

Article

Sustainability Assessment of Municipal Solid Waste in Baltimore USA

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Abstract: Sustainability assessment of municipal solid waste management requires a holistic approach in evaluating the impacts of current technology and processes. In this study, the sustainability analysis of the Municipal Solid Waste (MSW) incineration plant in Baltimore city was performed to determine its environmental, economic, and social impacts. The city's major waste-to-energy generation plant has benefitted the city of Baltimore since inception till date in terms of waste processing, resulting in electricity and steam production for more than 40,000 homes and over 200 businesses. The life cycle impact of the incineration plant was analyzed using the Simapro life cycle assessment (LCA) software with the Building for Environmental and Economic Sustainability (BEES) database for correlation. The results obtained upon analysis show larger values of Global Warming Potential and eutrophication potential as 6.46×10^8 Gg of CO₂ equivalence and 2.27×10^6 Gg N equivalence, respectively. These values resulted from the higher amount of fossil CO₂ and NO_x emitted from the plant. The acidification potential of 1.66×10^{17} H⁺ mmole eq resulted from the SO₂ emitted by the incineration plant. The incineration plant exceeded the limitations set by the Environmental Protection Agency (EPA) on NO_x (150 ppm), which is detrimental to the well-being of people as shown by this study. Installing an improved processing technology such as a Selected Catalytic Reactor (SCR) can drastically reduce the NO_x emission to 45 ppm. Life Cycle Assessment was confirmed suitable in evaluating the environmental impacts of the MSW-to-energy treatment approach.



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1. Introduction

Several researchers have explained the concept of sustainability with a Venn diagram encompassing three elements: Environment, Society, and Economy. Of much concern about the concept of sustainability is striking a balance between these three elements. Necessity is being regarded as the mother of invention according to the quote made by the ancient Greek philosopher Plato. The quest of man to satisfy his diverse needs brings about the advent of technology as we have it today. Sustainable development is defined as the development that meets the needs of the society of today without compromising the ability of future generations to meet their own needs [1]. A sustainable society is founded on equal access to health care, nutrition, clean water, shelter, education, energy, economic opportunities, and employment. In this ideal society, humans live in harmony with their natural environment, conserving resources not only for their generation but also for their children's children. As humans derive satisfaction in natural products and resource utilization to meet their needs, a need then arose for proper disposal/treatment/reuse of

their continuously generated waste (i.e., municipal solid waste, agricultural, and industrial waste).

Municipal Solid Waste (MSW), more commonly known as trash, comprises various items being thrown away daily. MSW materials can be broadly categorized into three viz: biomass (such as paper, food waste, grass clippings, leaves, wood, and leather products); non-biomass combustible materials (such as plastics, petroleum-based); and non-combustibles materials (such as glass, metals). A new study has revealed that the United States is at the top of the list of countries that are driving the global waste crisis, producing three times the global average of waste for 4% of the world population [2]. In 2015, a total of 262.4 million tons of MSW was generated in the USA, among which 52.5% was deposited in landfill, 25.8% recycled, 12.8% burnt for energy recovery, and the rest 8.9% was composted [3]. In 2017, the United States produced 258 million metric tons of MSW, followed by China and India which produced 220.4 and 168.4 million metric tons, respectively [4].

The idea of using waste as an energy source is not new. While Waste-to-Energy (WTE) has been slow to take off in the USA (i.e., converting a lesser amount of these enormous waste to energy), it is a big business in Europe, driven largely by EU waste legislation. Figure 1 shows the proportion of total solid wastes generated to the amount converted to energy in 2020, with USA having the least conversion rate of 12%. European countries and Japan convert large amounts of waste generated to energy due to the unavailability of open space for landfills [5]. In Asia, the Chinese government plans to build 300 waste-to-energy plants over the next three years, including the world's largest plant in Shenzhen, which, when open in 2020, is estimated to burn 5000 metric tons of trash every day. According to [6], the USA had 71 waste-to-energy plants that generated electricity in 20 states with a total generating capacity of 2.3 gigawatts. In 2019, 67 WTE plants generated about 13 billion kilowatt-hours of electricity from burning nearly 25 million tons of combustible MSW. Biomass materials accounted for about 63% of the weight of the combustible MSW and for about 47% of the electricity generated [5]. The global waste-to-energy market is increasing, it is expected to reach USD 37.64 billion by 2020 growing at a compound annual growth rate of 5.9 percent, up from USD 25.3 billion in 2013 [7].

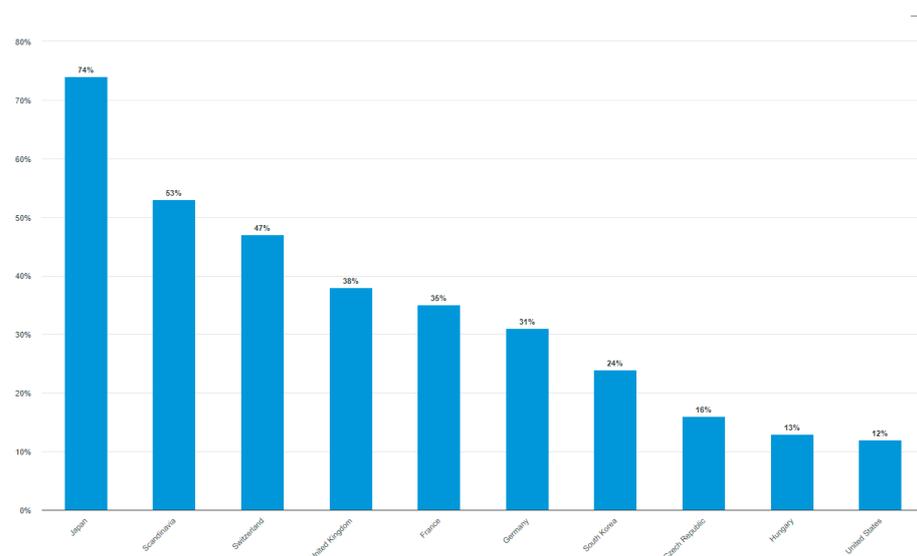


Figure 1. Percent of total solid waste vs. energy recovery [5].

Virtually every resident, organization, and human activity in the United States generates some type of waste. Different types of waste generated include municipal solid waste, agricultural and animal waste, medical waste, radioactive waste, hazardous waste, industrial non-hazardous waste, construction, and demolition debris, extraction and mining waste, oil and gas production waste, fossil fuel combustion waste, and sewage sludge. The

total generation of municipal solid waste in 2017 was 267.8 million tons of MSW, approximately 5.7 million tons more than the amount generated in 2015. MSW generated in 2017 increased to 4.51 pounds per person per day. This is an increase from the 262.1 million tons generated in 2015 and 208.3 million tons in 1990 [8]. In 2012, the total solid waste generated by Maryland's twenty-two counties is 12.3 million tons with Baltimore county generating the highest amount of solid waste [9]. This total solid waste was reduced to 11.9 million tons in 2016 with Prince George county generating the highest amount of solid waste. In 2018, Maryland counties and Baltimore City generated 14,310,933 tons of solid waste, much higher than the previous years as shown in Figure 2. Out of the total waste generated, only small percent is converted to energy.

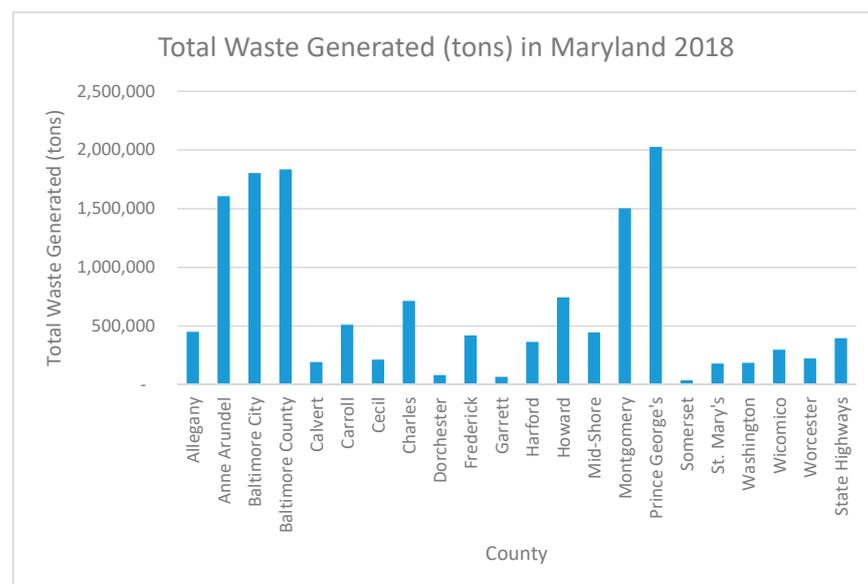


Figure 2. Total Solid Waste Generated in Maryland [10].

As communities and companies around the USA pursue zero-waste-to-landfill and look for renewable energy sources, waste-to-energy plays a major role in sustainable waste management and thereby impacts positively the health of the people in the community and environment at large, which is coupled with social and economic benefits. The incineration of waste is the most stringently regulated and controlled industrial activity. Waste-to-Energy plants are equipped with sophisticated filtering devices to deal with the pollutants that arise from the incineration process and minimize emissions released into the atmosphere. Some of these gaseous pollutants can be hazardous to people and the environment if they are not properly controlled. The U.S. Environmental Protection Agency (EPA) applies strict environmental rules to waste-to-energy plants, which require thermal plants to use pollution control devices such as scrubbers, fabric filters, and electrostatic precipitators to capture air pollutants. Direct industrial CO₂ emissions rose 0.3% to reach 8.5 Gt CO₂ in 2017 amounting to 24% of global emissions, this is a rebound from the 1.5% annual decline during 2014–2016 [11].

Before the advent of incineration technology in the United States, landfills had been in major use since the country has large land mass, unlike European or Asian countries. The major problem with landfills approach is the release of methane gas (i.e., a source of greenhouse gas (GHG) directly into the atmosphere, causing greater environmental havoc to the society. Another adverse effect is pollution to water bodies due to erosion and stormwater run-offs. Global concern with the landfill approach is that the world cannot keep dumping the waste on land forever because land space will soon be filled up. The incineration process was developed as an alternative to landfills. Incineration is a better waste management option; it can burn up to 90% of the total waste generated in a chosen area, saves on transportation cost for waste, as well as producing energy, among

others. The conversion process comes with so many advantages as well as disadvantages, the problem arises based on the drawbacks that the waste-to-energy conversion process creates. The process of burning waste to generate energy has been a better option when compared with its counterpart—anaerobic digestion, but of serious concern is the release of harmful gases (CO₂ and NO_x) into the atmosphere, causing a direct impact on public health such as the spread of diseases, etc., which relate to environmental, economic, and social issues of sustainability [12].

The objective of this research work is to assess the sustainability impacts of the thermo-chemical conversion processes of MSW-to-energy in terms of environmental friendliness, economic and social benefits. This is done by analyzing existing MSW incineration plants in Baltimore Maryland, to determine if the waste conversion process with the current operating technology is sustainable.

2. Methodology

The evaluation of the existing situation of MSW management from an environmental, economic, and social perspective via a life cycle approach is an important first step prior to making any decisions on the technologies to be selected, the policies to be developed and the strategies to be followed for a nation [13].

2.1. Study Area—Wheelabrator Technologies (BRESKO)

Waste management in Maryland USA has been solely relying on landfills and incineration plants. Maryland, in general, has 22 landfills with 9 landfills at least half full at the end of the year 2017. Baltimore City's Quarantine Road landfill was nearly 85 percent full at the end of 2017, according to an analysis of data from the Maryland Department of the Environment, and the Baltimore Department of Public Works estimates it will fill up by 2026 [9]. Figure 3 shows the system boundary used in explaining the current situation of MSW management and impacts in Baltimore.

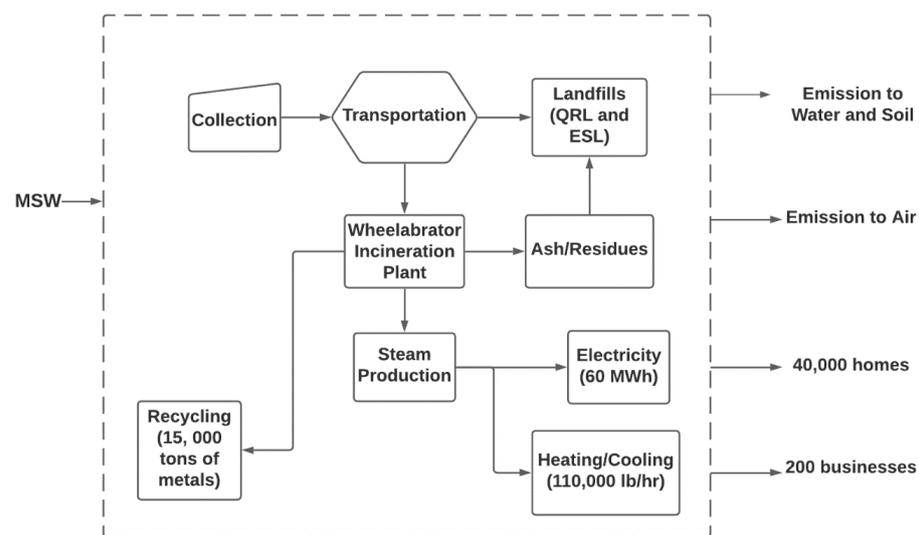


Figure 3. System Boundary for Municipal Solid Waste (MSW) in Baltimore Maryland.

Wheelabrator Technologies (WT) also known as BRESKO, is an incineration plant that has been located in the central city of Baltimore Maryland since 1985. WT has 65 full time employees with 7 needed for daily operations. The plant operates continuously 24 h/7 days/365 days a year. The plant serves as a major solution to MSW generated in the city with a daily capacity of 2250 tons of solid waste. WT processes about 700,000 tons of MSW yearly—about half of the waste comes from Baltimore households and nearly 40 percent from Baltimore County. The rest comes from Howard and Anne Arundel counties, other Maryland jurisdictions and out of state. The plant has a 4000-refuse pit capacity filled with

waste brought into the plant by 300 trucks daily. WT has 3 boilers each with 750 tons of waste handling capacity, producing 60 MW/h of electricity being supplied to 40,000 homes daily. Alongside this, WT supplies steam to 200 companies in the city for heating and cooling.

2.2. Life Cycle Assessment

A life cycle assessment (LCA) is a useful tool to demonstrate different impact categories quantitatively and qualitatively involved throughout the life cycle of the end-product. As shown in Figure 4, LCA is a holistic approach that quantifies all environmental burdens and therefore all environmental impacts throughout the life cycle of products or processes [14]. LCA is not an exact scientific tool, but a science-based assessment methodology for the impacts of a product or system on the environment [15]. It is increasingly utilized for solid waste management systems especially in the decision-making process and in strategy-planning. LCA has been utilized for sustainable MSW management since 1995 [16]. LCA analysis is broken into 3 parts: goal and scope definition, inventory analysis and impact assessment.

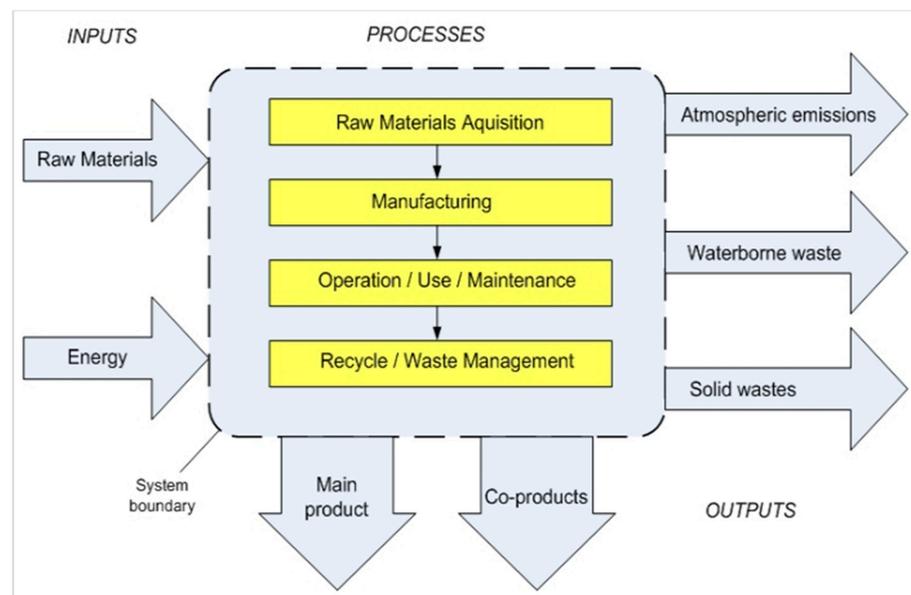


Figure 4. Schematic diagram of Life Cycle Assessment [17].

2.2.1. Goal and Scope Definition

The goal of this research work is to assess the waste-to-energy process in the United States using a case study of the incineration plant in Baltimore, Maryland. The data used for the analysis are obtained from the WT waste-to-energy plant which receives 2250 tons daily at the gate from 300 trucks. The system boundaries were extended from the gate (total waste received) to the grave (i.e., the disposal of all solid residues). The total energy produced in the form of electricity and steam, together with the recovered metals were included in the assessment. The operating cost of the plant (startup capital, maintenance, running cost, labor cost and others) was not considered. When compared with other methods of managing solid waste, such as compost, landfills, recycling, the incineration process has been looked upon as a major source of environmental pollution in the United States. This research work seeks to perform the life cycle assessment of this conversion process and determine its direct and indirect impact on Baltimore city. This, in turn, will serve to increase the societal perspective of this process and serve as an eye-opener on how to mitigate the problems arising from this process based on the environmental, economic, and social impacts from the LCA analysis.

2.2.2. Inventory Analysis

Life cycle Inventory analysis involves determining the quantitative values of the materials and the energy inputs and outputs of all process stages within the life cycle, as shown in Figure 5, of a typical incineration process. For the study area, the inventory analysis includes the daily input to the plant (2250 tons/day), energy input, the incineration process at elevated temperature 2500 °F, products, and co-products (electricity and steam), recycled metals (15,000 tons/yr) and transportation of ash and refuse (i.e., waste flow) from the plant to the Quarantine Road landfills (QRL) in amounts of 600 tons/day.

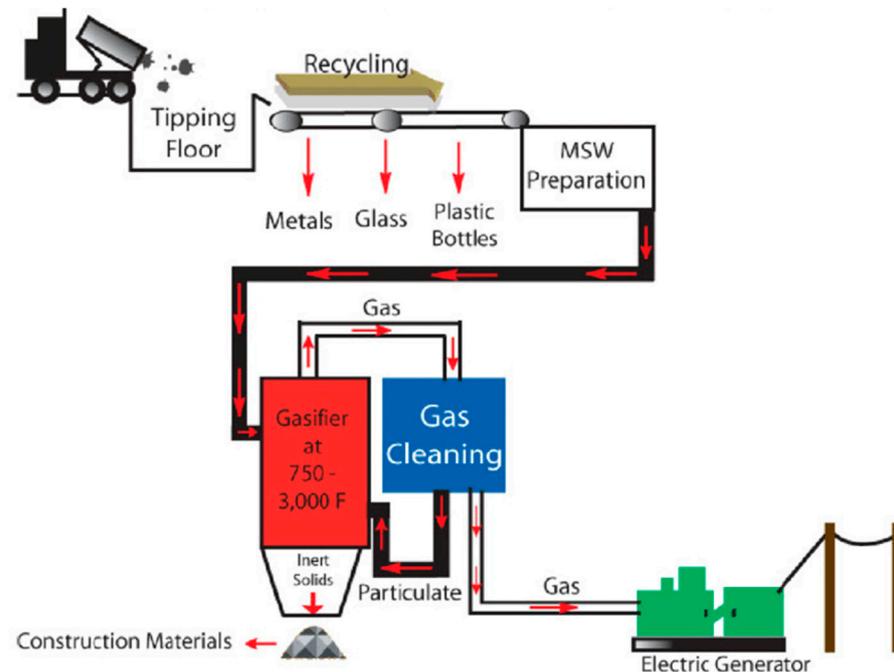


Figure 5. Typical MSW Incineration Process.

2.2.3. Impact Assessment

The assessment criteria used for LCA analysis include the Global warming potential (GWP), acidification potential (AP), Eutrophication, ozone depletion, natural resource consumption, fossil fuel, and social impacts. According to [18], several reasonable assumptions are required to simplify the complexity of an integrated MSW management system and overcome the problem of lack of data, so as to comply with the requirements of the SimaPro software and to obtain a proper comparison between the different scenarios. SimaPro software version 9.0 was used in this study to model the incineration system and to estimate environmental impacts. Since the ISO standard (ISO, 2006b) does not specify a particular impact assessment method to be used, the impacts in this study were estimated using the Building for Environmental and Economic Sustainability (BEES) method according to US EPA '97 impact assessment normalization. BEES is a software tool developed by the National Institute of Standards and Technology (NIST), it has been found to be adequate in analyzing all stages in the life of a product (LCA), including raw-material acquisition, manufacture, transportation, installation, use, recycling, and waste management [19]. The results are presented first for the daily processing of 2250 tons of MSW and 60 MWh of electricity alongside 110,000 lb/hr steam produced from the waste. The environmental impacts were determined according to equations 1–2 [20].

$$GWP = \sum_{i=1}^n ECO_{2i} \times w_i \quad [\text{kgSO}_{2\text{eq}}] \quad (1)$$

$$AP = \sum_{i=1}^n ESO_{2i} \times w_i \quad [\text{kgSO}_{2\text{eq}}] \quad (2)$$

where:

GWP is Global Warming Potential;

ECO₂ is coefficient of carbon dioxide equivalent for *i*th material [$\text{kgCO}_{2\text{eq}} \cdot \text{kg}^{-1}$];

AP is acidification potential;

ESO_{2i} is coefficient of sulphur dioxide equivalent for *i*th material [$\text{kgSO}_{2\text{eq}} \cdot \text{kg}^{-1}$].

W_i is weight of *i*th material [kg]

3. Results and Discussion

The life cycle assessment was performed using Simapro software. All data used were obtained from the company and EPA publication about the environmental concerns of the incineration plant. All materials and processes were calculated based on yearly usage, production, and consumption. A municipal waste scenario contained in the database demo7 was used for comparison.

3.1. Global Warming Potential (GWP)

The impact assessment analysis of the incineration plant was calculated with the Municipal waste/NL S demo7 scenario. The incineration process generated more greenhouse gases resulting in high impact expressed as the global warming potential with a value of 6.46×10^{17} gCO₂ eq which is 6.46×10^8 Gg of CO₂ equivalence over one year as shown in Table 1. The combustion of MSW normally generates both biomass and fossil CO₂. Biomass CO₂ is higher because of the higher fraction of organic waste such as food waste, yard waste, and paper than plastics that come from fossil fuel. This fraction does not contribute to global warming in contrast to fossil CO₂ since it is part of the global carbon cycle. Although the combustion of biomass helps reduce the generation of greenhouse gases in particular of CO₂, during the combustion process other fuels, for instance diesel, are used to help to burn MSW because it has high moisture content. A cleaner approach of burning the waste using other fuel sources could result in less *GWP* impact by the incineration plant.

Table 1. Normalized Result of the Environmental Impact Assessment.

Impact Category	Unit	Life Cycle (MSW-WTE)
Global Warming	g CO ₂ eq	6.46×10^{17}
Acidification	H+ mmole eq	1.66×10^{17}
HH (Human Health) Cancer	g C ₆ H ₆ eq	8.79×10^{15}
HH noncancer	g C ₇ H ₇ eq	1.70×10^{19}
HH criteria air pollutants	microDALYs	6.97×10^{13}
Eutrophication	g N eq	2.27×10^{15}
Ecotoxicity	g 2,4-D eq	2.38×10^{16}
Smog	g NO _x eq	2.05×10^{15}
Natural resource depletion	MJ (Mega Joule) surplus	1.29×10^{15}
Indoor Air quality	g TVOC eq	x
Habitat alteration	T&E (Threatened and endangered) count	1.32×10^1
Water intake	liters	3.92×10^{16}
Ozone depletion	g CFC (Chlorofluorocarbon) -11 eq	1.01×10^{10}

According to the study by [18], three waste management scenarios were analyzed using both CML 2001 and Eco-indicator 99 methods in the SimaPro software. Waste incineration (Scenario III) has very high environmental impacts compared to the other waste treatment processes in many categories, and especially regarding the global warming potential. This agrees with the result obtained in Table 1.

3.2. Acidification Potential (AP)

Acidification Potential (AP) is a consequence of acids being emitted to the atmosphere and subsequently deposited in surface soils and waters. AP classification factors are mainly based on the contributions of SO₂, NO_x, HCl, NH₃, and HF and expressed as SO₂ equivalent [21]. According to an LCA study by [22] on landfills vs. incineration, the incineration option performed more poorly from an environmental perspective than the landfill option in terms of AP. From this study, the AP impact is 1.66×10^{17} H⁺ mmole eq, it gives less impact when compared with the GWP and EP as shown in Table 1. Similarly, the study by [18] indicated that landfilling (scenario 0) and waste incineration (scenario III) have the highest contributions for the acidification impact category because of the SO₂, NO_x, HCL, and HF emissions to the air.

3.3. Eutrophication Potential (EP)

The major problem faced by the MSW incineration plant under study is nitrogen, which is a key substance in waste and possibly a major contributor to the EP. Fifty percent of total nitrogen in the waste can be found in leachate as NO₃⁻ and contributes a major share to eutrophication [23]. Moreover, fuel production, collection, and transportation also emit eutrophying substances such as NH₃, NO_x, N₂O, and NO₃⁻. From the analysis, the overall EP from the total tons of waste the incineration plant processed annually is 2.27×10^{12} kg of N equivalents as shown in Table 1. This accounts for total phosphorous and nitrogen in the water and the NO_x and N₂O emissions in the air. As shown in Table 2, the inventory analysis shows that oxides of Nitrogen produced are 1.63×10^3 Mtn, which results in a greater impact of eutrophication potential.

Table 2. Inventory Analysis Results of the MSW Baltimore Incineration Plant.

Impact Category	Unit	Life Cycle (MSW-WTE)
Methyl ethyl ketone	Kton	50.9
Methyl formate	tn.lg	1.3
Methylamine	tn.lg	65.8
Metolachlor	tn.lg	22.8
Molybdenum	Kton	58
Naphthalene	tn.lg	123
Nickel	Kton	311
Niobium-95	kBq	2.11×10^{13}
Nitrate	Kton	190
Nitrobenzene	tn.lg	744
Nitrogen fluoride	Kg	6.98
Nitrogen monoxide	tn.lg	731
Nitrogen Oxides	Mtn	1.63×10^3
Nitrogen, atmospheric	Mtn	16.5
NMVOC, non-methane VOC (Volatile Organic Compounds)	Mtn	401
Noble gases, radioactive, unspecified	kBq	5.42×10^{17}
o-Xylene	Kton	7.01
Organic carbon	Kton	1.01
Ozone	Mtn	2.84
PAH, polycyclic aromatic hydrocarbons	Kton	126
Paraffins	tn.lg	144
Particulates, <2.5 um	Mtn	255
Particulates, >10 um	Mtn	235
Particulates, >2.5 um, and <10 um	Mtn	101

3.4. Economic Analysis of Wheelabrator Technologies (WT)

The Economics of Life Cycle Assessment are dominated majorly by the cost and revenue review. Total capital expenditure (i.e., the present value of the investment cost of a particular waste management system); total operation and maintenance costs (that is, costs involved in waste collection and transportation, labor cost, and the costs involved in utilities, operating suppliers, insurance, taxes, etc.); and environmental cost (i.e., monetary value for the environmental emissions) must be incorporated in the LCA economic analysis [24]. It is important to also consider cost in terms of the area MSW processing plants occupy. WT sits on approximately 12 acres of land and can produce electricity along with by-products and co-products. At the waste collection end of the process, another cost appears in the form of handling and management of waste based on consumers and environmental factors. In the case where a consumer disposes of solar panels and glass, waste disposal trucks collect these non-combustibles and dump them on the tipping floor. WT pays for them to be disposed of, thereby impacting the cost structure (i.e., an unexpected cost that normally would not be included in cost analysis but contributes to the overall economics in the sustainability of the plant).

As shown in Figure 3, WT generates revenue from both its fuel source and its outputs. The WTE plant processes 2250 tons of waste daily with electricity generation of about 60 MW/h which powers 40,000 homes in Baltimore. An important aspect of electricity generation from waste is the fact that the heat produced from burning the waste at 2500 °F is used to heat water to produce steam. WT produces 110,000 lbs. of steam per hour and makes about \$4000 daily. The plant also makes revenue from sales of electricity at \$30/MW and charge a tipping fee of \$50/ton of waste collected from the city of Baltimore (with a rebate of \$5 to the Baltimore city waste management and \$7.50 to outsiders). In 2018, 690,000 tons of waste was processed by the plant. Another source of MSW plant revenue generation is the sale of Ferrous and Non-Ferrous metals from the recovery process. About 15,000 tons of metals are recovered yearly from the plant and are sold to buyers majorly in Europe and Asia. The price of metal sales is very unstable and can swing up to +/− 300%. According to the plant manager at WT, the plant was able to sell a ton of metals at \$1500 in 2018, but in 2019, only received \$500/ton. This is all based on forces of demand and supply in the market. In general, the cost of MSW operation is in the form of land cost, Operation and Maintenance costs, environmental costs, fuel costs, and labor costs. The revenue, on the other hand, comes from tipping fees, steam sales, electricity sales, and metal sales. According to the plant manager, about 66% of their revenue comes from the sale of steam.

3.5. Human Health Concerns

Waste incineration systems produce a wide variety of pollutants that are detrimental to human health. Such systems are expensive and do not eliminate or adequately control the toxic emissions from chemically complex MSW. Even new incinerators release toxic metals, dioxins, and acid gases. Far from eliminating the need for a landfill, waste incinerator systems produce toxic ash and other residues. The waste-to-energy program to maximize energy recovery is technologically incompatible with reducing dioxin emissions. Dioxins are the most lethal Persistent Organic Pollutants (POPs) which have irreparable environmental health consequences. Dioxin is a highly toxic compound that may cause cancer and neurological damage, and disrupt reproductive systems, thyroid systems, respiratory systems, etc. [25].

The affected populace includes those living near the incinerator as well as those living in the broader region. People are exposed to toxic compounds in several ways: (1) breathing the air which affects both workers in the plant and people who live nearby; (2) eating locally produced foods or water that have been contaminated by air pollutants from the incinerator; and (3) eating fish or wildlife that have been contaminated by the air emissions. According to the operation manager, WT has been working tremendously on reducing the negative impacts. Through the usage of local waste as a fuel to create a local-energy ecosystem, WT diverts waste from landfills and lowers greenhouse gases by recycling

metals, offsetting the use of fossil fuels, and reducing methane emissions from landfills. As a significant partner in the City of Baltimore's revitalization over 30 years, Wheelabrator has helped the city reduce its carbon footprint while providing Tier 1 renewable energy to tens of thousands of Maryland homes and businesses. Furthermore, it has been a supporter and contributor to several green initiatives within the city.

WT is committed to protecting public health and the environment through the use of a Continuous Emissions Monitoring System (CEMS) being monitored every 10 s. The facilities use advanced environmental control systems to meet and exceed some of the most stringent environmental standards in the world while safely producing clean, renewable energy for nearby homes and businesses. Wheelabrator facilities operate with superior environmental performance and are extensively regulated under state and federal air, water and solid waste laws and regulations to protect human health and the environment. All the WT facilities have maintained their environmental permits without exception, since commencing operations over 40 years ago and continue to perform, on average, four to five times better than standards set by the U.S. Environmental Protection Agency.

3.6. Environmental Achievements of Wheelabrator Technologies in USA

It is a known fact that WT was the first waste-to-energy plant in the U.S. to have a materials recovery facility on site. Wheelabrator Falls was the first and only privately owned, waste-to-energy plant to have a materials recovery facility on site.

Similarly, WT is the first to install advanced air pollution control technology. Wheelabrator Millbury was among the first waste-to-energy facilities in the U.S. to install advanced air pollution control technology designed to control SO₂ and other acid gas under EPA guidance; it has the best available control technology requirements needed to install carbon injection systems. Wheelabrator Falls was the first waste-to-energy facility to install a full-scale powder-activated carbon injection system in the U.S. to improve mercury emission control and to design the most efficient boiler. The WTE plant has the highest temperature and pressure steam conditions of any municipal solid waste-fired boiler in the world.

3.7. Social Concerns

Wheelabrator has been engaged in a tussle with the city of Baltimore and its residents due to environmental concerns majorly from their NO_x emissions. The Wheelabrator plant in Baltimore burns the majority of the city's garbage and is considered its single largest source of industrial air pollution. According to EPA release in 2014, the Baltimore incinerator is the source of so much of the city's pollution—it produced 82 percent of the sulfur dioxide and 64 percent of the nitrogen oxides emitted by smokestacks within city limits in 2014 [26]. Maryland State environmental officials are working with Wheelabrator to reduce the incinerator's emissions stating that a comparable facility in Montgomery County produces less than half as much nitrogen oxide.

In February 2019, the Baltimore Clean Air Act (BCAA) was approved by the city council to checkmate the activities of polluters in the city with Wheelabrator Technologies as number one in the city. The BCAA act requires the incineration plant to install a technology that will reduce the release of NO_x to 45 ppm, much less than the current 150 ppm rate. A non-compliance with this standard will result in non-renewal of the company's license for operation by the end of 2021 [27]. It is no doubt that the city has benefitted greatly from the plant for the past 34 years as MSW generated in the Baltimore environ is being processed by the plant as opposed to being dumped on land. The two landfills in Baltimore are being said to be filled in 5–10 years with the current intake of waste by these facilities. However, shutting down of WT by 2021 will cause these landfills to be filled much earlier than the proposed years. The impact of shutting this facility down has generated certain concerns in the minds of the researchers such as: (1) a safer option for MSW management in the city after WT shutting down; (2) an alternative source of electricity needed by more than 40,000 homes and steam for heating and cooling by over

200 businesses in the city; (3) employment opportunities for the laid-off workers from the plant. One major hypothesis which is yet to be accepted is that the city will effectively manage its waste after shutting down the incineration plant.

4. Conclusions

In this study, the life cycle analysis of the MSW incineration plant in Baltimore city (Wheelabrator Technologies) was performed to determine its sustainability impacts using Simapro software with a database from BEES, EPA 1997 for correlation with the Municipal waste/NL S demo7 scenario. The data obtained upon analysis show larger values of GWP and eutrophication potential as 6.46×10^8 Gg of CO₂ equivalence and 2.27×10^6 Gg N equivalence, respectively. These values resulted from the higher amount of fossil CO₂ and NO_x emitted from the plant. The acidification potential of 1.66×10^{17} H⁺ mmole eq is of less impact since the company complies with the state and federal regulations on SO₂ emission. Wheelabrator Technologies has benefitted the city of Baltimore since inception to date in terms of waste processing, resulting in electricity and steam production for more than 40,000 homes and over 200 businesses. Without this facility, the landfills in Baltimore might have been filled by now, thereby causing the city of Baltimore to spend more money to transport the waste to far away landfills in neighboring states. This result of this study could serve as a benchmark and a baseline for developing and implementing a suitable policy framework for solid waste disposal in Baltimore.

The economic analysis of this study was limited due to the insufficient data obtained from the company; this will be addressed in the future studies. Similarly, research findings will be extended to another MSW incineration plant in Maryland for a comparative study with Baltimore plant.

Author Contributions: This research project was conducted by S.O.A., A.W., and T.T. in fulfillment of the sustainability course requirement while G.O. served as the course instructor and the professor in charge. S.O.A., A.W., and T.T. developed the research methodology, planned, and visited the study area for data collection. S.O.A. performed the LCA analysis using SimaPro, discussed the environmental assessment, and the social concerns, A.W. discussed the economic analysis, and T.T. discussed the Health concerns. S.O.A. wrote the draft manuscript, and G.O. reviewed and provided some comments to improve the quality of the manuscript. S.O.A. made corrections received from the reviewers, and G.O. reviewed the corrections prior to submission. All authors have read and agreed to the published version of the manuscript.

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References

1. Brundtland, G.H.; World Commission on Environment and Development. *Presentation of the Report of the World Commission on Environment and Development to the Commission of the European Communities, the EC and EFTA Countries...* 5 May 1987, Brussels; World Commission on Environment and Development: Rio de Janeiro, Brazil, 1987.
2. Maplecroft, V. Waste Generation and Recycling Indices 2019. 2019. Available online: https://www.circularonline.co.uk/wpcontent/uploads/2019/07/Verisk_Maplecroft_Waste_Generation_Index_Overview_2019.pdf (accessed on 15 October 2020).
3. Environmental Protection Agency. *Advancing Sustainable Materials Management: 2015 Fact Sheet: Assessing Trends in Material Generation, Recycling, Composting, Combustion With Energy Recovery and Landfilling in the United States*; Environmental Protection Agency: Washington, DC, USA, 2018.
4. Wang, T. Generation of Municipal Solid Waste Worldwide in 2017, by Select Country (in Million Metric Tons). 2018. Available online: <https://www.statista.com/statistics/916749/global-generation-of-municipal-solid-waste-by-country/> (accessed on 15 October 2020).
5. U.S. Energy Information Administration—EIA—Biomass Explained: Waste-to-Energy (Municipal Solid Waste). 30 November 2020. Available online: <https://www.eia.gov/energyexplained/biomass/waste-to-energy.php> (accessed on 15 January 2021).

6. U.S. Energy Information Administration—EIA—Independent Statistics and Analysis. 8 April 2016. Available online: <https://www.eia.gov/todayinenergy/detail.php?id=25732> (accessed on 15 January 2021).
7. Greenwalt, M. Global WTE Industry to Reach \$37.6B by 2020. 6 April 2016. Available online: <https://www.waste360.com/waste-energy/global-wte-industry-reach-376b-2020> (accessed on 25 November 2020).
8. EIA. Biomass Explained. Waste-to-Energy (Municipal Solid Waste). 2019. Available online: <https://www.eia.gov/energyexplained/biomass/waste-to-energy.php/> (accessed on 15 October 2020).
9. O'Malley, M.; Brown, G.A.; Governor, L. *Zero Waste Maryland. Maryland's Plan to Reduce, Reuse and Recycle*; Department of the Environment: Baltimore, MD, USA, 2014.
10. O'Malley, M.; Brown, G.A.; Governor, L. *Maryland Solid Waste Management and Diversion Report*; Department of the Environment: Baltimore, MD, USA, 2019.
11. International Energy Agency (IEA). Tracking Clean Energy Progress. 2019. Available online: www.iea.org/tcep/industry/ (accessed on 15 September 2020).
12. Ashworth, D.C.; Elliott, P.; Toledano, M.B. Waste incineration and adverse birth and neonatal outcomes: A systematic review. *Environ. Int.* **2014**, *69*, 120–132. [[CrossRef](#)] [[PubMed](#)]
13. Den Boer, J.; den Boer, E.; Jager, J. LCA-IWM: A decision support tool for sustainability assessment of waste management systems. *Waste Manag.* **2007**, *27*, 1032–1045. [[CrossRef](#)] [[PubMed](#)]
14. Rebitzer, G.; Ekvall, T.; Frischknecht, R.; Hunkeler, D.; Norris, G.; Rydberg, T.; Schmidt, W.T.; Suh, S.; Weidema, B.P.; Pennington, A.W. Life cycle assessment—Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environ. Int.* **2004**, *30*, 701–720. [[CrossRef](#)] [[PubMed](#)]
15. Winkler, J.; Bilitewski, B. Comparative evaluation of life cycle assessment models for solid waste management. *Waste Manag.* **2007**, *27*, 1021–1031. [[CrossRef](#)] [[PubMed](#)]
16. Guereca, L.P.; Gassó, S.; Baldasano, J.M.; Jiménez-Guerrero, P. Life cycle assessment of two biowaste management systems for Barcelona, Spain. *Resour. Conserv. Recycl.* **2006**, *49*, 32–48. [[CrossRef](#)]
17. Fedkin, M. Life Cycle Assessment (LCA) Methodology. Available online: <https://www.e-education.psu.edu/eme807/node/690> (accessed on 7 January 2021).
18. Baniyas, G.; Batsioulas, M.; Achillas, C.; Patsios, S.I.; Kontogiannopoulos, K.N.; Bochtis, D.; Moussiopoulos, N. A Life Cycle Analysis Approach for the Evaluation of Municipal Solid Waste Management Practices: The Case Study of the Region of Central Macedonia, Greece. *Sustainability* **2020**, *12*, 8221. [[CrossRef](#)]
19. BEES Software from NIST. 11 August 2016. Available online: <https://www.greenbuildingsolutions.org/life-cycle-assessment/bees-national-institute-of-standards-and-technology/> (accessed on 13 January 2021).
20. Švajlenka, J.; Kozlovská, M.; Pošiváková, T. Analysis of selected building constructions used in industrial construction in terms of sustainability benefits. *Sustainability* **2018**, *10*, 4394. [[CrossRef](#)]
21. La Rosa, A.D. Life cycle assessment of biopolymers. In *Biopolymers and Biotech Admixtures for Eco-Efficient Construction Materials*; Woodhead Publishing: Cambridge, UK, 2016; pp. 57–78.
22. Assamoi, B.; Lawryshyn, Y. The environmental comparison of landfilling vs. incineration of MSW accounting for waste diversion. *Waste Manag.* **2012**, *32*, 1019–1030. [[CrossRef](#)] [[PubMed](#)]
23. Aye, L.; Widjaya, E.P. Environmental and economic analyses of waste disposal options for traditional markets in Indonesia. *Waste Manag.* **2006**, *26*, 1180–1191. [[CrossRef](#)] [[PubMed](#)]
24. Menikpura, S.N.M.; Gheewala, S.H.; Bonnet, S. Sustainability assessment of municipal solid waste management in Sri Lanka: Problems and prospects. *J. Mater. Cycles Waste Manag.* **2012**, *14*, 181–192. [[CrossRef](#)]
25. World Health Organization. Dioxins and Their Effects on Human Health. Available online: <https://www.who.int/news-room/fact-sheets/detail/dioxins-and-their-effects-on-human-health> (accessed on 27 November 2020).
26. Dance, S. How a Trash Incinerator—Baltimore's Biggest Polluter—Became 'Green' Energy. 15 December 2017. Available online: <https://www.baltimoresun.com/news/environment/bs-md-trash-incineration-20171107-story.html> (accessed on 13 January 2021).
27. Clean Air Baltimore: A Campaign to Replace Waste Incineration with Zero-Waste Jobs. 2019. Available online: <https://www.cleanairbmore.org/wheelabrator/lies/> (accessed on 15 September 2020).