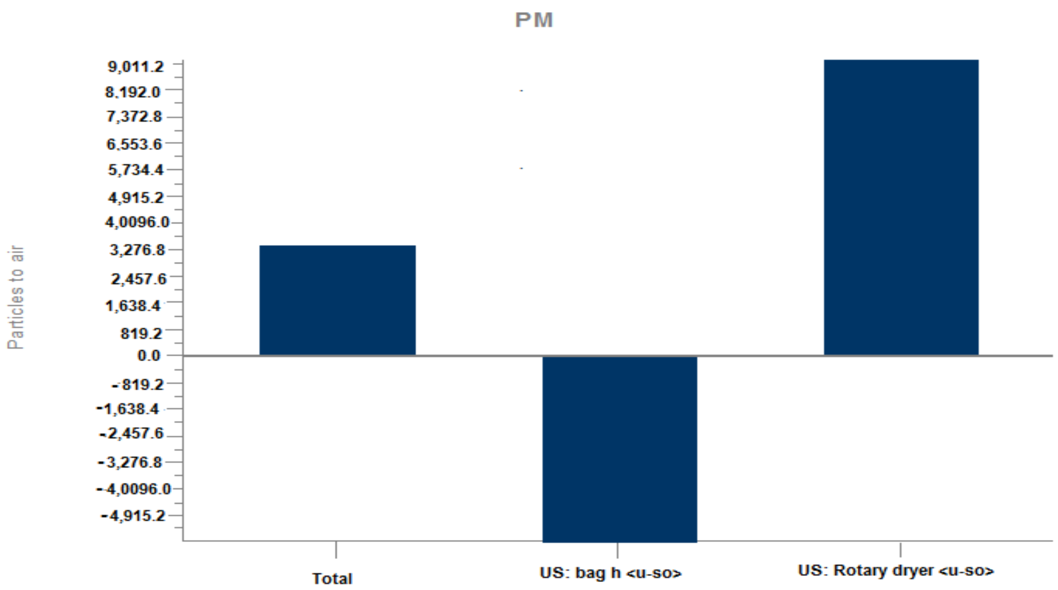

Figure 4: Plot of Particles to Air

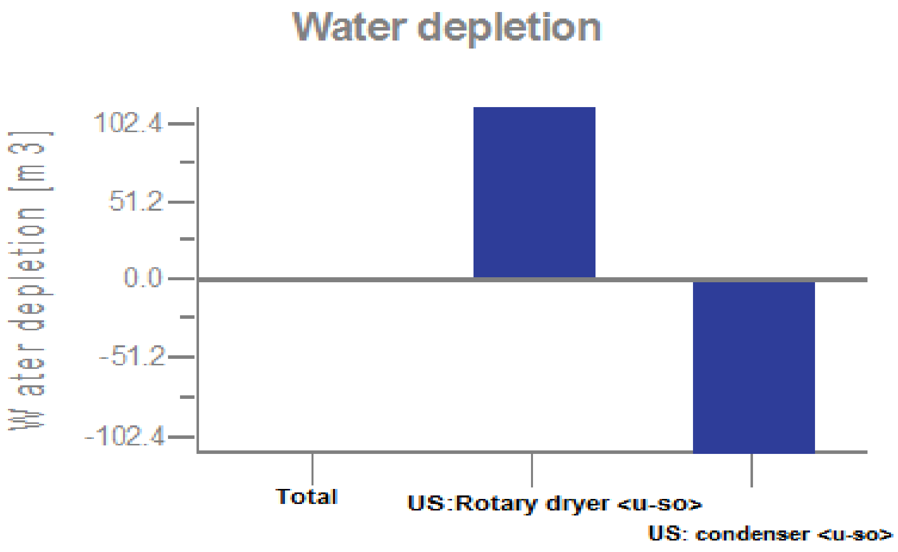

Figure 5: Plot of Water depletion

Particles to air are calculated as a function of the amount of substance emitted into the environment, the resulting increase in air concentration, and the breathing rate of the exposed population. The increasing air concentrations are a function of the location of the release and the accompanying meteorology and the background concentrations of substances, which may influence secondary particle formation. Substances were characterized using PM2.5 as the reference substance. The operation of the rotary dryer will normally release dust particles with the vapour stream. This is sent to the cyclone for separation and eventually, the dust particles are sent to the baghouse filter. In this process, the efficiency of the filter is on average therefore, dust particles are not properly contained as shown in Figure 4.

Water-related flows of GaBi LCI data are updated to enable consistent, high-quality water modelling for water use assessments and water footprinting according to the upcoming ISO Water Footprint standard, the Water Footprint Network Manual and other emerging guidelines (ISO, 1997, 2006). Figure 5 is a plot of the water depletion and it indicates that water is been utilized properly in this process due to recycling mediums. Although, there is still depletion that is almost negligible compared to if there were no means of recycling the produced water. The total depletion amounts to 0.883m^3, which indicates that the difference between the water used in the process and that recovered is 0.883m^3.

One of the largest uses for the material balances is to locate where in the system are the highest emission and this is done with the aid of the Weak Point Analysis. Some of the values are highlighted in red, as shown in Table 3. These are the weak points in the life cycle that correspond to more than 10% of the total sum in that specific category and are highlighted in bold-red. Black (non-bold) values are those that contribute minimally to the total result. Some rows and columns completely disappear since they have no contribution at all. Results indicate that environmental categories were most impacted by the implementation of PM formation, fossil depletion, and water depletion. Several past studies have shown life cycle assessment as a useful decision making tool to comprehend the environmental impacts along product life cycle and across geographic boundaries (Hou *et al.*, 2016; Lemming *et al.*, 2012; Lemming *et al.*, 2010). However, it is difficult to directly transfer or compare the LCA results from a case study at one site to another site. This is because most of the remediation LCA results are sensitive to site-specific conditions. For instance, Hou *et al.* (2016) studied the life cycle impact of treating mercury contaminated soil by using two thermal treatment methods. The remediation LCA results for both thermal desorption methods showed that electricity is the most important contributor to overall environmental impact.

CONCLUSIONS

This gate-to-gate LCA study demonstrates the dedication to transparent reporting of the environmental impacts of a thermal desorption unit for a year, using 365 days for worst case scenario. It reveals a number of hot spots in resource use and environmental impact of a thermal desorption unit that can be improved through operational adjustments. From the results, the most important contributors to the environmental impact of the TDU operation are particulate formation, fossil depletion, and water depletion. Water usage is known to be of high value in any plant or process, therefore, there is a need for sufficient supply. With the knowledge that not all flows and units are captured in this research and the water depletion is at 0.883 m^3, caution should be taken to avoid the increase in the water depletion. Although fossil depletion can be regarded manageable due to the recovery of crude oil in the condenser, an alternative method of generating power for the plant, with little or no environmental implication, should be implemented to totally eradicate this impact medium.

ACKNOWLEDGEMENTS

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Table 3: Weak Point Analysis

Input	Mass-kg	US: bag h <u-so>	US: condenser <u-so>	US: cyclone <u-so>	US: hot air generator USLCI <u-so>	US: oil tank <u-so>	US: Pug mill <u-so>	US: Rotary dryer <u-so>	US: water tank
Flows	**346187.59**	**25000**	**100000**	**12000**	**205427.14**	**261800**	700	**140060.46**	**95000**
Resources	**140760.46**	0	0	0	0	**261800**	700	**140060.46**	0
Energy resources	**26180.46**	0	0	0	0	**261800**	0	**26180.46**	0
Non renewable energy resources	**26180.46**	0	0	0	0	**261800**	0	**26180.46**	0
Crude oil (resource)	**26180.46**	0	0	0	0	**261800**	0	**26180.46**	0
Crude oil Nigeria	26180.46	0	0	0	0	261800	0	26180.46	0
Material resources	**114580**	0	0	0	0	0	700	**113880**	0
Renewable resources	**114580**	0	0	0	0	0	700	**113880**	0
Water	**114580**	0	0	0	0	0	700	**113880**	0
Water (fossil ground water)	113880	0	0	0	0	0	0	113880	0
Water (river water)	700	0	0	0	0	0	700	0	0
Valuable substances	**205427.14**	0	0	0	**205427.14**	0	0	0	0
Energy carrier	**205427.14**	0	0	0	**205427.14**	0	0	0	0
Fuels	**205427.14**	0	0	0	**205427.14**	0	0	0	0
Crude oil products	**205427.14**	0	0	0	**205427.14**	0	0	0	0
Refinery products	**205427.14**	0	0	0	**205427.14**	0	0	0	0
Diesel	205427.14	0	0	0	205427.14	0	0	0	0

Output	Mass-kg	US: bag h <u-so>	US: condenser <u-so>	US: hot air generator USLCI <u-so>	US: Pug mill <u-so>	US: Rotary dryer <u-so>
Flows	**11147060.30**	0	**356800**	**132060.30**	**11000000**	**152000**
Resources	**11000000**	0	0	0	**11000000**	0
Material resources	**11000000**	0	0	0	**11000000**	0
Nonrenewable resources	**11000000**	0	0	0	**11000000**	0
Soil	11000000	0	0	0	11000000	0
Emissions to air	**15000**	0	0	0	0	**40000**
Particles to air	**15000**	0	0	0	0	**40000**
Dust (combustion)	15000	0	0	0	0	40000
US LCI Database	**132060.30**	0	0	**132060.30**	0	0
Products and Intermediates	**132060.30**	0	0	**132060.30**	0	0
US: Diesel, combusted in industrial equipment	132060.30	0	0	132060.30	0	0

REFERENCES

Cheng, J.; Yuan, T.; Wang, W.; Jia, J.; Lin, X.; Qu, L. and Ding, Z. (2006). Mercury pollution in two typical areas in Guizhou province, China and its neurotoxic effects in the brains of rats fed with local polluted rice. *Environmental geochemistry and health, 28*(6): 499-507.

Clarens, A.F.; Zimmerman, J.B.; Keoleian, G.A.; Hayes, K.F. and Skerlos, S.J. (2008). Comparison of life cycle emissions and energy consumption for environmentally adapted metalworking fluid systems. *Environmental Science & Technology, 42*(22): 8534-8540.

Doyle, A.; Pappworth, S. and Caudle, D. (2008). Drilling and production discharges in the marine environment *Environmental Technology in the Oil Industry* (pp. 155-187): Springer.

Feeney, R.J.; Nicotri, P.J. and Janke, D.S. (1998). Overview of thermal desorption technology: Foster Wheeler Environmental Corp Lakewood Co.

Frischknecht, R.; Jungbluth, N.; Althaus, H.-J.; Doka, G.; Dones, R.; Heck, T.; Hellweg, S.; Hischier, R.; Nemecek, T. and Rebitzer, G. (2005). The ecoinvent database: Overview and methodological framework (7 pp). *The international journal of life cycle assessment, 10*(1): 3-9.

Gao, F. (2010). Pyrolysis of waste plastics into fuels. Ph.D. Thesis, University of Canterbury

Hou, D.; Gu, Q.; Ma, F. and O'Connell, S. (2016). Life cycle assessment comparison of thermal desorption and stabilization/solidification of mercury contaminated soil on agricultural land. *Journal of Cleaner Production, 139*: 949-956.

Inoue, Y. and Katayama, A. (2007). Evaluation of Site Remediation Technologies by Applying Risk Assessment and Life Cycle Assessment: Modification of Comprehensive Index, . *the Rescue Number for Soil, 07*: 1371–1375.

ISO. (1997). Environmental management—life cycle assessment, principles and framework, ISO 14040: 1997. *European Committee for Standardization CEN, Brussels, Belgium*.

ISO. (2006). *Environmental management: Life cycle assessment; requirements and guidelines*: ISO Geneva.

Jørgensen, K.; Puustinen, J. and Suortti, A.-M. (2000). Bioremediation of petroleum hydrocarbon-contaminated soil by composting in biopiles. *Environmental pollution, 107*(2): 245-254.

Lemming, G.; Bjerg, P.L.; Weber, K.; Falkenberg, J.; Nielsen, S.G.; Baker, R.; Heron, G.; Jensen, C.B. and Terkelsen, M. (2012). *Environmental optimization of in situ thermal remediation using life cycle assessment (LCA).* Paper presented at the 2nd International Conference on Sustainable Remediation 2012.

Lemming, G.; Hauschild, M.Z.; Chambon, J.; Binning, P.J.; Bulle, C.; Margni, M. and Bjerg, P.L. (2010). Environmental impacts of remediation of a trichloroethene-contaminated site: life cycle assessment of remediation alternatives. *Environmental Science & Technology, 44*(23): 9163-9169.

Okeke, P. and Obi, C. (2013). Treatment of oil drill cuttings using thermal desorption technique. *ARPN J. Syst. Software, 3*(7): 153-158.