A LIFE CYCLE ANALYSIS OF DOD EXPEDITIONARY WASTE MANAGEMENT PRACTICES USING SIMAPRO

THESIS

David J. Chester, Captain, USMC

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Abstract

The United States (US) Department of Defense (DoD) is investigating improved municipal solid waste (MSW) management techniques. Current techniques tax already limited land and energy resources at contingency bases and impart additional logistical support requirements and personnel commitments. Seeking a solution to this growing problem, the DoD is investigating waste-to-energy (WTE) systems to reduce the volume of hazardous and non-hazardous solid wastes while generating low emissions. The current barriers to the acquisition and utilization of viable WTE technologies are the high capital and operating and maintenance (O&M) costs. Using the Life-Cycle Analysis (LCA) software SimaPro, the human health, environmental quality, and climate change impacts of DoD expeditionary waste management practices were compared. These calculated impacts and the economic impacts confirm that the open-air burning of waste is not only dangerous to humans and the environment, but is costly to the US government. Considering the second and third-order economic effects and the mitigated human and environmental health impacts, WTE technologies may be a viable waste management strategy for the DoD.

Acknowledgments

I must first thank my wife; without her genuine love, support, and belief in me I could not have achieved this level of success. Thank you for staying in my corner, encouraging me through late nights, and continuing to raise our darling children all while managing your own career, your own Master's Degree program, and our marriage. You truly are exceptional and I'm honored to be your husband.

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David. J. Chester

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A LIFE CYCLE ANALYSIS OF DOD EXPEDITIONARY WASTE MANAGEMENT PRACTICES USING SIMAPRO

I. Introduction

General Issue

Waste is an inevitable byproduct of life. The management of waste is extremely important as poor waste management is known to have adverse human health effects and environmental health and aesthetic impacts (Rushton, 2003). To protect human and environmental health, the United States (US) government has codified law to ensure the proper handling and disposal of solid wastes in the Solid Waste Disposal Act (SWDA) of 1965. The need for improved waste management techniques grows as the production of municipal solid waste (MSW) continues to grow with the human population (Moya, Aldas, Lopez, & Kaparaju, 2017).

The US Department of Defense (DoD) is no exception to this need for improved MSW management techniques. Island bases and other remote forward operating bases (FOB) have limited land and energy resources to dispose of MSW (Macias, 2015). Open-air burn pits are discouraged and congressionally required to be nearly-eliminated (DoD, 2017). Current DoD waste disposal practices for contingency bases involve trucking away waste or bringing in additional fuel to burn the waste, adding to the transportation burden and increasing risk to personnel (Macias, 2015; Relph & Chiang, 2016).

The DoD is investigating waste-to-energy (WTE) systems with a goal of achieving net zero consumption of energy in the disposal of waste while still meeting air quality standards and reducing fuel consumption (Macias, 2015; Relph & Chiang, 2016;

DoD, 2016; Knowlton, 2013). The DoD initiated the Joint Deployable Waste to Energy (JDW2E) effort to develop, evaluate, and field containerized, deployable, and semi-autonomous systems that reduce the volume of solid waste produced from austere contingency operations while maintaining emissions and effluents below the levels of current contingency waste disposal practices and ideally meeting US regulations (Novotny, 2017; Knowlton, 2013). Eliminating the need to dispose of waste via other means or the increased need for fuel to burn the waste decreases the logistical support required per FOB. This reduced logistical footprint increases the independence of FOBs, reduces the need for logistics support missions, reducing the time logistics personnel spend outside the safety of an installation, thereby reducing unnecessary risk to deployed personnel.

Research Objective

This research is a life-cycle analysis (LCA) of a commercially available WTE technology that meets DoD specifications and requirements but fails to show economic feasibility. The purpose of this research is to determine whether this WTE technology as the waste management strategy of a DoD contingency base would benefit the DoD. This determination will be made by considering not only the economic benefit of the WTE system, but the human health, environmental quality, and climate change impacts between current DoD contingency base waste management strategies and a generic, commercially-available WTE technology. It is hypothesized that when all costs are considered, the money saved from mitigated human and environmental impacts will outweigh the high capital costs of current WTE technologies, thereby making WTE technology a viable waste management strategy for the DoD.

Methodology

The impacts to environmental and human health of differing expeditionary waste management strategies are compared using the LCA software SimaPro 8.0. Emissions of individual waste management scenarios were compiled from peer-reviewed literature, converted to values compatible with SimaPro's waste scenario inputs, and the calculated impacts compared using SimaPro's pre-loaded methodologies.

Assumptions and Limitations

All explored waste scenarios are compared in the Central Command (CENTCOM) area of responsibility (AOR), specifically southern Afghanistan. SimaPro's impact calculations are additive vice computational, meaning the addition of material/energy/processing to a waste management scenario does not change the currently computed impact, but simply adds the impact of the added material/energy/processing to the current computation. The outputs from SimaPro are calculated using SimaPro's pre-installed TRACI 2.1 methodology. The discrete impact values are calculated using SimaPro's pre-installed exposure assumptions, but their importance is minimal without a means for comparison. Knowledge that a process produces 1 million kg of CO_2 could easily be used to say "this process is detrimental to global warming," but if the process is a replacement to the 100 million kg of CO_2 of the current process, it is now seen as a massive improvement in the fight against global warming. Because this study compares the relative impact results between the waste management scenarios using the same TRACI 2.1 methodology and exposure calculations, meaningful qualitative comparisons can be drawn between scenarios.

Uncertainty

Despite the collection and use of real data in the creation of the waste treatment models, these data points represent values at a very specific point in time, with specific meteorological conditions, and are generated from a specific waste profile. Models are built by the averaging of multiple data points in an attempt to build representative models, but there will always be some degree of difference from the model to real world scenarios. The use of estimates in calculations with estimates of exposures only serves to compound this potential difference. The author attempts to minimize the effects of these differences by using the same methodology to calculate impacts in all scenarios, maintaining a comparable and representative scope, and keeping analysis and interpretation to reasonable qualitative comparisons between scenarios.

II. Literature Review

Chapter Overview

The purpose of this chapter is to explore current and prospective DoD expeditionary waste management strategies, understand LCA, and introduce the LCA software SimaPro.

The Need for Waste Management

Waste is the inevitable byproduct of life. This fact is especially true of the US military in deployed environments as all products and materials must survive shipping and austere conditions, and are therefore packaged effectively to increase survivability. Proper management of waste is extremely important as poor waste management is known to have adverse human health effects and environmental health and aesthetic impacts (Rushton, 2003). To prevent these adverse effects, the US has codified law and the DoD has published instructions on how to manage waste and conduct waste management programs (DoD, 2016). Current expeditionary waste management techniques tax already limited land and energy resources at contingency bases and impart additional logistical support requirements and personnel commitments (Macias, 2015; Relph & Chiang, 2016).

DoD Expeditionary Waste Management

Current DoD waste disposal practices for contingency bases involve trucking away waste or bringing in additional fuel to burn the waste, adding to the transportation burden and increasing risk to personnel (Macias, 2015; Relph & Chiang, 2016). Some larger FOBs have constructed waste incinerators to manage waste, but these see limited use, were never completed, or were simply abandoned after encountering maintenance problems deemed cost prohibitive and conflicts with military operational blackouts in favor of the simplicity of open-air burning, despite this action going against published guidance (SIGAR, 2015; Relph & Chiang, 2016). The disposal of waste in a sanitary landfill is generally an accepted waste management strategy, but the 30-year post-closure care requirements are too great a commitment for contingency bases (40 U.S.C., 2010). Current military expeditionary waste management options are therefore: more effectively utilize built incinerators, contract waste services with the host country, or burn the waste in open-air "burn pits."

Relevant WTE Research

The incineration of MSW and the gasification of specific biomass feedstocks are relatively mature technologies, commercially used as a source of renewable energy in many developed countries, to include but not limited to: Sweden, Germany, Japan, Korea, China, and even the US (Hwang, Choi, Kim, & Heo, 2017; Moya, Aldas, Lopez, & Kaparaju, 2017; Mühle, Balsam, & Cheeseman, 2010; EPA, 2017; WEC, 2016; Harris, et al., 2014). The DoD, through several initiatives including the Natick Soldier Research Development and Engineering Center (NSRDEC), JDW2E, the Air Force Research Laboratory (AFRL) and Air Force Civil Engineering Center (AFCEC), has several WTE methods undergoing current study. The current research, however, continues to be plagued with shortfalls: either the systems are very complex making them incompatible with DoD expeditionary use and deployability, too expensive or energy intensive, or require too much space or too large of a throughput of waste to be feasible with contingency operations (Davis, Gelman, Tomberlin, & Bain, 2010; Novotny, 2017; DLA, 2017).

A similar LCA research effort was executed by a previous Air Force Institute of Technology (AFIT) student (Hornstein, 2017). Due to time and resource constraints, Hornstein's analysis made several assumptions and very conservative simplifications to the LCA. Despite these conservative simplifications, Hornstein concluded a WTE conversion system should be considered over the other expeditionary waste management strategies. This continued research was afforded the time, opportunity, and resources for courses providing an in-depth understanding of the software SimaPro to execute the LCA without the simplifications, and therefore likely producing more accurate results. The differences between Hornstein's research and this LCA are explained in Chapter III.

Life Cycle Analysis

Environmental life-cycle analysis, also known as life-cycle assessment, is a systematic tool or framework used to identify and evaluate the environmental impacts associated with the energy and resources to create materials or services throughout the product's entire lifespan (ISO, 2006; Theis & Tomkin, 2013). LCA generally follows the ISO published framework:

1. Define Goal and Scope
2. Inventory Analysis
3. Impact Assessment
4. Interpretation

The first and arguably most important step is to define the scope of the LCA. This involves setting clear boundaries of the investigated system, allowing the quantity and quality of inputs and outputs across this boundary to be measured. The inventory analysis is the collecting of data on the use of energy and materials for the product or service. The life cycle impact assessment uses the inventory data to sum the resources and energy consumed and wastes emitted by all processes in the system to estimate potential impacts to the environment. Interpretation of these results allows decisions to be made to reduce potential impacts by changing energy/material sources or updating processes, or to decide between products/services. (Theis & Tomkin, 2013; ISO, 2006)

SimaPro

SimaPro is an LCA software containing inventory databases and impact assessment methodologies to perform LCA studies (PRé, 2019). These installed databases contain the energy and material requirements and waste emissions for over 10,000 industrial and commercial processes (PRé, 2016).

SimaPro models the end-of-life phase through waste scenarios and waste treatment processes. Waste treatments document the emissions and impacts that arise from landfilling, burning, recycling, or composting of waste (PRé, 2016). The waste scenarios in SimaPro are based on material flow and do not observe product characteristics (PRé, 2016). For example, the waste treatment “Landfilling of MSW” gives the emissions and fuel requirements to landfill a unit mass of generic MSW and does not delineate the chemical composition of the MSW.

SimaPro has several pre-installed waste treatment scenarios that are useful in LCA, but does allow for the creation of custom waste treatment scenarios. Using data, the material, fuel, and energy inputs and corresponding emissions to air, the ground, and water can be defined for a specified waste. These inputs to construct custom waste treatment scenarios are in units of mass, meaning energy and fuel requirements and emissions are calculated as masses given the mass of treated waste.

SimaPro uses the previously defined boundaries and pulls inventory data from its database to perform the impact assessment. An indicator substance is used in each impact category, and all emissions across material and fuel inputs and waste are converted to equivalents of these indicator substances (PRé, 2016). For example, to measure impacts to Global Warming, emissions from all steps or system processes are converted to equivalent masses of CO_2 and totaled. This conversion and summation is performed for all categories to allow meaningful comparison between products or processes.

The outputs provided by SimaPro can then be displayed in an easy-to-read bar chart. For each impact category, the scenario with the largest impact will be scaled to 100, and the remaining processes will have their impact scaled off of the 100. For example, comparing two generic waste treatments 1 and 2 for impacts to global warming: If treatment 1 has 50kg CO_2 equivalent emissions and treatment 2 has 25kg CO_2 equivalents, treatment 1 will be represented by a bar with height 100, and treatment 2 with a bar height of 50. This is done for each impact category and all impact categories are shown on the same graph.

TRACI 2.1

The Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) is an environmental impact assessment tool created by the US Environmental Protection Agency (EPA) (EPA, 2016; PRé, 2016). TRACI calculates impact assessments based on ten impact categories:

1. Ozone depletion (measured in kg CFC-11 (Freon-11) equivalents)
2. Global warming (measured in kg CO_2 equivalents)
3. Smog (measured in kg O_3 equivalents)
4. Acidification (measured in kg SO_2 equivalents)
5. Eutrophication (measured in kg N equivalents)
6. Carcinogenics (measured in comparative toxic units (CTU) for morbidity (h))
7. Non-carcinogenics (measured in CTUh)
8. Respiratory effects (measured in kg particulate matter (PM) 2.5 equivalents)
9. Ecotoxicity (measured in CTU for aquatic ecotoxicity (CTUe))
10. Fossil Fuel Depletion (measured in MJ)

TRACI has factors for normalization to allow for comparison between impact categories. The normalization divides the calculated outputs for the individual impact categories by the averaged impact values of a US or Canadian citizen for each impact category for a year (PRé, 2016). This division will mean relative bar height is scaled off of how much more or less impact the scenario produces compared to the average citizen. A higher bar would mean more detrimental impacts than an average citizen, while lower bars mean relatively less detrimental impacts. This allows for qualitative comparison between impact categories.

III. Methodology

Chapter Overview

The purpose of this chapter is to design the LCA and outline the creation of the waste treatment scenarios in SimaPro for comparison. It follows the LCA framework and begins defining the scope of the LCA. After determining the goal, defining scenario boundaries, and defining the functional unit of the LCA, data for the scenarios is collected for the inventory analysis. Data for inputs and emissions for the four waste scenarios is compiled from research and converted to SimaPro-ready values in the appendices. A life-cycle impact assessment is then conducted using SimaPro's TRACI 2.1 methodology. Interpretation of the results is available in Chapter IV.

Beginning the Life Cycle Analysis

The goal of this LCA is to compare the environmental, human health, global warming, and economic impacts of available DoD expeditionary waste management strategies. Available expeditionary waste management strategies can be summarized in four categories: 1. an incinerator with potential for energy capture (WTE technology), 2. contracted sanitary landfilling, 3. contracted local waste management, or 4. the open-air burning of waste. As stated earlier, the construction of an on-base sanitary landfill is not considered because the long-term closure commitments are precluded by the base's expeditionary and temporary nature.

In all scenarios, waste from all base tenants must be collected before disposal. This impact is therefore the same across all scenarios and can be removed from consideration. The boundary of all four scenarios then begins with all base wastes collected at a single waste collection point and then considers all energy and resource inputs and emissions until the final disposal of the waste. To allow for meaningful comparison between strategies, the functional unit of comparison is 1kg of generic waste. For all scenarios, all impact and emission calculations are for the disposal of 1kg of waste in an expeditionary environment.

Difference from Previous Research

This research is a continuation of the LCA performed by former AFIT student, Thomas Hornstein. Hornstein's LCA considered the environmental and human health impacts from three DoD expeditionary waste management strategies: WTE conversion, long-haul transportation to a sanitary landfill, and open-air burning of waste. This LCA includes a fourth consideration: local landfilling in a landfill without landfill gas or leachate capture, and this research considers the economic implications of the waste treatment scenarios.

Also, due to time and resource constraints, Hornstein made several simplifications to his models: Hornstein's Open-air Burn model used an installed SimaPro incinerator model that includes the flue gas treatment and cleaning. His simplification significantly reduces the calculated impacts for the open-air burn model. This research used literature on the emissions of open-air burn pits to create a custom model in an attempt to accurately portray the emissions and impacts of an open-air burn pit. Also, Hornstein's open-air burn model assumed 1 gallon of diesel per ton of burned waste, but continued literature review will reveal that number is much higher later in this chapter.

Scenario Building and Selection

A combination of SimaPro's available inventory data on waste treatment requirements and emissions, and emissions data collected from relevant literature are used in the construction of the four modeled scenarios.

WTE Incinerator

An on-base WTE incinerator will model the disposal of the waste in a commercially available WTE technology. The model assumes that the incinerator is constructed on base and transportation from the waste collection point to the incinerator is negligible. The model captures the energy input requirements to operate the incinerator including waste homogenization and flue gas treatment, the emissions to the air, and the required storage or disposal of incinerator residuals like slag or ash. SimaPro is equipped with multiple incinerator models that consider the inputs, emissions, and avoided products from energy generation. A comparison of three pre-installed WTE incinerators is made in SimaPro with results shown in **Error! Reference source not found.**:

1. "Municipal Solid Waste (RoW)|treatment of, incineration" - The data represents the activity of waste disposal of MSW in a waste incinerator for average municipal/communal waste mixtures. The rest of world (RoW) label represents a global data-set and represents activities considered to be an average valid for all countries in the world (ecoinvent, n.d.).

2. "Waste incineration of municipal solid waste EU-27" - The model represents the incineration of MSW in an average European WTE plant and includes flue gas treatment and NOx removal technologies. The model assumes the generation of 1.09 GJ electricity per ton of incinerated MSW.

3. “Waste incineration of municipal solid waste EU-27 S” - An update to the average European WTE plant with the separation of certain waste fractions like glass. The model includes flue gas treatment and NOx removal technologies. The model assumes the generation of 1.09 GJ electricity per ton of incinerated MSW.

Across all categories, the RoW incinerator has the highest calculated impacts with impact values also shown in Appendix A. This is due to the lack of flue gas treatment before emission and the lack of captured energy offsetting fossil-fuel generated energy. The updated European WTE incinerator accounts for increased efficiencies in the incineration process, and the avoided emissions from the generated electricity create “negative” impacts as the generated electricity lowers the requirement for fossil-fuel-derived electricity sources with their own environmental impacts.

The expeditionary and austere nature of contingency bases would limit the ability of construction and maintenance by contracted services, and likely limit the availability of the best available technologies for flue gas treatment. Of the available models, the RoW incinerator is therefore likely the most accurate, available model to simulate emissions and impacts for an incineration technology in an expeditionary environment. Consideration for offset costs of energy generation will be considered in Chapter IV.

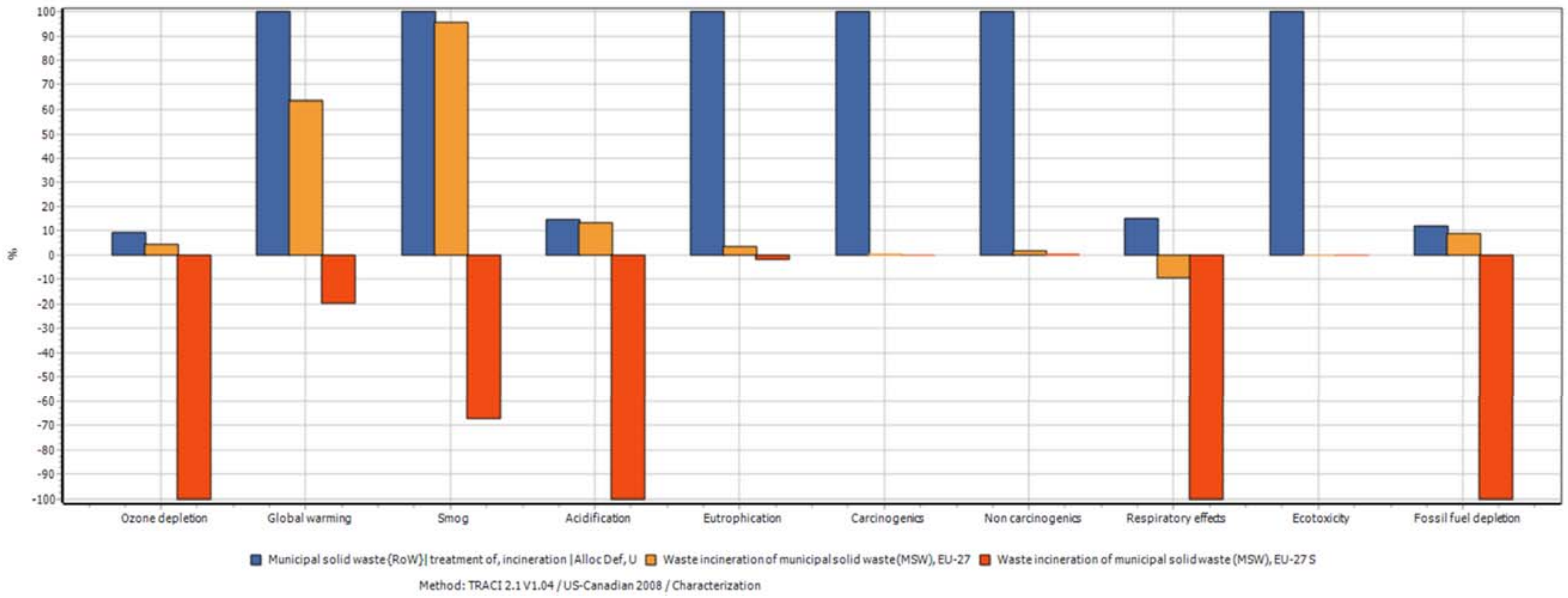

Figure 1. Comparison of incineration technology models

Sanitary Landfill

The second disposal scenario is the contracting of sanitary landfilling for the waste. While contracted services present security concerns, the disposal of waste in sanitary landfills with landfill gas and leachate capture may offset many environmental impacts. The model assumes that the waste is collected from the collection point and delivered to the sanitary landfill with all emissions and energy requirements for the transportation and the operation of the landfill. In the CENTCOM AOR, specifically southern Afghanistan, sanitary landfills are hard to come by, requiring transportation to Kabul or Iran (Forouhar & Peterson, 2007). The model assumes a conservative, one-way 400km of transportation in a refuse truck to the nearest sanitary landfill and takes advantage of SimaPro's installed sanitary landfill waste treatment scenarios. Two potential landfilling scenarios are compared in **Error! Reference source not found.**:

1. "MSW (RoW)|treatment of, sanitary landfill, distance haul" - The sanitary landfilling of waste averaged for the RoW with the required 400km transportation in a refuse truck.

2. "MSW (RoW)|treatment of, sanitary landfill" - The sanitary landfilling of waste averaged for the RoW without the transportation.

Due to the additive nature of SimaPro, the addition of the transportation to the waste disposal scenario has additional impacts in all categories. The impact values are found in Appendix A. The required diesel fuel for the transportation vehicle contributes significantly to smog production, acidification, and fossil fuel use, but contributes only a minor amount to the remaining categories. For a 21-ton refuse truck hauling MSW for 400km, assuming a conservative 10kmpg, the required fuel is only 1.9 gallons of fuel per ton of MSW. The requirement to transport the waste to a sanitary landfill is extremely likely due to southern Afghanistan's lack of sanitary landfills, and therefore the impacts including the transportation are a more accurate representation of impacts for this waste treatment scenario.

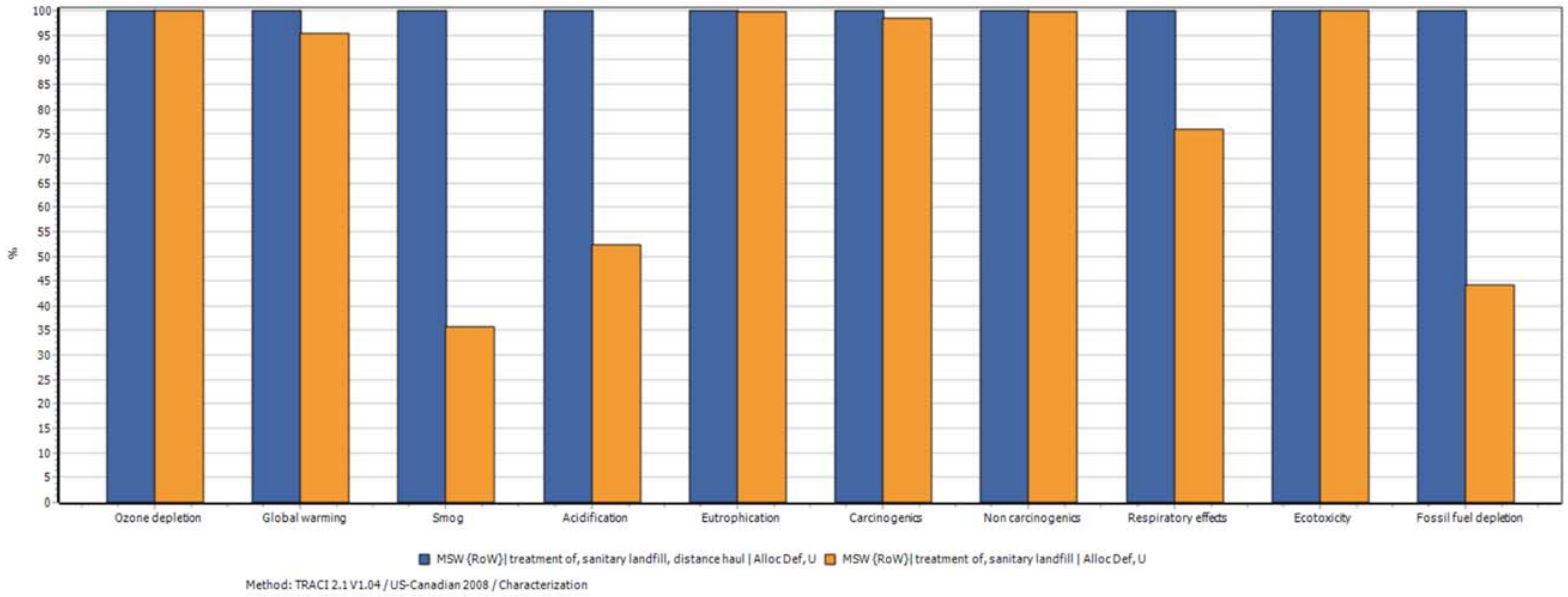

Figure 2. Comparison of sanitary landfilling models

Unregulated Landfill

The third available waste treatment scenario is also contracting waste disposal services, but with a local landfill. It is already assumed that sanitary landfills in southern Afghanistan do not exist, and therefore the assumption is that a local landfill would not have landfill gas or leachate capturing. SimaPro does not contain data for models of unregulated landfills, and therefore a representative waste treatment scenario was constructed from available data. Some assumptions were made on the emissions of unregulated landfills, namely that the make-up of landfill gas and leachate is the same between regulated to unregulated landfills, the only difference being that sanitary landfills engineer mechanisms to capture these emissions for treatment. This is likely a conservative assumption because the turning and layering of soil in sanitary landfills creates an environment with pressure and temperature different from an open-air environment, but allows the use of available literature on the chemical make-up of landfill gas and leachate to construct the model. A second assumption is the transportation requirement for a local landfill is negligible from the base collection point.

Data from published sources on landfill gas and leachate make-up was aggregated and converted to SimaPro input values in Appendix B (EPA, 2008; EPA, 2005; Petrescu, Batrinescu, & Stanescu, 2011; Durmusoglu, Taspinar, & Karademir, 2009; Johansen & Carlson, 1976; Kulikowska & Klimiuk, 2008; Christensen, et al., 2001; Mali & Patil, 2016; Ogundipe & Jimoh, 2015). For landfill gas, an EPA model allows the prediction of landfill gas volume per unit MSW in an arid environment per year, and the contaminant emission data given in concentrations is converted to a unit mass of contaminant per unit mass of MSW using the ideal gas law. An example calculation for mass of emitted CO_2

per kg of landfilled waste is below. The average measured concentration of 29.45% by volume at 1 atm and 25 Celcius yields:

$$mass \ = \frac{P*V*MW}{R*T} = \frac{1atm*.2945*6.5\frac{m^3}{Mg}*44\frac{g}{mol}}{.08206\frac{atm*L}{mol*K}*298.15K}*\frac{Mg}{10^3kg}*\frac{10^3L}{m^3} = 3.443\frac{g\ CO_2}{kg\ waste}$$

P = Air Pressure

V = Gas Volume

MW = Molecular Weight

R = Ideal Gas Law Constant

T = Temperature

For landfill leachate, a conservative estimate of landfill leachate per unit mass MSW is assumed for the arid climate of southern Afghanistan (Climate-Data.org, n.d.; Fenn, Hanley, & DeGeare, 1975; Brennan, Healy, Morrison, & Hynes, 2015). The concentrations of contaminant per liter of leachate are converted to masses of contaminant per mass MSW by dividing by the estimated leachate volume. A comparison of potential unregulated landfill models is shown in **Error! Reference source not found.**:

1. “Unregulated Landfill” - Unregulated landfill model including emissions to air as landfill gas and emissions to groundwater as leachate

2. “Unregulated Landfill (longterm emissions)” – The same unregulated landfill model including air and groundwater emissions, but impacts calculated for “long-term emissions” via SimaPro’s pre-installed methodology

3. “Unregulated Landfill (no leachate)” - Only landfill gas air emissions

4. “Unregulated Landfill (no leachate/longterm emissions)” - Only landfill gas air emissions with “long-term emissions” calculations

The calculated impact values are listed in Appendix A. The impact values for six of ten categories are identical, with significant changes in the remaining four categories due to either inclusion or exclusion of leachate emissions. These categories are eutrophication, carcinogens, non-carcinogens, and ecotoxicity. Per SimaPro’s outputs, the sharp drop-off in calculated eutrophication impacts is due to removing the significant biological and chemical oxygen demands and nitrogen and phosphorous from leaching into the ground water. The drop in carcinogenic toxicity impact is due to removing the chromium, lead, benzene, and toluene from leaching into the ground water. The drop in non-carcinogenic toxicity impact is due to removing the leaching of metals like zinc, cadmium, nickel, and copper into ground water. And finally, the drop in ecotoxicity impact is due to the same removal of metals from leaching into the ground water.

To assume that there will be absolutely no leachate reaching groundwater is a very conservative estimate, even for the desert climate in southern Afghanistan, and will therefore be kept in the model to capture these potential impact contributions. There is only a slight difference between short-term and long-term emissions in SimaPro’s TRACI 2.1 calculated impacts in the non-carcinogenic category.

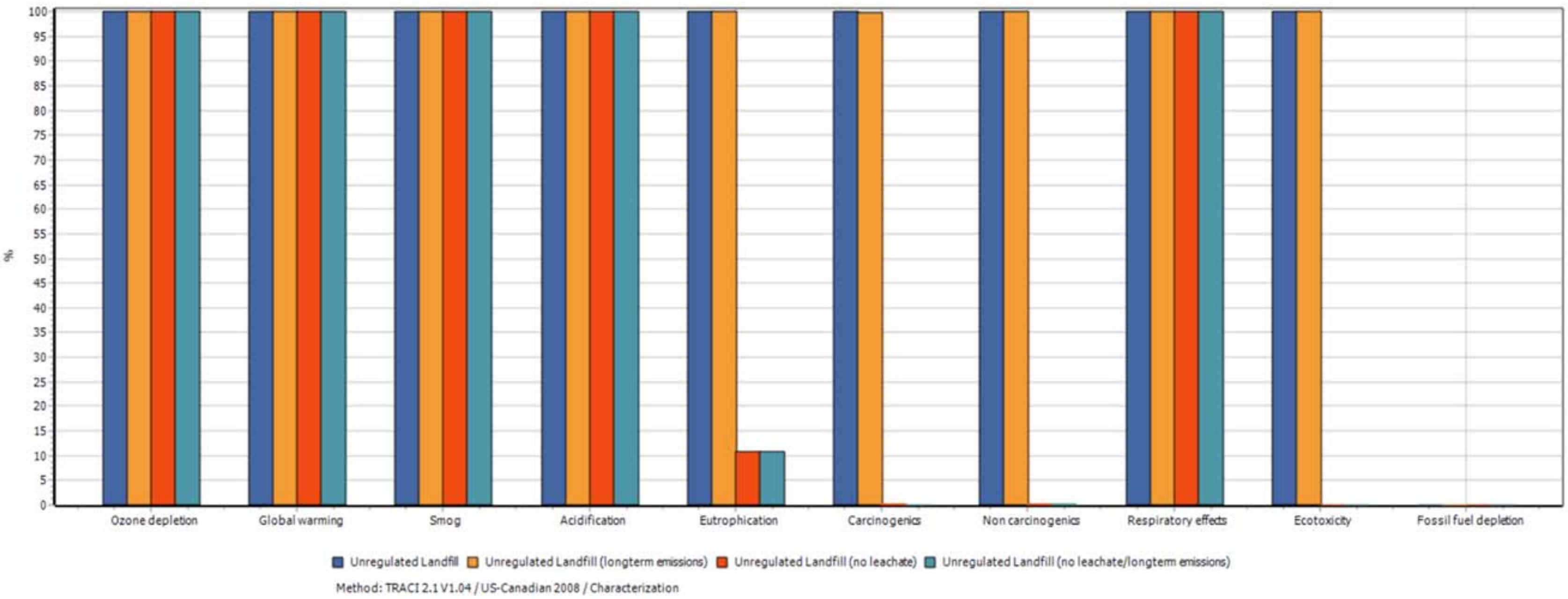

Figure 3. Comparison of unregulated landfill models

Open-Air Burn

The final waste treatment scenario is the open-air burning of waste. It is assumed that this will take place on the base, and transportation from the waste collection point to the open-air burn pit is negligible. Due to the low-caloric value and typically high moisture content of MSW, the direct combustion of waste requires the addition of a substantial amount of fuel (WEC, 2016; Macias, 2015; Relph & Chiang, 2016). The model assumes a lower-end estimate of 54 gallons fuel per ton of waste, a stark contrast to Hornstein's assumed 1 gallon of fuel per ton of waste, and some waste incinerators have shown to require much higher fuel to waste ratios, some reaching 153 gallons of fuel per ton of waste (Knowlton, 2013). After the direct combustion of material, there remains a volume of slag or ash. The model accounts for 30% non-combustible material by weight that must be landfilled (Tchobanoglous, Theisen, & Vigil, 1993).

Data from published sources is aggregated and converted to SimaPro input values in Appendix B (Aurell & Gullett, 2017; Dominguez, Aurell, Gullett, Eninger, & Yamamoto, 2018; Woodall, Yamamoto, Gullett, & Touati, 2012; Gerstle & Kemnitz, 2012; EPA, 1996). Papers sampled emissions from the open-air burning of waste and converted concentrations of contaminants to masses of contaminant by dividing by the measured air flow. These masses of emitted contaminants are then compared to the mass of waste combusted. These masses are averaged as unit mass contaminant emitted to air per kg waste burned. **Error! Reference source not found.** compares potential open-air burn models:

1. “Open Burn” - The constructed open-air burn model including air emissions from both the burning of waste and diesel fuel and includes the treatment of remaining ash in a landfill

2. “Open Burn (no ash)” - The open-air burn model with air emissions from the burning of waste and diesel fuel but without the treatment of remaining ash in a landfill

3. “Open Burn (no diesel)” - The open-air burn model with air emissions from only the burning of waste, not including the diesel fuel, and including the treatment of remaining ash in a landfill

4. “Open Burn (no diesel/no ash)” - The open-air burn model with only the air emissions from the burning of waste, not considering the contributions from diesel or treatment of ash in a landfill

Again, due to the additive nature of SimaPro’s life-cycle impact assessments, the model that includes the waste burning emissions, the fuel use, and the non-combustible material treatment has the highest impact across all categories, shown in Appendix A. The removal of the ash from the scope causes minor changes in seven of ten impact categories, but significantly lowers the impacts for the eutrophication, carcinogenics, and ecotoxicity. This change is likely due to the highly concentrated and leachable nature of landfilled ash affecting groundwater. The diesel fuel requirement and its subsequent emissions are significant contributors to most impact categories, accounting for over half of the impact on five of the ten impact categories. The amount of diesel fuel selected for the model was a low-end estimate, and therefore these impacts are conservative estimates from fuel use. Because the fuel must be used in the open-air burning of waste, it is included in the selected model. The remaining ash in the bottom of the burn pit and the potential impacts of this ash are also included in the final model.

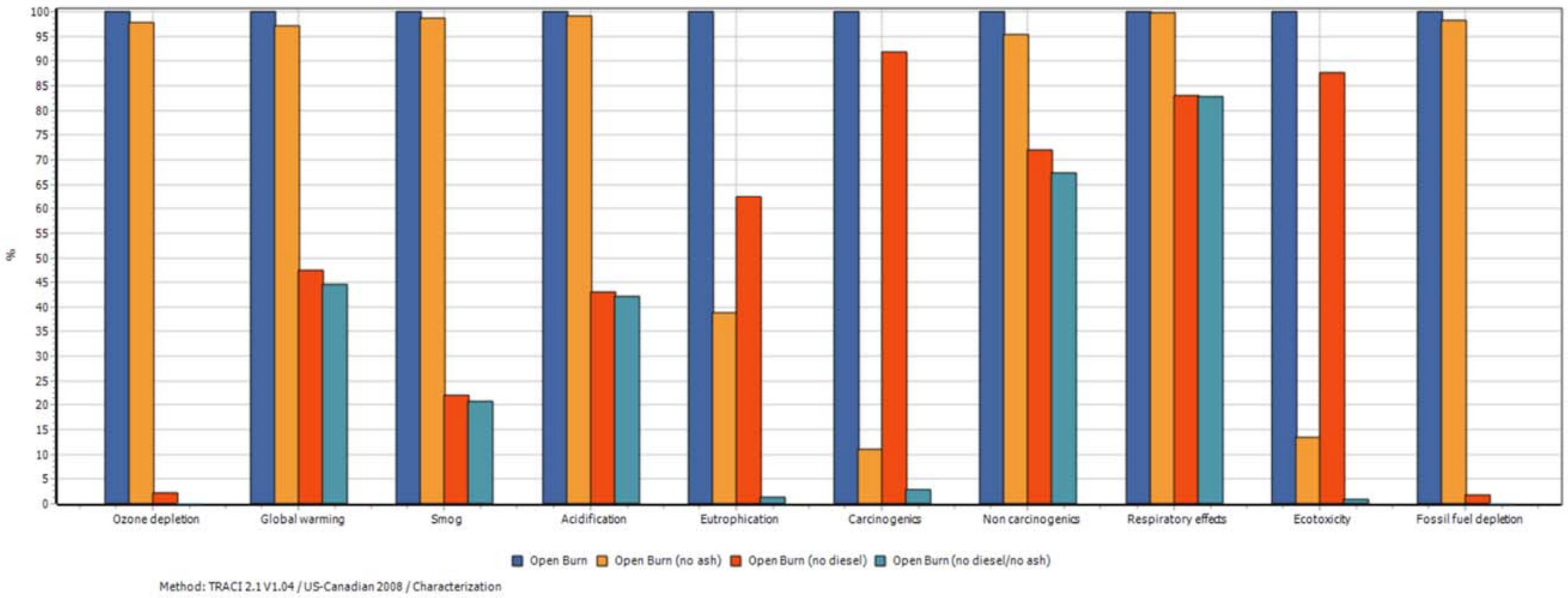

Figure 4. Comparison of open-air burn models

Summary

This chapter details the scope and inventory analysis in the construction of the representative models for DoD expeditionary waste management. The life-cycle impact assessment was then performed comparing the impacts of the four waste treatment scenarios.

IV. Analysis and Results

Chapter Overview

This chapter reviews the results of the life-cycle impact assessment between the four selected representative models of DoD expeditionary waste management. After comparing the human and environmental health implications of the waste management strategies, consideration is given to economics, reviewing potential costs, benefits, and mitigated costs.

Life-Cycle Impact Assessment Results

The results of the life-cycle impact assessment comparing the impacts of the four DoD expeditionary waste management scenarios are shown in **Error! Reference source not found.**.

The open-air burning of wastes has the highest impacts across eight of the ten impact categories (global warming, smog, acidification, eutrophication, carcinogenics, non-carcinogenics, respiratory effects, and fossil fuel depletion), significantly so in seven of those eight categories, and is a close second in the remaining two categories (ozone depletion and ecotoxicity). These calculated impact values are shown in Appendix A. The high impacts for ozone depletion for unregulated landfills is directly caused by the releasing of chloroflurocarbons (CFCs) likely from refrigerants or propellants in the waste. In regulated landfills, open-air burn pits, and WTE incinerators, these CFCs are captured and/or combusted. The high impact results associated with ecotoxicity for landfilling, WTE incineration, and open-air burning are associated with the emission of heavy metals including copper, zinc, nickel, etc. into ground water from landfilled material. The results of the normalization for this comparison are shown in **Error! Reference source not found.**.

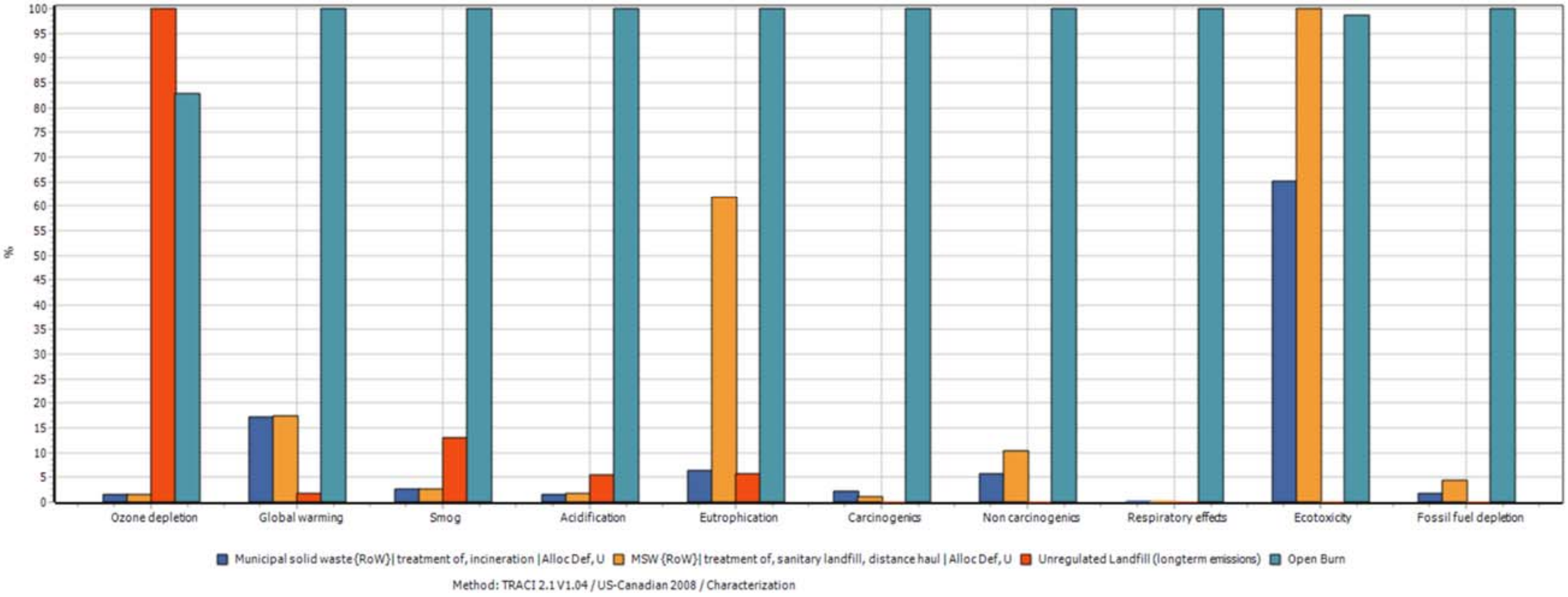

Figure 5. Characterization of four DoD expeditionary waste management options

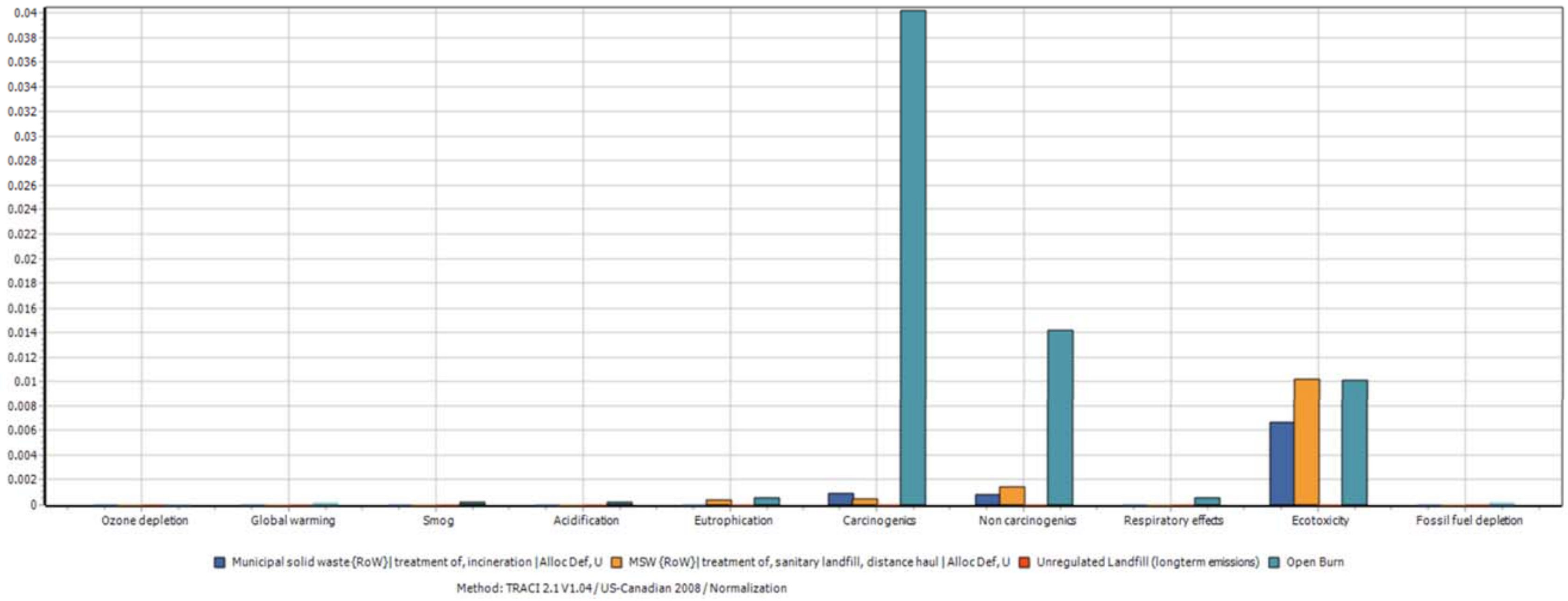

Figure 6. Normalization of four-scenario comparison

Compared to the average impacts of US and Canadian citizens in 2008, the most detrimental impact categories are carcinogenics, non-carcinogenics, and environmental ecotoxicity, all shared by the open-air burning of waste. **Error! Reference source not found.** and **Error! Reference source not found.** point to the open-air burning of waste as the most harmful expeditionary waste treatment scenario to human and environmental health.

From these results, the impacts associated with open-air burning of waste are recognizable as likely the most detrimental to human and environmental health and resource consumption, however, the dwarfing of the remaining waste scenarios in these eight categories precludes further analysis. The results of an identical comparison, but with open-air burning removed from consideration, are shown in **Error! Reference source not found.**.

Overall, the impact values compared between the remaining three waste treatment scenarios are closer than when open-air burning is considered. In this three-scenario comparison, the transportation and sanitary landfilling of wastes accounts for the highest impacts of six of ten categories (global warming, eutrophication, non-carcinogenics, respiratory effects, ecotoxicity, and fossil fuel depletion), and a local unregulated landfill accounts for the highest impacts in three categories (ozone depletion, smog, and acidification). The conversion of waste in a WTE incinerator is most impactful in only one category (carcinogenics), and a close second in a second category (global warming). **Error! Reference source not found.** would suggest that WTE technologies and unregulated landfills in arid environments are preferred expeditionary waste management options. This impact assessment is normalized in **Error! Reference source not found.**.

Relative to the average impacts of US and Canadian citizens in 2008, the most detrimental impact category is now ecotoxicity. Also, the normalization shows that although the unregulated landfilling is the most impactful waste management scenario in ozone depletion, smog, and acidification, these are relatively smaller impacts compared to ecotoxicity and carcinogenic and non-carcinogenic human health impacts.

At first glance of Figure 8, an unregulated landfill in an arid environment appears to be the least impactful expeditionary waste management option in terms of human and environmental health, but aesthetic concerns, public perception, and the threat of diseases from pests and vectors would likely weigh in against the use of “dumps” to dispose of FOB waste. Also worth consideration are the potential security concerns with unmanaged military waste specifically, as information about a FOB can theoretically be collected from waste: unit sizes and compositions estimated from food waste, or information gathered from trashed documents can be aggregated to discern critical operational information.

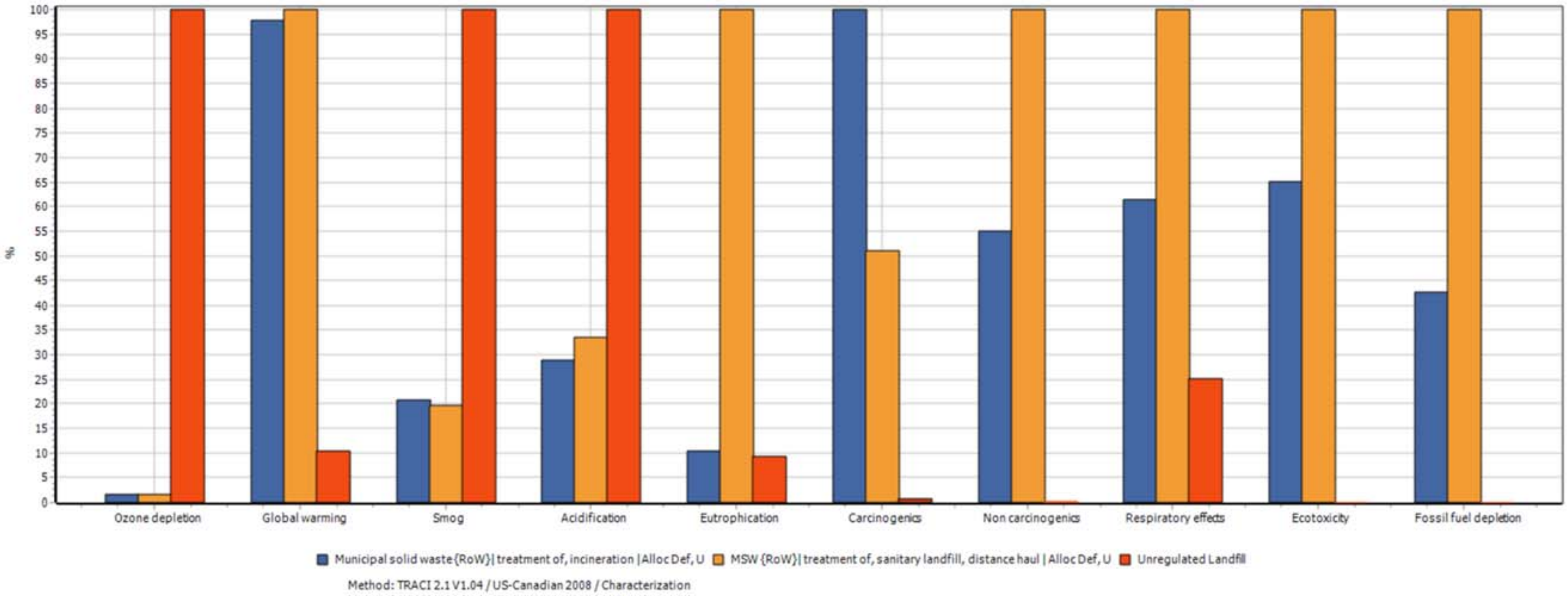

Figure 7. Characterization of three DoD expeditionary waste management options

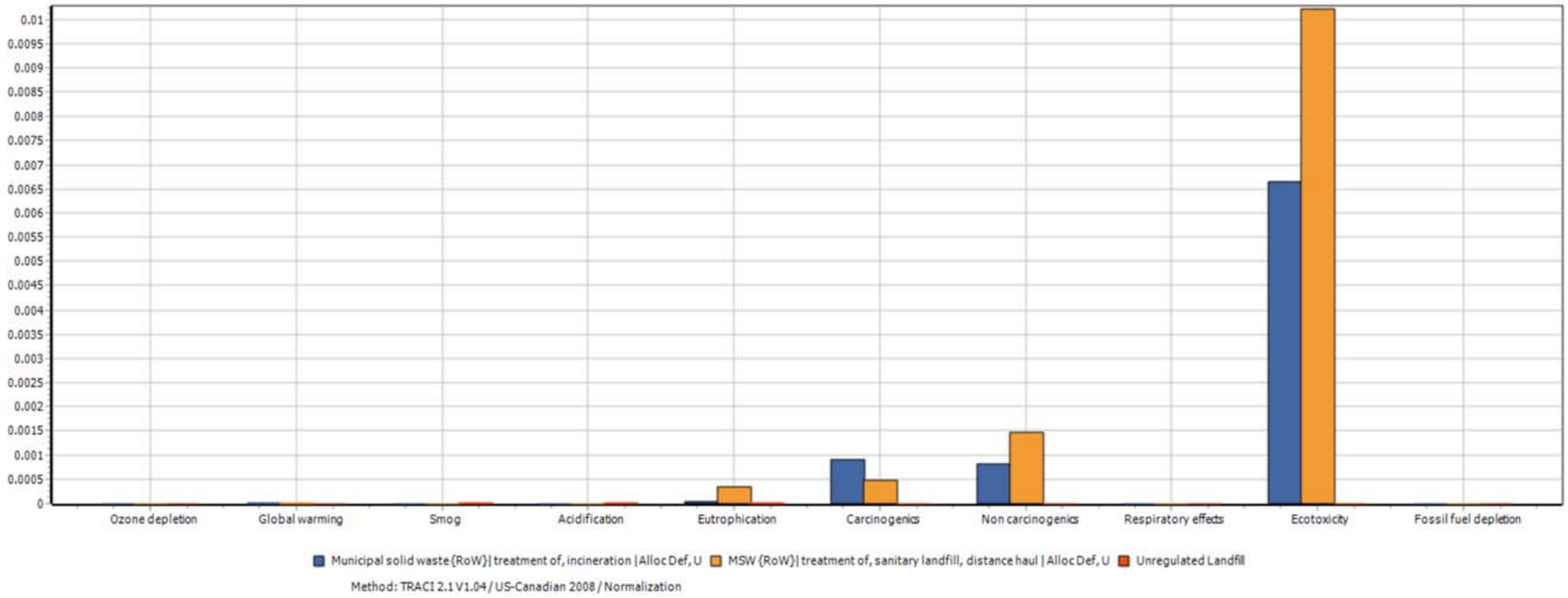

Figure 8. Normalization of the three-scenario comparison

Economic Considerations

An impact factor not explored in SimaPro life-cycle assessments is the cost of the waste treatment scenarios. Mentioned earlier, the high capital cost of WTE technologies has been a substantial obstacle to their acquisition and use. To compare costs, the requirements and contracts for the expeditionary waste management of Marine Corps FOB Camp Leatherneck in Southern Afghanistan is explored.

Following congressional mandates to eliminate burn pits, the Marine Corps in RC(SW) shifted to incinerators to manage regional FOB wastes. On Camp Leatherneck, the DoD spent 18 million US dollars (USD) to purchase and install four waste incinerators to meet the daily 54 tons of solid waste (SIGAR, 2015). However, two of the incinerators were never used due to their high operation and maintenance costs reaching approximately 1 million USD annually, and instead Camp Leatherneck chose to burn the wastes in open-air burn pits (SIGAR, 2015). At a throughput of 54 tons of solid waste per day, using the same fuel to waste ratio used in this paper, this would require just under 3,000 gallons of diesel fuel for the open-air burn pit each day or over 1 million gallons each year for Camp Leatherneck alone. At a very conservative 4 USD per gallon of diesel in the deployed environment, this is still over 4 million USD per year for the fuel to burn waste in an open-air burn pit, well above the estimated O&M costs of the incinerator. Camp Leatherneck also investigated a local contract to landfill the waste instead of burning the waste in an open-air pit, at the potential cost of 1.1 million USD annually (SIGAR, 2015).

Assuming a WTE technology captures the 1.09 GJ of electricity per ton of waste (or 1.2 MJ per kg waste) designed in SimaPro's WTE models, a value confirmed in WEC's 2016 report of 8-12 MJ per kg waste with 15% conversion efficiency, Camp Leatherneck's 54 daily tons of waste could theoretically produce:

$$\frac{1.09 GJ}{ton\, waste} \times \frac{54\, tons}{day} \times \frac{365\, days}{year} \times \frac{278\, kWh}{GJ} = 5{,}972{,}500\ kWh \text{ per year}$$

Assuming FOB electricity is produced by generators using diesel fuel, this could replace over 450,000 gallons of diesel (or 1.8 million USD of diesel fuel) to meet the same electrical requirement (a 750kWh generator running 24 hours each day for an entire year would produce 6,500,000 kWh and use 53.4 gallons of diesel per hour at maximum efficiency) (Diesel Service and Supply, 2018).

An additional benefit of a WTE conversion technology is the ability to safely convert hazardous waste (used petroleum, oils, and lubricants (POLs), medical waste, and potentially batteries). The conversion of hazardous waste could save the US Government approximately 219 thousand USD annually for the transportation and landfilling of hazardous wastes from a FOB the size of Camp Leatherneck (DLA, 2017).

As of January 2019, over 165,000 Veterans and service members voluntarily registered with the US Department of Veterans Affairs (VA) in the Airborne Hazards and Open Burn Pit (AH&OBP) Registry to report exposure to the open-air burning of waste, a fraction of the estimated 3.5 million individuals eligible to participate in the registry (VA, 2019; VA, 2015). A report on the AH&OBP Registry found that registry participants who reported exposure to burn pits had higher prevalence of asthma, high blood pressure, COPD, chronic bronchitis, and emphysema than those with no exposure (VA, 2015). While difficult to place a monetary value on this higher prevalence of adverse health conditions, the correlation extrapolated across the 3.5 million service members exposed to open-air burn pits allows speculation of increased medical costs.

These explored costs and benefits are summarized below in Table 1 using the Federal Reserve Discount Rate of 3%, an estimated 4 USD per gallon of diesel, and calculating the net present value (NPV) over 5,10, and 15 years, approximating the length of the current Afghan War (Federal Reserve, 2019).

Table 1. Camp Leatherneck Waste Management Costs (in millions of USD)

	Capital Cost	Annual O&M	Annual Benefits	**NPV 5 Years**	**NPV 10 Years**	**NPV 15 Years**
WTE	-18	-1	2	**-13.420**	**-9.470**	**-6.062**
Landfill	0	-1.1	0	**-5.038**	**-9.383**	**-13.132**
Burn Pits	0	-4.38	0	**-20.059**	**-37.362**	**-52.288**

Despite the inability to quantify the medical costs associated with exposure to open-air burn pits, the sheer cost of diesel fuel in their use makes them the least cost-effective means of expeditionary waste management. In this simplified cost analysis, contracted landfilling services are initially less costly than WTE conversion technologies due to the high capital costs of WTE technology. But the longer the waste management requirement, the more cost effective WTE technologies become, surpassing contracted services around the 10-year mark in this analysis. This cost difference will only become more substantial when considering the fully-burdened cost of fuel or as the prices of liquid fuels continue to increase, driving up the price of open-air burning and increasing the benefits of WTE technologies by offsetting fuel use for electricity generation. Considering these more expensive fuel scenarios would also see the cost effectiveness of WTE technologies well before the 10-year mark, a time period that could easily be seen in the life-span of a US contingency base. Also not considered in this analysis is the security concern with contracted services, opening the base to possible attack or the leaking of critical information via waste (papers, counts of sustenance materials, etc.).

Summary

This chapter listed the environmental and human health impacts of the four expeditionary waste management scenarios using SimaPro's life cycle impact assessment software. Consideration was then given to the costs and benefits of each waste scenario and a basic net present value calculated across the life of the Afghan war. The life-cycle impact assessment found that open-air burn pits are the most impactful waste management strategy in all categories: environmental health, human health, and economic "health." While the remaining waste scenarios have similar human and environmental health impacts, WTE technologies are more cost effective than contracted services after 10 years.

V. Conclusions and Recommendations

Conclusions of Research

1. Stop the open-air burning of waste. The dominance of impact results for open-air burning points to the open-air burning of waste as the most damaging DoD expeditionary waste management option to human and environmental health, and the fuel requirements alone have cost the US DoD more than the capital costs of an incinerator, let alone the medical, legal, and administrative costs associated with the AH&OBP Registry.

2. Accounting for the very real threat of disease-carrying vectors and pests associated with unregulated landfilling, WTE technologies have the lowest environmental and human health impacts of expeditionary waste management strategies.

3. Considering the mitigated security risks and the net positive annual benefit of WTE technologies with offset fuel costs and potential for heat and electricity, WTE technologies may be the most economical expeditionary waste management strategy for prolonged waste management scenarios, especially considering the fully-burdened cost of fuels and the potential rise in price of liquid fuels.

Significance of Research

LCA comparing waste management scenarios has been done in the cost/benefit analysis of cities and countries around the world; this research cites a dozen of such studies in its execution. But, the application of LCA on DoD expeditionary waste management strategies is an underexplored case with most studies exploring WTE technology on a business-case model, and not giving weight to the economic and human health impacts. The inclusion of these impacts only further bolsters the need for the DoD to sincerely explore WTE technologies as an expeditionary waste management strategy.

Recommendations for Future Research

More detailed cost analysis should consider the variability in fuel pricing, the variability in WTE power generation, and should attempt to affix dollar amounts to the medical impacts of burn pits and the security associated with contracted waste management services.

Summary

When consideration is given to all potential costs and benefits of a waste management strategy, WTE technology’s mitigated human and environmental health impacts and cost effectiveness make them a viable expeditionary waste management strategy for DoD contingency bases. The DoD should continue investment and research into their utilization.

Appendix A

Table 2. WTE Incinerator Comparison Impact Values

Impact category	Unit	Municipal solid waste {RoW}| treatment of, incineration | Alloc Def, U	Waste incineration of municipal solid waste (MSW), EU-27	Waste incineration of municipal solid waste (MSW), EU-27 S
Ozone depletion	kg CFC-11 eq	4.06895E-09	1.9791E-09	-4.31333E-08
Global warming	kg CO2 eq	0.520279346	0.330032971	-0.102068191
Smog	kg O3 eq	0.007943111	0.007580156	-0.005344847
Acidification	kg SO2 eq	0.00031165	0.000282794	-0.002130853
Eutrophication	kg N eq	0.000701961	2.4868E-05	-1.38115E-05
Carcinogenics	CTUh	4.54059E-08	1.73226E-10	-6.92584E-11
Non carcinogenics	CTUh	8.29981E-07	1.45275E-08	4.18096E-09
Respiratory effects	kg PM2.5 eq	2.71569E-05	-1.70591E-05	-0.000181611
Ecotoxicity	CTUe	73.08255629	-0.015475994	-0.029048709
Fossil fuel depletion	MJ surplus	0.039254133	0.029696492	-0.33241816

Table 3. Sanitary Landfill Comparison Impact Values

Impact category	Unit	MSW {RoW}| treatment of, sanitary landfill, distance haul | Alloc Def, U	MSW {RoW}| treatment of, sanitary landfill | Alloc Def, U
Ozone depletion	kg CFC-11 eq	4.19623E-09	4.1952E-09
Global warming	kg CO2 eq	0.532218976	0.507963989
Smog	kg O3 eq	0.00747426	0.002673502
Acidification	kg SO2 eq	0.000362207	0.000189194
Eutrophication	kg N eq	0.006814006	0.006804137
Carcinogenics	CTUh	2.31436E-08	2.27764E-08
Non carcinogenics	CTUh	1.51126E-06	1.50772E-06
Respiratory effects	kg PM2.5 eq	4.41825E-05	3.35588E-05
Ecotoxicity	CTUe	112.1420162	112.0735862
Fossil fuel depletion	MJ surplus	0.092373276	0.040876518

Table 4. Unregulated Landfill Comparison Impact Values

Impact category	Unit	Unregulated Landfill	Unregulated Landfill (longterm emissions)	Unregulated Landfill (no leachate)	Unregulated Landfill (no leachate/longterm emissions)
Ozone depletion	kg CFC-11 eq	2.77205E-07	2.77205E-07	2.77205E-07	2.77205E-07
Global warming	kg CO2 eq	0.054897045	0.054897045	0.054897045	0.054897045
Smog	kg O3 eq	0.038130573	0.038130573	0.038130573	0.038130573
Acidification	kg SO2 eq	0.001076646	0.001076646	0.001076646	0.001076646
Eutrophication	kg N eq	0.000633092	0.000633092	6.80294E-05	6.80294E-05
Carcinogenics	CTUh	2.90837E-10	2.90367E-10	6.9884E-13	2.28815E-13
Non carcinogenics	CTUh	3.39538E-09	3.39489E-09	7.49804E-12	7.00609E-12
Respiratory effects	kg PM2.5 eq	1.10949E-05	1.10949E-05	1.10949E-05	1.10949E-05
Ecotoxicity	CTUe	0.10867439	0.108674371	8.50217E-07	8.31343E-07
Fossil fuel depletion	MJ surplus	0	0	0	0

Table 5. Open-air Burn Comparison Impact Values

Impact category	Unit	Open Burn	Open Burn (no ash)	Open Burn (no diesel)	Open Burn (no diesel/no ash)
Ozone depletion	kg CFC-11 eq	2.29517E-07	2.2454E-07	4.97672E-09	0
Global warming	kg CO2 eq	3.040540244	2.952993131	1.445047117	1.3575
Smog	kg O3 eq	0.291023476	0.287347656	0.064051844	0.060376024
Acidification	kg SO2 eq	0.019619855	0.019441019	0.008432336	0.0082535
Eutrophication	kg N eq	0.011008646	0.004271553	0.006881257	0.000144164
Carcinogenics	CTUh	1.99948E-06	2.20835E-07	1.83648E-06	5.78433E-08
Non carcinogenics	CTUh	1.46175E-05	1.39333E-05	1.05338E-05	9.84959E-06
Respiratory effects	kg PM2.5 eq	0.014565899	0.014547388	0.01208233	0.012063818
Ecotoxicity	CTUe	110.6283141	14.83679376	96.88264429	1.091123141
Fossil fuel depletion	MJ surplus	2.13606534	2.096925419	0.039139949	0

Table 6. Life-Cycle Impact Assessment Values

Impact category	Unit	MSW {RoW}| treatment of, incineration | Alloc Def, U	MSW {RoW}| treatment of, sanitary landfill, distance haul | Alloc Def, U	Unregulated Landfill (longterm emissions)	Open Burn
Ozone depletion	kg CFC-11 eq	4.06895E-09	4.19623E-09	2.77205E-07	2.29517E-07
Global warming	kg CO2 eq	0.520279346	0.532218976	0.054897045	3.040540244
Smog	kg O3 eq	0.007943111	0.00747426	0.038130573	0.291023476
Acidification	kg SO2 eq	0.00031165	0.000362207	0.001076646	0.019619855
Eutrophication	kg N eq	0.000701961	0.006814006	0.000633092	0.011008646
Carcinogenics	CTUh	4.54059E-08	2.31436E-08	2.90367E-10	1.99948E-06
Non carcinogenics	CTUh	8.29981E-07	1.51126E-06	3.39489E-09	1.46175E-05
Respiratory effects	kg PM2.5 eq	2.71569E-05	4.41825E-05	1.10949E-05	0.014565899
Ecotoxicity	CTUe	73.08255629	112.1420162	0.108674371	110.6283141
Fossil fuel depletion	MJ surplus	0.039254133	0.092373276	0	2.13606534

Appendix B

Table 7. Landfill Gas Emissions Calculations

	EPA 2008		EPA 2005		Petrescu 2011		Durmusoglu 2010		MW	Value Used	
	Value	**Unit**	**Value**	**Unit**	**Value**	**Unit**	**Value**	**Unit**	**g/mol**	**Value**	**Unit**
Gas Volume	6.5	m^3/Mg									
CO2	34.2	% by V			24.7	% by V			44	3.44259	g/kg waste
CH4	40.8	% by V			50.3	% by V			16	1.93622	g/kg waste
CO	20.9	ppmv	140	ppmv	19.15	ppmv			28	0.000446	g/kg waste
N2	21.9	% by V			19.4	% by V			28	1.53612	g/kg waste
O2	2.5	% by V			5.6	% by V			32	0.34431	g/kg waste
1,1,1-Trichloroethane	2.43E-01	ppmv	0.48	ppmv					133.41	1.3E-05	g/kg waste
1,1,2,2-Tetrachloroethane	5.35E-01	ppmv	1.1	ppmv					167.85	3.6E-05	g/kg waste
1,1,2,3,4,4-Hexachloro-1,3butadiene	3.49E-03	ppmv									
1,1,2-Trichloro-1,2,2Trifluoroethane	6.72E-02	ppmv									
1,1,2-Trichloroethane	1.58E-01	ppmv									
1,1-Dichloroethane	2.08E+00	ppmv	2.4	ppmv					98.97	5.9E-05	g/kg waste
1,1-Dichloroethene	1.60E-01	ppmv	0.2	ppmv					96.94	4.6E-06	g/kg waste
1,2,3-Trimethylbenzene	3.59E-01	ppmv									
1,2,4-Trichlorobenzene	5.51E-03	ppmv									
1,2,4-Trimethylbenzene	1.37E+00	ppmv									
1,2-Dibromoethane	4.80E-03	ppmv	1.00E-03	ppmv					187.88	1.4E-07	g/kg waste
1,2-Dichloro-1,1,2,2tetrafluoroethane	1.03E-01	ppmv									
1,2-Dichloroethane	1.59E-01	ppmv	0.41	ppmv					98.96	7.5E-06	g/kg waste
1,2-Dichloroethene	1.14E+01	ppmv									
1,2-Dichloropropane	5.20E-02	ppmv	0.18	ppmv					112.99	3.5E-06	g/kg waste

1,2-Diethylbenzene	1.99E-02	ppmv									
1,3,5-Trimethylbenzene	6.23E-01	ppmv									
1,3-Butadiene (Vinyl ethylene)	1.66E-01	ppmv									
1,3-Diethylbenzene	6.55E-02	ppmv									
1,4-Diethylbenzene	2.62E-01	ppmv									
1,4-Dioxane (1,4-Diethylene dioxide)	8.29E-03	ppmv									
1-Butene / 2-Methylbutene	1.22E+00	ppmv									
1-Butene / 2-Methylpropene	1.10E+00	ppmv									
1-Ethyl-4-methylbenzene	9.89E-01	ppmv									
1-Ethyl-4-methylbenzene	5.79E-01	ppmv									
1-Heptene	6.25E-01	ppmv									
1-Hexene / 2-Methyl-1pentene	8.88E-02	ppmv									
1-Methylcyclohexene	2.27E-02	ppmv									
1-Methylcyclopentene	2.52E-02	ppmv									
1-Pentene	2.20E-01	ppmv									
1-Propanethiol	1.25E-01	ppmv									
2,2,3-Trimethylbutane	9.19E-03	ppmv									
2,2,4-Trimethylpentane	6.14E-01	ppmv									
2,2,5-Trimethylhexane	1.56E-01	ppmv									
2,2-Dimethylbutane	1.56E-01	ppmv									
2,2-Dimethylpentane	6.08E-02	ppmv									
2,2-Dimethylpropane	2.74E-02	ppmv									
2,3,4-Trimethylpentane	3.12E-01	ppmv									
2,3-Dimethylbutane	1.67E-01	ppmv									
2,3-Dimethylpentane	3.10E-01	ppmv									
2,4-Dimethylhexane	2.22E-01	ppmv									
2,4-Dimethylpentane	1.00E-01	ppmv									
2,5-Dimethylhexane	1.66E-01	ppmv									

2,5-Dimethylthiophene	6.44E-02	ppmv									
2-Butanone (Methyl ethyl ketone)	4.01E+00	ppmv	7.1	ppmv					72.11	0.00011	g/kg waste
2-Ethyl-1-butene	1.77E-02	ppmv									
2-Ethylthiophene	6.29E-02	ppmv									
2-Ethyltoluene	3.23E-01	ppmv									
2-Hexanone (Methyl butyl ketone)	6.13E-01	ppmv									
2-Methyl-1-butene	1.79E-01	ppmv									
2-Methyl-1-propanethiol	1.70E-01	ppmv									
2-Methyl-2-butene	3.03E-01	ppmv									
2-Methyl-2-propanethiol	3.25E-01	ppmv									
2-Methylbutane	2.26E+00	ppmv									
2-Methylheptane	7.16E-01	ppmv									
2-Methylhexane	8.16E-01	ppmv									
2-Methylpentane	6.88E-01	ppmv									
2-Propanol (Isopropyl alcohol)	1.80E+00	ppmv	50	ppmv					60.11	0.00041	g/kg waste
3,6-Dimethyloctane	7.85E-01	ppmv									
3-Ethyltoluene	7.80E-01	ppmv									
3-Methyl-1-pentene	6.99E-03	ppmv									
3-Methylheptane	7.63E-01	ppmv									
3-Methylhexane	1.13E+00	ppmv									
3-Methylpentane	7.40E-01	ppmv									
3-Methylthiophene	9.25E-02	ppmv									
4-Methyl-1-pentene	2.33E-02	ppmv									
4-Methyl-2-pentanone (MIBK)	8.83E-01	ppmv									
4-Methylheptane	2.49E-01	ppmv									
Acetaldehyde	7.74E-02	ppmv									
Acetone	6.70E+00	ppmv	7	ppmv					58.08	0.00011	g/kg waste
Acetonitrile	5.56E-01	ppmv									

Benzene	2.40E+00	ppmv	1.9	ppmv			140.3	µg/m^3	78.11	0.00033	g/kg waste
Benzyl chloride	1.81E-02	ppmv									
Bromodichloromethane	8.78E-03	ppmv	3.1	ppmv					163.83	6.8E-05	g/kg waste
Bromomethane (Methyl bromide)	2.10E-02	ppmv									
Butane	6.22E+00	ppmv	5	ppmv					58.12	8.7E-05	g/kg waste
Carbon disulfide	1.47E-01	ppmv	0.58	ppmv					76.13	7.4E-06	g/kg waste
Carbon tetrachloride	7.98E-03	ppmv	4.00E-03	ppmv					153.84	2.4E-07	g/kg waste
Carbon tetrafluoride (Freon 14)	1.51E-01	ppmv									
Carbonyl sulfide (Carbon oxysulfide)	1.22E-01	ppmv	0.49	ppmv					60.07	4.9E-06	g/kg waste
Chlorobenzene	4.84E-01	ppmv	0.25	ppmv					112.56	1.1E-05	g/kg waste
Chlorodifluoromethane (Freon 22)	7.96E-01	ppmv	1.3	ppmv					86.47	2.4E-05	g/kg waste
Chloroethane (Ethyl chloride)	3.95E+00	ppmv	1.3	ppmv					64.52	4.5E-05	g/kg waste
Chloromethane (Methyl chloride)	2.44E-01	ppmv	1.2	ppmv					50.49	9.7E-06	g/kg waste
cis-1,2-Dichloroethene	1.24E+00	ppmv									
cis-1,2-Dimethylcyclohexane	8.10E-02	ppmv									
cis-1,3-Dichloropropene	3.03E-03	ppmv									
cis-1,3-Dimethylcyclohexane	5.01E-01	ppmv									
cis-1,4-Dimethylcyclohexane	2.48E-01	ppmv									
cis-2-Butene	1.05E-01	ppmv									
cis-2-Heptene	2.45E-02	ppmv									
cis-2-Hexene	1.72E-02	ppmv									
cis-2-Octene	2.20E-01	ppmv									
cis-2-Pentene	4.79E-02	ppmv									
cis-3-Methyl-2-pentene	1.79E-02	ppmv									
Cyclohexane	1.01E+00	ppmv									
Cyclohexene	1.84E-02	ppmv									
Cyclopentane	2.21E-02	ppmv									
Cyclopentene	1.21E-02	ppmv									

Decane	3.80E+00	ppmv									
Dibromochloromethane	1.51E-02	ppmv									
Dibromomethane	8.35E-04	ppmv									
Dichlorobenzene	9.40E-01	ppmv	0.21	ppmv					147	2.2E-05	g/kg waste
Dichlorodifluoromethane (Freon 12)	1.18E+00	ppmv	16	ppmv					120.91	0.00028	g/kg waste
Dichloromethane	6.15E+00	ppmv	14	ppmv					84.94	0.00023	g/kg waste
Diethyl sulfide	8.62E-02	ppmv									
Dimethyl disulfide	1.37E-01	ppmv									
Dimethyl sulfide	5.66E+00	ppmv	7.8	ppmv					62.13	0.00011	g/kg waste
Dodecane (n-Dodecane)	2.21E-01	ppmv									
Ethane	9.05E+00	ppmv	890	ppmv					30.07	0.00359	g/kg waste
Ethanol	2.30E-01	ppmv	27	ppmv					46.08	0.00017	g/kg waste
Ethyl acetate	1.88E+00	ppmv									
Ethyl mercaptan (Ethanediol)	1.98E-01	ppmv	2.3	ppmv					62.13	2.1E-05	g/kg waste
Ethyl methyl sulfide	3.67E-02	ppmv									
Ethylbenzene	4.86E+00	ppmv	4.6	ppmv			239.9	μg/m^3	106.16	0.00061	g/kg waste
Formaldehyde	1.17E-02	ppmv									
Heptane	1.34E+00	ppmv									
Hexane	3.10E+00	ppmv	6.6	ppmv					86.18	0.00011	g/kg waste
Hydrogen sulfide	3.20E+01	ppmv	36	ppmv	186.9	ppmv			34.08	0.00077	g/kg waste
Indan (2,3-Dihydroindene)	6.66E-02	ppmv									
Isobutane (2-Methylpropane)	8.16E+00	ppmv									
Isobutylbenzene	4.07E-02	ppmv									
Isoprene (2-Methyl-1,3butadiene)	1.65E-02	ppmv									
Isopropyl mercaptan	1.75E-01	ppmv									
Isopropylbenzene (Cumene)	4.30E-01	ppmv									
Methanethiol (Methyl mercaptan)	1.37E+00	ppmv	2.5	ppmv					48.11	2.5E-05	g/kg waste
Methyl tert-butyl ether (MTBE)	1.18E-01	ppmv									

Methylcyclohexane	1.29E+00	ppmv									
Methylcyclopentane	6.50E-01	ppmv									
Naphthalene	1.07E-01	ppmv									
n-Butylbenzene	6.80E-02	ppmv									
Nonane	2.37E+00	ppmv									
n-Propylbenzene (Propylbenzene)	4.13E-01	ppmv									
Octane	1.08E+00	ppmv									
p-Cymene (1-Methyl-4lsopropylbenzene)	3.58E+00	ppmv									
Pentane	4.46E+00	ppmv	3.3	ppmv					72.15	7.4E-05	g/kg waste
Propane	1.55E+01	ppmv	11	ppmv					44.09	0.00016	g/kg waste
Propene	3.32E+00	ppmv									
Propyne	3.80E-02	ppmv									
sec-Butylbenzene	6.75E-02	ppmv									
Styrene (Vinylbenzene)	4.11E-01	ppmv									
Tetrachloroethylene	2.03E+00	ppmv	3.7	ppmv					165.83	0.00013	g/kg waste
Tetrahydrofuran (Diethylene oxide)	9.69E-01	ppmv									
Thiophene	3.49E-01	ppmv									
Toluene (Methyl benzene)	2.95E+01	ppmv	39	ppmv			1271.7	µg/m^3	92.13	0.00332	g/kg waste
trans-1,2-Dichloroethene	2.87E-02	ppmv	2.8	ppmv					96.94	3.6E-05	g/kg waste
trans-1,2Dimethylcyclohexane	4.04E-01	ppmv									
trans-1,3-Dichloropropene	9.43E-03	ppmv									
trans-1,4Dimethylcyclohexane	2.05E-01	ppmv									
trans-2-Butene	1.04E-01	ppmv									
trans-2-Heptene	2.50E-03	ppmv									
trans-2-Hexene	2.06E-02	ppmv									
trans-2-Octene	2.41E-01	ppmv									
trans-2-Pentene	3.47E-02	ppmv									
trans-3-Methyl-2-pentene	1.55E-02	ppmv									

Tribromomethane (Bromoform)	1.24E-02	ppmv									
Trichloroethylene (Trichloroethene)	8.28E-01	ppmv	2.8	ppmv					131.4	6.3E-05	g/kg waste
Trichlorofluoromethane (Freon 11)	2.48E-01	ppmv									
Trichloromethane (Chloroform)	7.08E-02	ppmv	0.03	ppmv					119.39	1.6E-06	g/kg waste
Undecane	1.67E+00	ppmv									
Vinyl acetate	2.48E-01	ppmv									
Vinyl chloride (Chloroethene)	1.42E+00	ppmv	7.3	ppmv					62.5	7.2E-05	g/kg waste
Xylenes (o-, m-, p-, mixtures)	9.23E+00	ppmv	12	ppmv			341.3	µg/m^3	106.16	0.00094	g/kg waste

Table 8. Landfill Leachate Emissions Calculations

	Johansen 1976		**Kulikowska 2007**		**Christensen 2001**		**Mali 2016**		**Ogundipe 2015**		**Values used**	
	Average	**Unit**	**Mean**	**Unit**	**Mean**	**Unit**	**Average**	**Unit**	**Value**	**Unit**	**Value**	**Unit**
Volume			0.458333	L/kg waste							.4	L/kg waste
COD	7245.625	mg/L	1200	mg/L	22000	mg/L	82984	mg/l	2390	mg/l	9265.57	mg/kg waste
BOD	4542.5	mg/L	388	mg/L	13000	mg/L	944	mg/l			1887.45	mg/kg waste
TOC	510	mg/L									204	mg/kg waste
Total N	212.45	mg/L	248	mg/L			49.8	mg/l			68.03333	mg/kg waste
NH3 (as N)	134.5333	mg/L	215	mg/L	740	mg/L			33.33	mg/l	112.2863	mg/kg waste
NO3 (as N)	0.263333	mg/L							20.5	mg/l	4.152667	mg/kg waste
Organic N	34.16667	mg/L	39	mg/L							14.63333	mg/kg waste
Total P	5.525	mg/L	8.5	mg/L	6	mg/L			0.12	mg/l	2.0145	mg/kg waste
Suspended Solids	368.75	mg/L	405	mg/L			7154	mg/l			1057.033	mg/kg waste
Volatile Susp Solids	183.375	mg/L	163	mg/L							69.275	mg/kg waste
Total Solids	2916.667	mg/L	4576	mg/L			7866	mg/l			2047.822	mg/kg waste
pH	6.375		7.84		6.1		8.74				7.26375	
Alkalinity	40.6	meq/L					980	mg/l			204.12	mg/kg waste
Ca	212.6667	mg/L	342	mg/L	1200	mg/L					233.9556	mg/kg waste
Mg	55.33333	mg/L	281	mg/L	470	mg/L					107.5111	mg/kg waste
Mn									7.1	mg/l	2.84	mg/kg waste
Na	240.1333	mg/L			1340	mg/L					316.0267	mg/kg waste
K	168.8833	mg/L			1085	mg/L					250.7767	mg/kg waste
Chloride	388	mg/L	954	mg/L	2120	mg/L	2395	mg/l			585.7	mg/kg waste
Sulfate	53	mg/L	224	mg/L	500	mg/L	509	mg/l	45	mg/l	106.48	mg/kg waste
Fe	194.0875	mg/L			780	mg/L			9.25	mg/l	131.1117	mg/kg waste

Zn	20.49438	mg/L	0.29	mg/L	5	mg/L			0.6	mg/l	2.638438	mg/kg waste
Cr	0.177125	mg/L	0.06	mg/L	0.28	mg/L			0.025	mg/l	0.054213	mg/kg waste
Ni	0.19875	mg/L			0.17	mg/L					0.07375	mg/kg waste
Cu	0.2045	mg/L	0.03	mg/L	0.065	mg/L			0.2	mg/l	0.04995	mg/kg waste
Cd	0.0056	mg/L	0.009	mg/L	0.005	mg/L					0.002613	mg/kg waste
Pb	0.190375	mg/L	BDL		0.09	mg/L					0.056075	mg/kg waste
Co	0.0268	mg/L			0.05	mg/L					0.01536	mg/kg waste
Benzene			0.0013	mg/L	0.0002	mg/L					0.0003	mg/kg waste
Ethylbenzene			0.0314	mg/L	0.000223	mg/L					0.006325	mg/kg waste
Toluene			0.0611	mg/L	0.001	mg/L					0.01242	mg/kg waste
Xylene			0.0827	mg/L	0.0008	mg/L					0.0167	mg/kg waste
Chlorobenzene					0.0001	mg/L					0.00004	mg/kg waste
Dichlorobenzene					0.0054	mg/L					0.00216	mg/kg waste

Table 9. Open-Air Burn Emissions Calculations

	Aurell et al 2017		Dominguez 2018		Woodall 2012		Gerstle 2012		EPA 1996		Values Used	
Pollutant	avg	unit	avg	unit	avg	unit	avg	unit	avg	unit	Amount	Unit
Co2			1200	ppm	1000	ppm	1250	lb/ton waste	1340	kg/Mg Waste	0.9825	kg/kg waste
CO							90	lb/ton waste	0.96	kg/Mg Waste	22.98	g/kg waste
SO2					20	ppm			1.95	kg/Mg Waste	5.975	g/kg waste
NO2					8	ppm	8	lb/ton waste	2.51	kg/Mg Waste	3.255	g/kg waste
CH4							30	lb/ton waste			15	g/kg waste
PM2.5	7.3	g/kg waste	10.5	g/kg waste	43	g/kg C					11.66667	g/kg waste
PM10			11	g/kg waste	46	g/kg C	16	lb/ton waste			12.46667	g/kg waste
Metals												
Pb	2158	mg/kg waste	0.07	mg/kg waste	24	mg/kg C			0.1	kg/Mg waste	566.9175	mg/kg waste
Cu	55.4	mg/kg waste	0.2	mg/kg waste	2.2	mg/kg C					18.82667	mg/kg waste
Cl	255.5	mg/kg waste									255.5	mg/kg waste
Ca	6.91	mg/kg waste	0.1	mg/kg waste								
K	138	mg/kg waste										
As	4.62	mg/kg waste							0.00297	kg/Mg Waste		
Fe	1.7	mg/kg waste	0.3	mg/kg waste	4.3	mg/kg C					1.24	mg/kg waste
Br	4.86	mg/kg waste										
Ge	2.09	mg/kg waste										
Y	2.53	mg/kg waste										
Rb	2.57	mg/kg waste										
Ba	0.75	mg/kg waste										
Al												
Cd	0.62	mg/kg waste							0.00437	kg/Mg Waste	2.495	mg/kg waste

Cr	0.12	mg/kg waste							0.007	kg/Mg Waste	3.56	mg/kg waste
Zn	24.1	mg/kg waste									24.1	mg/kg waste
Hg					17	mg/kg C			0.0028	kg/Mg Waste	4.8	mg/kg waste
Ni					1.5	mg/kg C			0.00218	kg/Mg Waste	1.39	mg/kg waste

Dioxins												
PCDD/PCDF	1.77	ng TEQ/kg waste	0.904	ng TEQ/kg waste	270	ng TEQ/ kg C			4.73E-6	kg/Mg Waste	28.851	ng TEQ/kg waste

VOCs											250	mg/kg waste
1,1,2-Trichloroethane	1.11	mg/kg waste										
1,2,4-Trimethylbenzene	27.17	mg/kg waste										
1,2-Dichloro-1,1,2,2-tetrafluoroethane	0.15	mg/kg waste										
1,2-Dichloroethane	0.1	mg/kg waste										
1,2-Dichloropropane	1.34	mg/kg waste										
1,3,5-Trimethylbenzene	7.28	mg/kg waste										
1,3-Butadiene	19.67	mg/kg waste	82	mg/kg waste	540	mg/kg C						
1,3-Dichlorobenzene	0.11	mg/kg waste										
1,4-Dichlorobenzene	0.17	mg/kg waste										
1,4-Dioxane	0.69	mg/kg waste										
2,2,4-Trimethylpentane	0.72	mg/kg waste										
2-Butanone (MEK)	10.24	mg/kg waste			540	mg/kg C						
2-Hexanone	6.43	mg/kg waste										
2-Propanol	3.95	mg/kg waste										
4-Methyl-2-pentanone	1.47	mg/kg waste										
Acetone	44.7	mg/kg waste			1600	mg/kg C					342.35	mg/kg waste
Acetonitrile	26.9	mg/kg waste			100	mg/kg C						
Acrolein			120	mg/kg waste	1200	mg/kg C						

Benzene	310.88	mg/kg waste	266	mg/kg waste	2000	mg/kg C					458.96	mg/kg waste
Bromodichloromethane												
Bromoform												
Carbon Disulfide	1.07	mg/kg waste			160	mg/kg C						
Carbon Tetrachloride	1.09	mg/kg waste			1.5	mg/kg C						
Chlorobenzene	1.71	mg/kg waste										
Chloroethane	2.35	mg/kg waste										
Chloroform	0.22	mg/kg waste										
Chloromethane	7.58	mg/kg waste			220	mg/kg C						
cis-1,2-Dichloroethene												
cis-1,3-Dichloropropene												
Cumene	3.75	mg/kg waste										
Cyclohexane	8.71	mg/kg waste										
Dibromochloromethane												
Dichlorodifluoromethane	6.72	mg/kg waste										
Ethanol	10.63	mg/kg waste										
Ethylbenzene	20.8	mg/kg waste	18	mg/kg waste								
Hexachlorobutadiene												
m,p-Xylenes	41.14	mg/kg waste			150	mg/kg C					50.57	mg/kg waste
Methyl tert-Butyl Ether												
Methylene Chloride	125.62	mg/kg waste										
Naphthalene	144.54	mg/kg waste										
n-Heptane	4.7	mg/kg waste										
n-Hexane	16.35	mg/kg waste										
n-Octane	15.62	mg/kg waste										
o-Xylene	16.12	mg/kg waste									16.12	mg/kg waste
Styrene	50.71	mg/kg waste	210	mg/kg waste							130.355	mg/kg waste
Tetrachloroethene	0.61	mg/kg waste										

Tetrahydrofuran (THF)	0.73	mg/kg waste										
Toluene	326.46	mg/kg waste	52	mg/kg waste	860	mg/kg C					240.82	mg/kg waste
trans-1,2-Dichloroethene												
trans-1,3-Dichloropropene												
Trichloroethene	0.28	mg/kg waste										
Trichlorofluoromethane	2.48	mg/kg waste										
Trichlorotrifluoroethane	1	mg/kg waste										
Vinyl Chloride			0.55	mg/kg waste								
Vinyl Acetate			100	mg/kg waste	1500	mg/kg C					350	mg/kg waste

PAHs			1.2	mg TEQ/kg waste							1.2	mg TEQ/kg waste

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14. ABSTRACT

The United States (US) Department of Defense (DoD) is investigating improved municipal solid waste (MSW) management techniques. Current techniques tax already limited land and energy resources at contingency bases and impart additional logistical support requirements and personnel commitments. Seeking a solution to this growing problem, the DoD is investigating waste-to-energy (WTE) systems to reduce the volume of hazardous and non-hazardous solid wastes while generating low emissions. The current barriers to the acquisition and utilization of viable WTE technologies are the high capital and operating and maintenance (O&M) costs. Using the Life-Cycle Analysis (LCA) software SimaPro, the human health, environmental quality, and climate change impacts of DoD expeditionary waste management practices were compared. These calculated impacts and the economic impacts confirm that the open-air burning of waste is not only dangerous to humans and the environment, but is costly to the US government. Considering the second and third-order economic effects and the mitigated human and environmental health impacts, WTE technologies may be a viable waste management strategy for the DoD.

15. SUBJECT TERMS
Life Cycle Assessment, LCA, SimaPro, DoD, Waste Management, Waste-to-Energy, WTE

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