Development of Waste Management Systems: Applications of Durham Region

By

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A thesis submitted to the
School of Graduate and Postdoctoral Studies in partial
fulfillment of the requirements for the degree of

Master of Applied Science in Mechanical Engineering

Faculty of Engineering and Applied Sience

University of Ontario Institute of Technology (Ontario Tech University)

Oshawa, Ontario, Canada

August 2021

Thesis Examination Information

Submitted by: Bogachan Gungor

Master of Applied Science in Mechanical Engineering

Thesis title: Development of Waste Management Systems: Applications of Durham Region

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Abstract

This thesis aims to reduce environmental impacts and increase overall efficiencies of domestic waste management systems by proposing case studies for Durham Region. Case study 1 integrates an anaerobic digestion facility with an incinerator to produce biogas and electricity. Case study 2 combines a gasification unit with an anaerobic digestion to generate biogas, syngas, and electricity. Case study 3 uses a pyrolysis unit for biogas, gasoline, and electricity. Diesel and alternative-fueled trucks are also compared based on their environmental impacts. According to the results, case study 2 is observed to be the most sustainable case with the highest energy and exergy efficiencies, 58.7% and 56.8%, the lowest global warming potential, 0.167 kgCO_2 eq, and a competitive levelized cost of 0.23$/kWh. Electric fueled trucks have better overall environmental impacts with the least in global warming, ozone depletion, and acidification potential with 3.92E-05 kgCO_2 eq, 5.57E-12 kgCFC-11 eq and 2.19E-07 kgSO_2 eq.

Keywords: sustainable community; waste to energy; circular waste management; exergy; life cycle assessment

Author's Declaration

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Statement of Contributions

I hereby certify that I am the sole author of this thesis and that no part of this thesis has been published or submitted for publication. I have used standard referencing practices to acknowledge ideas, research techniques, or other materials that belong to others. Furthermore, I hereby certify that I am the sole source of the creative works and/or inventive knowledge described in this thesis.

Acknowledgements

First and foremost, I would like to thank my supervisor Dr. Ibrahim Dincer for his continuous support throughout my time at Ontario Tech University. Dr. Ibrahim Dincer has provided a supportive environment, he is always willing to help his students and has provided me with endless wisdom during my journey in this Master's Program. Again, I would like to express my gratitude to him for showing me the right path and giving me a bright future as an Engineer. I would also like to thank Durham Region for providing me with all the data and technical support needed to complete my comprehensive analysis within this thesis. I would like to say a special thank you to O'Neil Wright who spend many hours guiding me and providing the necessary information to be able to finish my thesis. Finally, I am truly grateful of all the emotional support and encouragement my Wife and the rest of the family provided me throughout my Master's Program. I would like to thank my Wife, Brittany, my mother, and father Sibel and Adnan, and my in-laws Sandra and Chris, for everything they have done. I dedicate this thesis to my wife, my mother and my father who are the most important people I have.

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Nomenclature

$\dot{E}x_{dest}$	exergy destruction rate (kW)
$\dot{S}_{gen}$	specific entropy generation rate (kW/K)
ex_{CH}	standard chemical exergy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
$\dot{Q}$	heat rate (kW)
$\dot{W}$	work rate (kW)
CE	chemical exergy (kJ/kg)
E	total energy (kJ)
ex	specific exergy (kJ/kg)
G	Gibbs free energy (J)
g	gravitational acceleration constant (m/s^2)
h	specific enthalpy (kJ/kg)
HHV	higher heating value (kJ)
LHV	lower heating value (kJ)
m	mass (kg)
$\dot{N}$	molar flow rate (mol/s)
P	pressure (kPa)
s	specific entropy (kJ/kg K)
T	temperature (^oC)
V	velocity (m/s)
wt	weight (%)
yr	year
Z	height (m)

Greek letters

η	energy efficiency
ρ	density
ψ	exergy efficiency
σ	ionic conductivity

Subscripts

PO_4^{3-}	Phosphate
SO_4^{2-}	Sulfate
1,4 DB	1,4 Dichlorobenzene
AD	anaerobic digestion
ADP	abiotic depletion potential
AP	acidification potential
B	boiler
BG	biogas
C	Carbon
CFC-11	Trichlorofluoromethane
CH_4	Methane
Cl	Chlorine
CML	Center of Environmental of Leiden University
CNG	compressed natural gas
CO_2	Carbon dioxide
CU	composting unit
DRC	Durham Recycling Center
DS	dry solid

DYEC	Durham York Energy Center
EES	Engineering Equation Solver
EP	eutrophication potential
eq	equivalent
Et	annual electricity generation
EV	expansion valve
E-waste	electronic waste
Ft	annual fuel expenditures
G	gasifier
GCU	gas cleaning unit
GHG	green house gas
GN	gasoline range pyrolysis oil
GWP	global warming potential
GWP100	global warming potential for time horizon 100 years
H	Elemental Hydrogen
H_2O	water
HDPE	high-density polyethylene
HEX	heat exchanger
HHW	hazardous waste
HR	heat recovery heat exchangers
HTP	human toxicity potential
IA	impact assessment
IGCC	integrated gasification combined cycle
In	inlet

IPCC	Intergovernmental Panel on Climate Change
It	annual investment expenditures
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
LCOE	levelized cost of electricity generation
LDCs	least developed countries
LTP	lower temperature pyrolysis
MBP	mechanical-biological pre-treatments
MBT	mechanical biological treatment
MHSW	municipal hazardous solid waste
MRF	material recovery facility
MSW	municipal solid waste
Mt	annual operation and maintenance expenditures
MW	Miller Waste
MWC	Miller Waste Clarington
MWM	municipal waste management
MWP	Miller Waste Pebblestone
n	economic life of the system
N	Elemental Nitrogen
N_2	Dinitrogen
NG	natural gas
NH_3	Ammonia
O	Elemental Oxygen

O_2	Oxygen
ODP	ozone layer depletion potential
OM	organic matter
P	pump
PET	Polyethylene terephthalate
POP	photochemical oxidation
PR	pyrolysis
r	discount rate
RDF	refuse-derived fuel
RK-SOAVE	Redlich-Kwong-Soave
S	Sulfur
SB eq	Antimony equivalent
SG	syngas
SO_2	Sulfur dioxide
ST	steam turbine
UV-B	Ultraviolet B
VCC	hydrogenation reactor
WEE	waste electric and electronic
WGSR	water-gas shift reactor
WMC	Waste Management of Canada
WMF	waste management facility
WMO	World Meteorological Organization
WtE	waste-to-energy
Xmas	Christmas

Chapter 1: Introduction

1.1 Current Waste Management Crisis

On average humans dump over 2 billion tonnes of waste on the planet each year, this is equivalent to dump trunks revolving around the world over 24 times. Global waste generation has been increasing each year and is set to increase about 70% by 2050 (The World Counts, 2020) (Gautam & Agrawal, 2021). Improper waste management can lead to many negative consequences for the environment including soil pollution, air pollution, aquatic pollution, and agriculture pollution. Inadequate waste management methods are one of the leading contributors to emitting greenhouse gas (GHG) due to methane production mainly from landfills and other current outdated waste management technologies (Powell et al., 2018).

In developed countries more the 50% of the municipal solid waste (MSW) is mismanaged and ends up in open burning or landfilling applications as a final waste disposal method, which contributes to about 5% of the global greenhouse gas emission in the atmosphere. This results in negative environmental impacts on living organisms and materials (Gautam & Agrawal, 2021). Furthermore, developed countries are using outdated CH_4 global warming values and inadequate waste management data values which together causes these countries to undervalue the significance current waste management technologies have on greenhouse gas emissions and negative effects on the environment (Powell et al., 2018).

In the least developed countries (LDCs) the waste management crisis is more severe due to their inability to apply proper waste management technologies. Municipal solid waste mostly consists of organics, 52%, and recycles, 26% and these wastes are mismanaged by illegal dumping and open burning applications due to the insufficient waste collection services in LDCs. Due to the lack of government funding and policies and environmental public awareness, the current waste management methods are not properly handled which in turn has a negative environmental impact and low waste utilization (Bundhoo, 2018).

In Canada, about 97% of waste's final disposal goes into landfills and the other 3% goes to incineration (Municipal Solid Waste Management, 2021). On average about 64%

of waste which is disposed in Canadian landfills each year is degradable and has the potential to be recovered and reused to create useful outputs such as energy, fertilization, etc. Figure 1.1 shows the yearly average amount of residual waste in Canada, as seen in the figure items such as wood paper and food which are usually disposed in landfills can be recovered and reused to create more cradle to cradle circular waste management methods (ECCC, 2020).

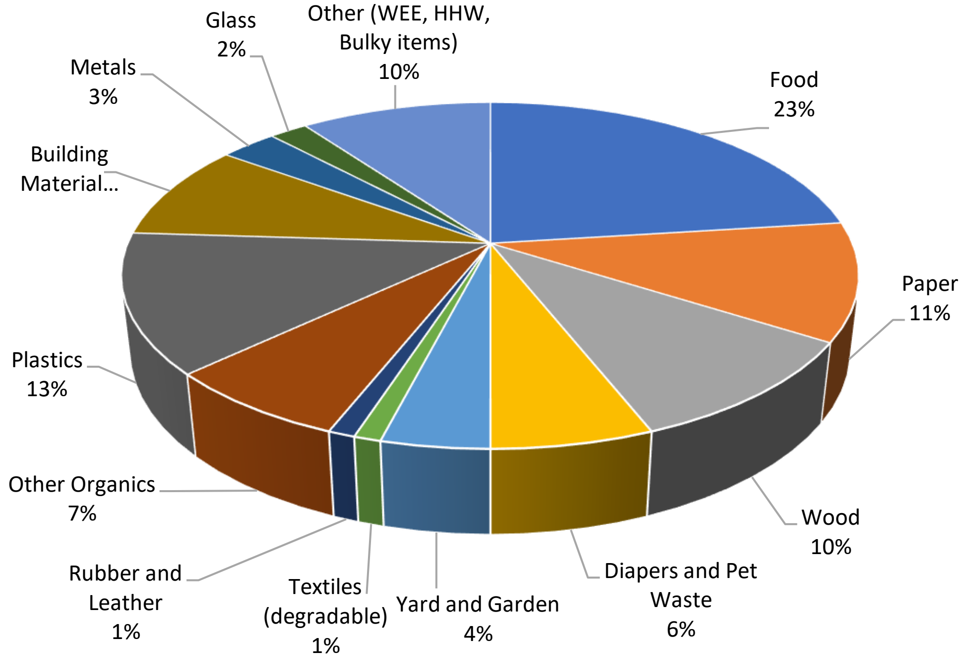

Figure 1.1: Canadas average amount of residual waste disposed in landfills yearly (Data from ECCC (2020))

1.2 Current Waste Management Approaches in Canada

In this section, current waste management approaches and strategies in Canada are discussed in detail and categorized in five subsections: landfilling, incineration and thermal treatment, organic waste, e-waste, and recyclables.

1.2.1 Landfill Applications

In Canada, landfilling and incineration are the two most common methods for waste management. Landfilling is the main waste management method used for municipal waste disposal. Modern landfills try and reduce environmental impact by collecting and treating leachate, wastewater for rainfall, as well as capture greenhouse gases to reduce the greenhouse effect from landfilling. Landfill gas can be captured and reused to produce useful outputs such as generating electricity, heating, and fuel resources. By recovering and reusing these landfill gases we are reducing the amount of greenhouse gas, such as methane, from entering the earth’s atmosphere as well as reducing the number of fossil fuels needed to produce electricity for society (Municipal Solid Waste Management, 2021).

1.2.2 Incineration and Thermal Treatment Applications

Incineration is the next major waste method used in Canada, there are different types of incinerators used including waste to energy facilities, wastewater sludge incinerators, hazardous waste (HHW) incinerators, and biomedical incinerators. Incinerators are beneficial to use as they can reduce up to 90% of waste volume compared to landfilling as well as technologies can be put into place to reduce the greenhouse gases and toxins that can be produced when using incineration (Municipal Solid Waste Management, 2021). Incineration technologies are traditionally indicated as waste to energy systems. However, with the growing need to find ways to produce green energy and minimize waste production, bioeconomy has become an important topic regarding waste-to-energy systems (Tsui & Wong, 2019) One method that has become popular for waste to energy utilization is the re-utilization of food waste as organics within the frame of bioeconomy. Organic waste can be used as a feedstock to generate useful outputs such as electricity, heat, cooling, and waste-derived fuel. Some waste treatment technologies that utilize organics include composting, anaerobic digestion (AD), fermentation or bioprocessing and thermochemical conversion technologies (combustion, gasification, pyrolysis (PR), and hydrothermal carbonization). The above methods for waste management allow for a reduction in negative environmental impact and the creation of a circular economy (Melikoglu, 2020)

1.2.3 Management of Organic Waste

Every year Ontario generates over 12 million tonnes of municipal solid waste with over ¾ of this waste sent to disposal and approximately 30% of these municipal solid wastes contain organics that can re-utilized. Canada has started to invest in waste management technologies to help reduce, recover, and reuse waste to create a more circular economy. A circular waste management approach for organics can be implemented by reducing organic waste generation, reusing organic waste, recycling organics, and recovering energy through composting and digesting applications (Perger, 2019). Figure 1.2 shows the current waste management policy to help reduce greenhouse gas emissions and create a more circular economy where the cradle-to-cradle approach is adapted rather than the traditional cradle-to-grave approach (Municipal Solid Waste Management, 2021). By implementing this hierarchy, organic waste can be reused to reduce transporting and disposing applications which in turn decreases greenhouse gas emissions. Useful outputs can be derived in the form of biogas, electricity, heat, and cooling from the utilization of organics, and this can result in less fossil fuel-based energy resources consumption (Perger, 2019).

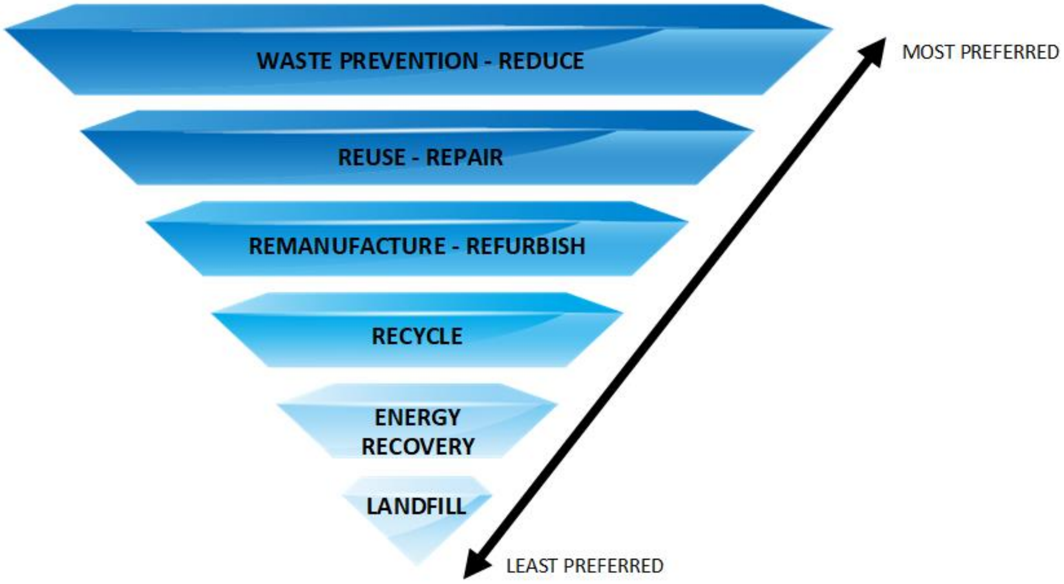

Figure 1.2: Waste Hierarchy in Canada (Data from Municipal Solid Waste Management (2021))

1.2.4 Management of E-Waste

E-waste is one of the important waste types which can be refurbished, re-manufactured, and recycled into the economy. The management of e-waste is significant as it can contain hazardous material which can cause negative outcomes for the environment as well as human health if not managed correctly. In Canada, about 20% of Canadians have e-waste in their homes which are not properly disposed of and not regained back into the economy. This is due to the lack of public awareness of where they can properly dispose of these e-wastes and the lack of availability of e-waste centers within their community (Xavier et al., 2021) Canada has implemented electronic product recycling policies to increase awareness of the need to recycle e-waste properly as well as improve the e-waste collection in municipalities. It is important to implement these regulations to decrease possible negative environmental impacts caused by the management of the e-waste (Municipal Solid Waste Management, 2021).

1.2.5 Management of Recyclables

Another way to decrease greenhouse gas emissions is to increase the recycling rate in material recovery facilities where plastics, newspapers, cardboard, and other marketable recyclables are separated and utilized to have an economical advantage. Currently, about 95% of plastics are single-use products and due to insufficient recovery and recycling of these materials only 14% of these plastics are recycled. Moreover, approximately 8 million tonnes of plastic waste end up in the oceans globally causing a negative environmental impact on living marine organisms. The hierarchy methodology mentioned above can be implemented in the management of plastics waste recovery to create a circular economy. Canada aims at reducing plastic waste by implementing a zero-plastics waste strategy across the country. This strategy focuses on containing all plastics in the economy and minimizing the number of plastics entering the environment. This can be achieved by prevention of plastic waste accumulation, collecting, and cleaning all existing plastic waste, and recovering and reusing plastic waste. Figure 1.3 demonstrates the integrated strategy for a circular plastics economy in Canada (CCME, 2018).

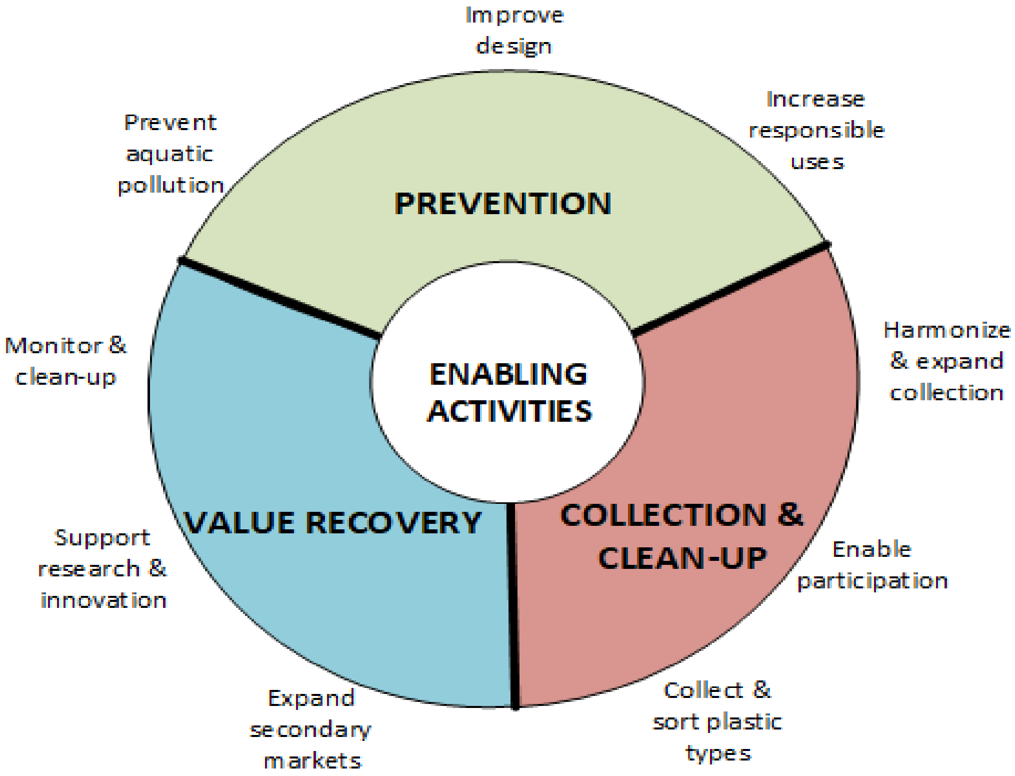

Figure 1.3: Zero Plastics Waste Integrated Strategy in Canada (Data from CCME (2018))

1.3 Current Domestic Solid Waste Management and Composition in Durham Region

In Durham Region, approximately 241619 tonnes of municipal solid waste were generated in the year 2020. The composition of the domestic waste consisted of black bag garbage, green bin, blue bin, other organics, hazardous waste, and others.

Black bag garbage accounted for approximately 64% of the total domestic waste generated. 88% of black bag garbage generated within Durham Region was sent to the municipal incinerator which is located in Courtice for final disposal and energy recovery while the remaining 12% was sent to landfilling as by-pass waste.

Green bins which consist of domestic food waste, from single-residential houses, are sent to industrial composting facilities which are located in Pickering, Clarington, and Whitby for compost production. Other organics which consist of yard waste and Christmas trees are also sent to the industrial composting facilities along with green bins. The total organics produced within the region was responsible for approximately 26% of total domestic waste generated in 2020.

Blue bins which consist of marketable recyclables and non-favorable recyclables are sent to Durham Region Material Recovery Facility which is located in Whitby. In 2020, approximately 98% of this waste composition was regained into the economy and the garbage residue was sent to the municipal incinerator for further energy recovery. Furthermore, the total blue bin recyclables collected in this material recovery were observed to be about 19% of the total domestic solid waste generated in the region.

Hazardous waste was collected in waste management and hazardous waste management facilities which are located in Oshawa, Scugog, Brock, Pickering, and Clarington. This waste was then transferred to a third-party organization for its management. In 2020, about 317 tonnes of other waste which includes e-waste, batteries, and porcelain were collected under the recycling program in Durham Recycling Center to be sorted and regained into the economy.

1.4 LCA of Waste Management Technologies

Implementing proper and site-specific waste management technologies into the existing waste management plans has recently become an attractive environmental solution to create a circular economy. This can be achieved by adopting a cradle-to-cradle approach over the traditional, cradle-to-grave, waste management approach. Life cycle assessment (LCA) is an environmental decision-making technique that is standardized according to ISO 14040. LCA has become a widely used tool to investigate environmental impacts of a product, a process, or an activity according to selected environmental impact categories as a result of increased environmental awareness on the public, industry, and government side (Iqbal et al., 2020) (Muralikrishna & Manickam, 2017). LCA is used to investigate the environmental impact of the existing waste management technologies and demonstrate environmental opportunities by implementing site-specific waste management technologies. There is a number of studies completed that show the importance of LCA, chapter 3 discusses these studies in a comprehensive literature review.

1.5 Motivation

Each year about 2 billion tonnes of waste is produced, and this waste is set to increase up to 70% by 2050. Waste that is not effectively managed can have a negative environmental impact on living organisms and materials. This can result in air, soil, aquatic, and agriculture pollution which can be costly to the economy to recover. Furthermore, using site-specific technologies and waste management methods are significant to reduce greenhouse gas emissions caused by improper waste management applications (Powell et al., 2018) (Gautam & Agrawal, 2021). Environmental awareness should be increased in the public to create a sustainable economy and prevent negative environmental impacts. It was reported that all countries, regardless of their income class, showed an insufficiency in waste collection and management with least developed countries less than 50%, middle-income countries 50-80%, and developed countries about 90% of their waste collected properly. The increase in the population resulted in the shortage of landfill space and the need for integrated waste management technologies where the waste is used as a source to generate useful outputs such as electricity, heat, cooling, and hydrogen (Debrah et al., 2021).

Circular waste management has become more attractive and important in response to the growing waste management, global warming, and energy crisis seen in the world today. This can be achieved by implementing integrated solid waste management systems where useful outputs are generated through the utilization of solid waste. These technologies can be further improved by integrating renewable energy resources into existing waste management systems. The 3R principle, reduce, reuse, and recycle, has become an essential approach to creating a more circular economy when it comes to waste management systems. By integrating this approach into the existing systems self-sustainability can be achieved in the community and environmental risks can be mitigated (Asefi et al., 2020) (Das et al., 2019).

Waste can be utilized as a source to generate useful outputs to create a circular economy. This can be achieved by conducting LCA and integrating energy systems into the existing waste management technologies. The following facts reflect the importance of this study:

- More sustainable communities can be created by using site-specific data through LCA.
- The environmental burden generated by the traditional waste management systems can be decreased by completing LCA and integrating waste-to-energy (WtE) systems.
- The vast amount of energy consumption and GHG emission is caused by the transportation of waste therefore optimization of waste transportation can be completed by conducting LCA.
- Integrated waste management technologies, where the cradle-to-cradle approach is used, are significant to decrease GHG emissions and recover energy to create a sustainable community.
- Energy systems should be integrated with waste management technologies for further material and energy recovery.

1.6 Scope and Objectives of the Study

Durham Region aims to create a circular economy within the region as a response to the rise in global warming. In this study, a comprehensive LCA of Durham Region’s existing waste management system and possible improvement case studies are considered. This study focuses on ways to reduce greenhouse gas emissions caused by the waste collection, transportation, management, and treatment within the region. This study includes waste management activities through 3rd party organizations and residential visits to regional waste management facilities. Furthermore, GHG emissions and environmental impact assessment are quantified for Durham York Energy Center (DYEC) and closed landfills within the region. For this study, the CML-IA method has been selected to complete the LCA of Durham Region. Furthermore, SimaPro software is used to perform the life cycle impact analysis of the study.

The primary objective of this study is to complete a comprehensive LCA of the existing municipal waste management (MWM) and discuss possible improvement case studies of how to decrease greenhouse gas emissions within the region. The specific objectives are listed as follows:

1. To develop three different waste-to-energy systems where solid waste is utilized into more useful outputs such as energy, domestic hot water and, hydrogen-enriched syngas, biogas, gasoline, fuel-gas, and off-gas.
2. To propose these integrated waste-to-energy systems for the existing waste management system in Durham Region where mainly incineration and composting processes are used for energy recovery.
3. To investigate the proposed waste-to-energy systems feasibility realistically by conducting a comparative thermodynamic analysis to improve the existing waste management system's energy and exergy efficiencies.
4. To conduct a comprehensive life cycle assessment for these integrated systems and compare them with the base case study.
5. To propose alternative-fueled garbage trucks such as compressed natural gas, electricity, and hydrogen-fueled trucks for the existing waste collection and transportation services in Durham Region where the diesel-fueled garbage trucks are used.
6. To complete a comparative life cycle assessment of these alternative-fueled garbage trucks and compare with the existing diesel fueled garbage trucks for a possible reduction in environmental impacts caused by waste collection and transportation.

Chapter 2: Literature Review

In this chapter, a comprehensive literature review was completed to determine the traditional waste management systems, integrated waste management systems, and advanced WtE technologies applied in various cities in the world. LCA was used as a methodology to evaluate the current technologies used in these cities and possible future development case studies for these existing waste management systems. In this literature review, life cycle analysis of 22 cities' waste management plans and WtE technologies were assessed according to environmental impact categories and were summarized in Sections 2.1, 2.2, and 2.3.

2.1 Traditional Waste Management Methods and Improvement Case Studies

In this section, the cities where the traditional waste management plan was mainly used, are taken into account to investigate the environmental impacts and benefits of these cities' existing systems via conducting a life cycle assessment. Furthermore, various improvement case studies were considered to create a circular economy, where the cradle-to-cradle approach is aimed instead of the cradle-to-graveyard approach by integrating robust waste management systems (Malinauskaite et al., 2017).

Nabavi-Pelesaraei et al. aimed to assess the energy consumption and environmental impacts of the existing waste management system in Tehran, Iran by using site-specific data. The model analyzed includes collecting and transportation, incineration, and landfill processes. The results of this study show that the vast amount of energy consumption, which was approximately 80%, was due to the transportation of the waste between facilities. According to the LCA results, the incinerator was found to be more environmentally friendly technology compared to landfilling applications. However, Nabavi-Pelesaraei et al. stated that the GHG emissions can be reduced by integrating gas engines into the landfill for further energy utilization which would allow landfills to become more environmentally friendly (Nabavi-Pelesaraei et al., 2017).

Yadav and Samadder conducted an LCA analysis to investigate possible improvements in the existing waste management technologies in Dhanbad City, India. The base waste management case study, which is the current waste management plan, consisted of recycling, open burning, open dumping, and landfilling without energy recovery. This base case study was compared to other case studies where composting, recycling, and landfilling were integrated into the existing system. The existing waste management plan was found to have the highest environmental impact when compared to other case studies according to the following impact categories: global warming potential (GWP), photochemical oxidation potential (POP), acidification potential (AP), and eutrophication potential (EP). The case study where municipal solid waste was separated, recycled and the organic fraction of MSW was sent to composting resulted in the least environmental impact. This study concluded that the current environmental practice in waste management in Dhanbad City is not sustainable and sufficient (Yadav & Samadder, 2018).

Hadzic et al. aimed to improve existing municipal solid-waste management systems in Zagreb, Croatia and analyzed two waste management case studies. The first case study was the use of the traditional waste management system where approximately 94% of residual waste was transported to landfills for final disposal and energy was recovered through landfill gases. The rest of the recyclables were sent to recycling facilities. The second case study consisted of the integration of mechanical sorting, thermal treatment, and anaerobic digestion units into the existing waste management system to create a circular economy for Zagreb, Croatia. In this case study, energy was recovered through the thermal treatment and anaerobic digestion processes and calculated to be 5076MJ while in the first case study, this value was 472MJ. The environmental impacts of both systems were analyzed by using an LCA method and the integrated system, second case study, was determined to have significantly less environmental impact than the existing waste management system as the waste load of landfills was decreased to less than 4% and the waste was further utilized in the anerobic digestion and thermal treatment units (Hadzic et al., 2018).

Belboom et al. conducted an LCA to improve the existing solid management systems in Liege, Belgium by using site specific data for that region. Four different case studies were considered in this paper, these case studies included: the fractions of landfilling, incineration, and anaerobic digestions processes. The base case study assumed that all the waste was sent to a sanitary landfill for final disposal and the rest of the case studies were compared to this base case study. The fourth case study, where organics was collected separately and treated in anaerobic digestion and the residue was incinerated, had the least environmental impact in terms of climate change and particulate matter formation. Furthermore, the overall results show that greenhouse gas emissions emitted can be decreased by approximately 46% when using integrated waste management systems (Belboom et al., 2013).

Liikanen et al. conducted an LCA to gradually decrease loads of landfills by analyzing various case studies for Sao Paulo, Brazil. In this model, anaerobic digestion, mechanical biological treatment (MBT), and refuse-derived fuel (RDF) waste management methods were implemented into the existing waste management plan where all MSW were transported to landfills for final disposal. When RDF was utilized in cement production rather than in the incineration process, global warming potential and acidification potential were calculated to be lower. Furthermore, when organics were collected, separated, and utilized in AD rather than in composting units (CU), GWP and AP were also reported to be lower (Liikanen et al., 2018).

Silva et al. also completed an LCA to improve the existing waste management which mostly relies on landfilling as final disposal for Brasilia, Brazil. In this study, four case studies were considered three focusing on integrating RDF into the existing waste management system with various fractions and one case study only landfilling application. The existing case included: landfill, recycling, and composting. According to the results of this study, the case studies where RDF was integrated, energy recovery ratio was concluded to be higher compared to the base case study. Furthermore, the existing waste management system was calculated to have approximately 14% less GHG emissions compared to the case study where all MSW was sent to landfills for final disposal. By integrating RDF into the existing MSW system, GHG emissions were decreased by about 2-23% according to the different fractions (Silva et al., 2021).

2.2 Integrated Waste Management Methods and Improvement Case Studies

In this section, integrated waste management technologies, possible improvements of the integrated systems, and the cities where these integrated systems were implemented are mentioned. To create a sustainable environment, using the most relevant technologies, which meet society's needs, is significant (Dincer & Acar, 2017). LCA was used as a methodology to assess the environmental impacts of integrated waste management systems and improve the existing systems by considering city-specific technologies.

Yay conducted a life cycle assessment for municipal solid waste management for Sakarya, Turkey, and investigated the environmental impacts of municipal solid waste management systems in various case studies. The solid waste management systems analyzed in this study included: Collection and transportation of MSW, material recovery, incineration, composting, and landfilling. The data gathered was assessed according to CML-IA method which consists of abiotic depletion, abiotic depletion (fossil fuels), acidification, global warming, ozone depletion, human toxicity, freshwater aquatic toxicity, marine aquatic toxicity, terrestrial ecotoxicity, and photochemical oxidation. Yay stated that landfilling and incineration of MSW were the least environmentally friendly while composting and material recovery systems were determined to have less environmental impact in the above waste management systems. In a case study in which the above systems were integrated into a waste management strategy holistically, the environmental impacts were calculated to be the lowest compared to the other case studies considered within this study (Erses Yay, 2015).

In a study conducted by Liikanen et al. two cities, South Karelia, Finland, and Hangzhou, China using mixed MSW management systems were compared using LCA analysis. This study looked at the following environmental impact categories: GWP, AP, and EP, to investigate possible improvements for the compared cities' waste management systems. South Karelia, Finland's waste management plans were mainly based on incineration and landfilling applications while Hangzhou, China's waste management plan consisted of mechanical treatment, incineration, anaerobic digestion, bio-drying, and ethanol production. For South Karelia, incineration was found to be the most environmentally friendly compared to landfills in all impact categories due to energy utilization in incineration. When analyzing Hangzhou's waste management systems, the case studies where AD and ethanol production was integrated, it was reported to have the least environmental impact in all impact categories (Liikanen et al., 2017).

In a study completed by Mikiute and Staniskis, an LCA analysis was completed to optimize existing municipal waste management systems ecologically in Alytus, Lithuania.

The waste treatment methods analyzed in this study included: landfilling, incineration, material recovery facility (MRF), MBT, anaerobic digestion, and home composting. The energy was recovered through the utilization of landfill gases, incinerated waste, and biogas in AD. Furthermore, marketable recyclables were also separated through MRF. Five different case studies were considered within this study and compared to the base case where most of the municipal solid waste was sent to a landfill for final disposal. According to the results of this study, expectedly, GWP was found to be higher in the case studies where the landfill was the main disposal method. In the other case studies where the above systems were integrated, GHG emissions were reported to be high due to the transportation needed between facilities. However, the environmental impact was mostly compensated through the environmental benefits of these integrated systems. Mikiute and Staniskis concluded that the incineration option can be more environmentally friendly than composting and landfilling applications (Miliute & Kazimieras Staniškis, 2010).

Zhou et al. completed an LCA study to evaluate the environmental performance of the existing municipal solid waste management system in Hangzhou, China. These existing waste management systems include landfills, incineration, anerobic digestion, and separated collection of marketable recyclables. The results of this study showed that incineration had a better environmental impact and more energy production when compared to landfilling applications. Landfills had the highest GWP, and POP compared to all other case studies, while AD had the most environmentally friendly technology. In addition, Zhou et al recommended the integration of anaerobic digestion process into the existing waste management plan for food waste treatment for Hangzhou, China. The results of this study show the importance of reducing the load of landfilling applications and implementation of separation at the source (Zhou et al., 2018).

Herva et al. completed an LCA study based on different impact categories; energy and material flow and ecological footprint to evaluate the existing integrated waste management in Porto, Portugal. The integrated system analyzed for the above study included: sorting plant, composting plant, energy recovery plant, and landfill. After LCA analysis was completed for the above system, it was found that the composting plant had the highest ecological footprint in the integrated system. However, for the integrated system, the environmental gains were calculated to be higher than its environmental impacts. The results of this study show the significance of integrating waste management systems for a sustainable society (Herva et al., 2014).

In another study conducted by Fernandez-Nava et al., an LCA of five different municipal waste management strategies for Asturias, Spain was completed. These strategies consisted of landfilling, incineration, biomethanization, and aerobic stabilization methods and the environmental impacts of these strategies on human health, ecosystem quality, global warming, and resource depletion were investigated. Fernandez-Nava et al. stated that the case study where the organics were separated at source and utilized in biomethanization, incineration, and aerobic stabilization processes, had the least impact in the impact categories mentioned above. Whereas the case studies where landfilling was used as a waste management option, the LCA analysis found that these case studies had a higher environmental impact for the above impact categories (Fernández-Nava et al., 2014).

Zarea et al. compared the existing waste management systems in Ahvaz, Iran to different case studies. These case studies considered the utilization of wastes by applying different case studies including landfilling, composting, anaerobic digestion, and incineration waste management processes. According to the existing system, 40% of the total wastes were separated and sent to composting, 3% of the total wastes were recycled and the remaining amount was transported to a landfill for the final disposal where no energy recovery was reported. The results of the above study showed that the case study which included an integrated anaerobic digestion and incineration system had a higher waste-to-energy ratio and minimum environmental impact in the eco-toxic solid waste impact category but the highest impact in the photochemical oxidant impact category. The results of this study show the importance of utilizing the existing systems according to the waste-to-energy approach and the significance it can have on creating a sustainable society (Zarea et al., 2019).

Koroneos and Nanaki completed an LCA of landfilling, paper recycling, and anaerobic digestion of food waste in a biological treatment facility to investigate the possible environmental impacts for Thessaloniki, Greece. This study focused on the importance of innovative strategies in MWM to prevent possible damage to the environment. The impact categories included: contribution to global warming, ecosystem quality, human health and eutrophication, and acidification. It was reported that the environmental impacts were decreased with respect to the increase in energy and material recovery. Furthermore, integration of anaerobic digestion facilities was found to be more attractive over landfilling applications as anerobic digestion facilities had a lower environmental impact and more energy recovery ratio compared to landfills. Koroneos and Nanaki also mentioned that the residue of the anaerobic digestion process can be further utilized to produce low-grade fertilizer by integrating bio cells and therefore produce to more useful outputs (Koroneos & Nanaki, 2012).

In an LCA study completed by Ripa et al., site-specific data was used to compare the waste management case studies for Naples, Italy. Ripa et al. stated the importance of using site-specific data in LCA analysis for a sustainable community. They highlighted the significance of site-specific data compared to generalized analysis as well as identifying alternative waste management hierarchies to help policymakers with decision-making about the costs and benefits for waste management locally. In the existing waste management system, approximately 37% of the total production of municipal solid waste was recovered in a separate collection system. The composition of MSW included: fibers, plastic, glass, metal, organics, and mixed municipal solid waste. The existing environmental technologies included: landfills, incineration, anerobic digestion, composting, material recovery, and mechanical biological treatment plants. This study considered six different case studies by varying percentages of separate collection, transportation routes, and options for the disposal of residual waste in the existing waste management plan to improve the environmental impacts of waste management technologies. The result of this study showed that mixed municipal solid waste had the highest environmental impact due to landfilling applications in the original case. Expectedly, the environmental impacts were found to be lowest in the case study which had a higher recovery ratio and optimum location for existing waste management technologies (Ripa et al., 2017).

Tulokhonova et al. developed waste management case studies and assessed them by using LCA to improve the existing waste management system in Irkutsk, Russia. The waste management case studies consisted of collection and transportation, landfilling, recycling, composting, and mechanical-biological pre-treatment (MBP). Tulokhonova et al. stated after stabilization of organic matter in aerobic MBP the fraction which had high caloric value can be further utilized in a cement kiln to recover energy. The systems were analyzed according to the following environmental impact categories: abiotic depletion, global warming, human toxicity, photo-oxidation, acidification, and eutrophication potentials. The results of the study showed that the case study which consisted of separate collection and utilization of recyclables integrated with an anaerobic mechanical-biological pre-treatment facility had the lowest environmental impact in the above impact categories. However, this case study was found to be approximately 3.6 times more expensive compared to the existing waste management technologies in Irkutsk, Russia (Tulokhonova & Ulanova, 2013).

Reza et al. performed an LCA to examine the environmental impact of waste-to-energy strategies to replace the use of conversational fossil fuel in Vancouver, Canada. This study aimed to discover the benefits of RDF production through MSW in Metro Vancouver area. In addition, economic benefits, and environmental impacts of the use of RDF production were explored for two cement kilns in the region. The case study considered within this study included a mechanical treatment facility where raw MSW was separated into inert, RDF, and metal fractions. Furthermore, the inert fraction was sent to landfills, RDF, and metals were utilized in cement kiln industry and metal recovery plants, respectively. Reza et al. (Reza et al., 2013) concluded that the use of RDF to replace traditional fossil fuel for MSW was shown to be economically viable and more environmentally friendly. In addition, the use of RDF can lead to a 60% reduction in the waste load of landfills due to less than 40% of MSW needed to be sent to the landfill for final disposal (Reza et al., 2013).

2.3 LCA Analysis of Advanced Waste-to-Energy Technologies

Integrating waste management technologies with energy systems has become more attractive as the population and industrialization continue to grow. There are several applications conducted to investigate the improvements in environmental impact and energy production to create a circular economy for sustainable cities. These WtE technologies can be categorized as biological treatment technologies, anaerobic digestion technologies, and thermal treatment technologies (Moya et al., 2017). In this section, these advanced WtE applications and their advantages in terms of environmental impacts and possible energy recovery are discussed.

In a study completed by Ayodele et al. twelve cities in Nigeria were selected to evaluate electricity generation potential, GWP, AP, and dioxin/furan potential. The system analyzed included various waste-to-energy technologies such as landfill gas to energy, hybrid of incineration and anaerobic digestion, and hybrid of incineration and landfill gas to energy. These WtE systems were compared to the base case where all MSW was sent to landfill for final disposal. The result of the study showed that the integrated incineration and anaerobic digestion had economic benefits regarding electricity generation potential and had lower impacts according to GWP and AP. Moreover, landfill gas-to-energy was reported to be the most viable method for carcinogenic reduction potential according to dioxin/furan emission. For the above WtE systems, the GWP reduction rate was calculated to be between 75-93% compared to the base case (Ayodele et al., 2017).

Zaman developed an advanced WtE system to robust the current waste management technologies by reducing the environmental burden. In this system, a pyrolysis-gasification unit was integrated and compared to the existing incineration plant in terms of environmental impact categories. According to the results of this study, the case study where the environmental impacts of pyrolysis-gasification were investigated, it was found that this system had important environmental burdens in AP, EP, and aquatic eco-toxicity impact categories. However, in the other case study, where pyrolysis-gasification was compared to the incineration plant, the study reported to have a lower environmental impact in AP, EP, and aquatic eco-toxicity impact categories (Zaman, 2013).

Al-Salem et al. aimed to improve the existing waste management facilities in the Greater London area by integrating new waste management technologies and completing an LCA of these case studies. The existing waste management system included: a material recovery facility, a landfill, and an incineration unit with combined heat and power. For the improved waste management system case studies, two alternative thermochemical treatment technologies, low-temperature pyrolysis and hydrogenation reactor were considered. These new waste management technologies were used to generate useful outputs such as valuable chemicals, steam, petrochemicals, Syncrude, and e-gas. Al-Salem et al. (Al-Salem et al., 2014) stated that the Syncrude and e-gas produced via hydrogenation process was similar to natural gas (NG). These two case studies were assessed according to the GWP, AP, POP, and EP impact categories. For the considered case study, all the impact categories were shown to be positive, indicating that the problems associated with the processes were larger than the benefits they can produce. This shows that the existing MRF currently is more environmentally friendly than the hydrogenation reactor (VCC). When the products of MRF become unfavorable, by means that lower substitution factor, lower temperature pyrolysis (LTP), and VCC become more environmentally friendly (Al-Salem et al., 2014).

Wang et al. conducted an LCA to investigate the environmental benefits of fast pyrolysis of MSW in North Carolina, United States of America. The pyrolysis plants were environmentally assessed and compared to anaerobic digestion, landfill, and incineration case studies according to human toxicity potential (HTP), GWP, AP, and POP. The main outputs of pyrolysis were found to be hydrogen and char while the co-product of pyrolysis was bio-oil. These main outputs and co-products were able to generate 5.5 MJ and 2.7 MJ energy recovery per kg MSW, respectively. Wang et al. concluded that fats pyrolysis for bio-oil had the least environmental impact while landfilling expectedly had the highest environmental impact (Hui Wang, Lijun Wang & Abolghasem, 2015).

Dong et al. developed an advanced integrated WtE system where MSW was utilized in the incineration, pyrolysis, and gasification process. This study performed an LCA of this integrated system according to impact categories for possible improvements. The outputs of these sub-systems were further used to generate power in the steam cycle, gas turbine combined cycle, and internal combustion engine. This study aimed to decrease the use of traditional fossil fuels by integrating these advanced sub-systems into the existing waste management systems where incineration was stated as a main thermal treatment process. The result of this study showed that the modern incinerator is more environmentally friendly than the case studies where gasification and pyrolysis were implemented because of the modern gas cleaning, heat and power recovery, and ash recycling. Dong et al. also stated that with the improvement of syngas (SG) purification technologies, the environmental impact of these advanced systems can be decreased (Dong et al., 2018).

Evangelisti et al. further investigated advanced WtE to decrease the load of landfilling and mass-burn incineration. An LCA was completed to compare the environmental impacts of these advanced technologies with the existing incineration plant located in Lincolnshire, United Kingdom, and landfill application with electricity production. The advanced technologies considered within this study included gasification and plasma gas cleaning, fast pyrolysis, and combustion and gasification and syngas combustion. Evangelisti et al. stated that the above advanced systems have a capability of 20MWe net output. The case study where gasification and plasma were used was found to have a lower environmental impact than landfilling application with energy recovery in GWP and AP. Moreover, this case study was stated to be more environmentally friendly than the existing incineration plant in terms of AP (Evangelisti et al., 2015).

Chapter 3: Descriptions of Waste Management Systems

In this chapter, the existing waste management systems in Durham Region will be discussed in detail. These systems are split into two categories which are curbside and multi-residential collection and transportation of MSW, and region-owned waste management facilities for residential visits. Figure 3.1 illustrates the existing MSW system while Table 3.1 demonstrates the waste management terminology used in Durham Region. The curbside and multi-residential collection and transportation of the MSW subsection will further be divided into each city within Durham Region. Furthermore, blue bin and black bag garbage composition, used within this study, is given in Table 3.2 and Table 3.3

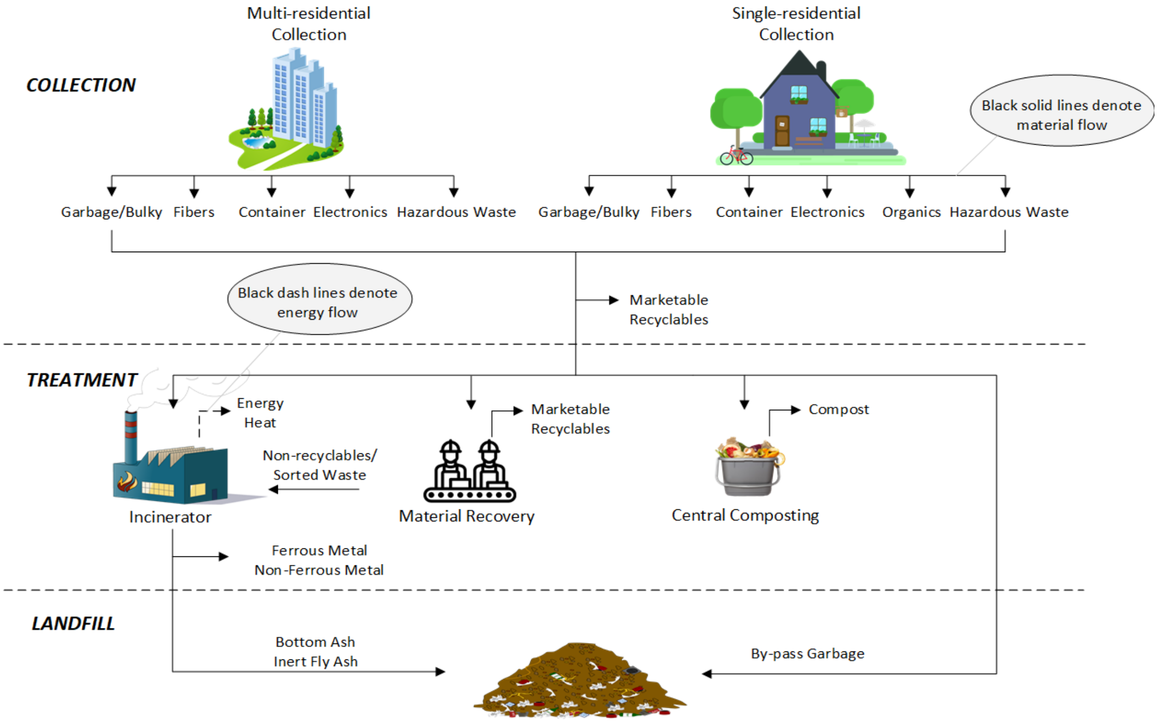

Figure 3.1: Existing Waste Management System of Durham Region

Table 3.1: Waste Management Terminology in Durham Region

Waste Type	Contents
Blue Bin	Containers, paper products
Green Bin	Food waste, other compostable items
Black Bag Garbage	Non-recyclables, recyclables, organics, others
Other Organics	Yard waste, Christmas trees
Bulky İtems	Furniture, large items
Metal Goods	Scrap metals, metal items
Porcelain	Bathtubs, sinks, toilets
E-Waste and Batteries	Electronics, standard batteries, heavy duty batteries

Table 3.2: Blue Bin Composition Collected at Material Recovery Facility in Durham Region

Waste Type	**Mass Percentage (%)**
Newspaper	0.43
Cardboard	0.19
Aluminum containers	0.02
Steel containers	0.03
PET containers	0.07
HDPE containers	0.01
Broken Blue Boxes & Green Bins	0.00
Rigid Mixed Plastic containers	0.03
Tetra and Gable containers	0.01
Scrap Metal	0.00
Glass containers	0.11
Unfavorable Recyclables	0.01
Garbage Residue	0.09

Table 3.3: Black Bag Garbage Composition in Durham Region

Waste Type	**Mass Percentage (%)**
Recyclable Fiber	0.079
Non-Recyclable Fiber	0.009
PET Bottles and Thermoform	0.012
HDPE Bottles, Jars, and Jugs	0.005
Recyclable Plastics (mixed plastics),	0.010
Non-Recyclable Plastics	0.186
Recyclable Non-Ferrous Metals	0.007
Recyclable Ferrous Metals	0.005
Non-Recyclable Metals	0.011
Recyclable Glass	0.006
Non-Recyclable Glass	0.005
Accepted Organics	0.305
Other Organics	0.008
Sanitary and Pet Waste	0.118
Construction and Demolition	0.065
Ceramics	0.011
Tires and other Rubber	0.004
Textiles	0.061
MHSW	0.002
Electronics	0.013
Bulky Items	0.019
Other Waste	0.033
Fines	0.014
Recyclable with Contents	0.014

3.1 Curbside and Multi-Residential Collection and Transportation of MSW

In this section, the municipal solid waste management for each city in Durham Region will be discussed in detail.

3.1.1 City of Oshawa

In 2020, the City of Oshawa generated a total amount of 55311 tonnes of municipal solid waste. Residential and multi-residential garbage was the largest amount of waste type generated at approximately 54%, while the blue box collection, organics were reported to be about 20% and 26% in that order. Table 3.4 shows the waste composition and related disposal facilities for the City of Oshawa.

Table 3.4: Waste Composition and Disposal Facilities for the City of Oshawa

Waste Type	Composition (wt%)	Waste Load(tonnes/yr)	Waste Disposal Facilities
Residential Garbage	0.38	20890.2	1. Miller Waste Pebblestone 2. WMC 3. DYEC
Multi-Res Garbage	0.16	8587.9	1. Miller Waste Pebblestone 2. Waste Management Canada 3. DYEC
Other Goods Disposal	0.01	277.8	1. Miller Waste Pebblestone 2. WMC 3. DYEC
Blue Box	0.20	11300.5	1. Region of Durham MRF 2. DYEC
Food Waste	0.13	7026.7	Miller Waste Pebblestone
Yard Waste	0.13	7162.3	Miller Waste Clarington
Xmas Tree	0.00068	37.7	Miller Waste Clarington
WEE	0.00011	6.1	Durham Recycling Center
Batteries	0.00022	12.3	Durham Recycling Center
Textile Pilot	0.00018	9.9	Diabetes Canada

Figure 3.2 demonstrates the LCA system boundary for the City of Oshawa waste management system. As seen, food waste is collected in green bins by Miller Waste Systems (MW) and transported to the Miller Waste Systems Pebblestone Facility (MWP) along with the black bag garbage. Furthermore, black bag garbage is transported to Waste Management of Canada (WMC) transfer station and some bulky items are removed from the waste. Blue bins are collected from the single and multi-residential houses and sent to

the Region of Durham Material Recovery Facility. In this facility, recyclables are sorted and marketed, and the garbage residue is transported, along with the black bag garbage, to the Durham York Energy Center for further energy utilization. Yard waste and Christmas trees are transported to the Miller Waste Clarington Facility (MWC) for compost production. E-waste and batteries are sent to Durham Recycling Center (DRC) and sold to third-party organizations.

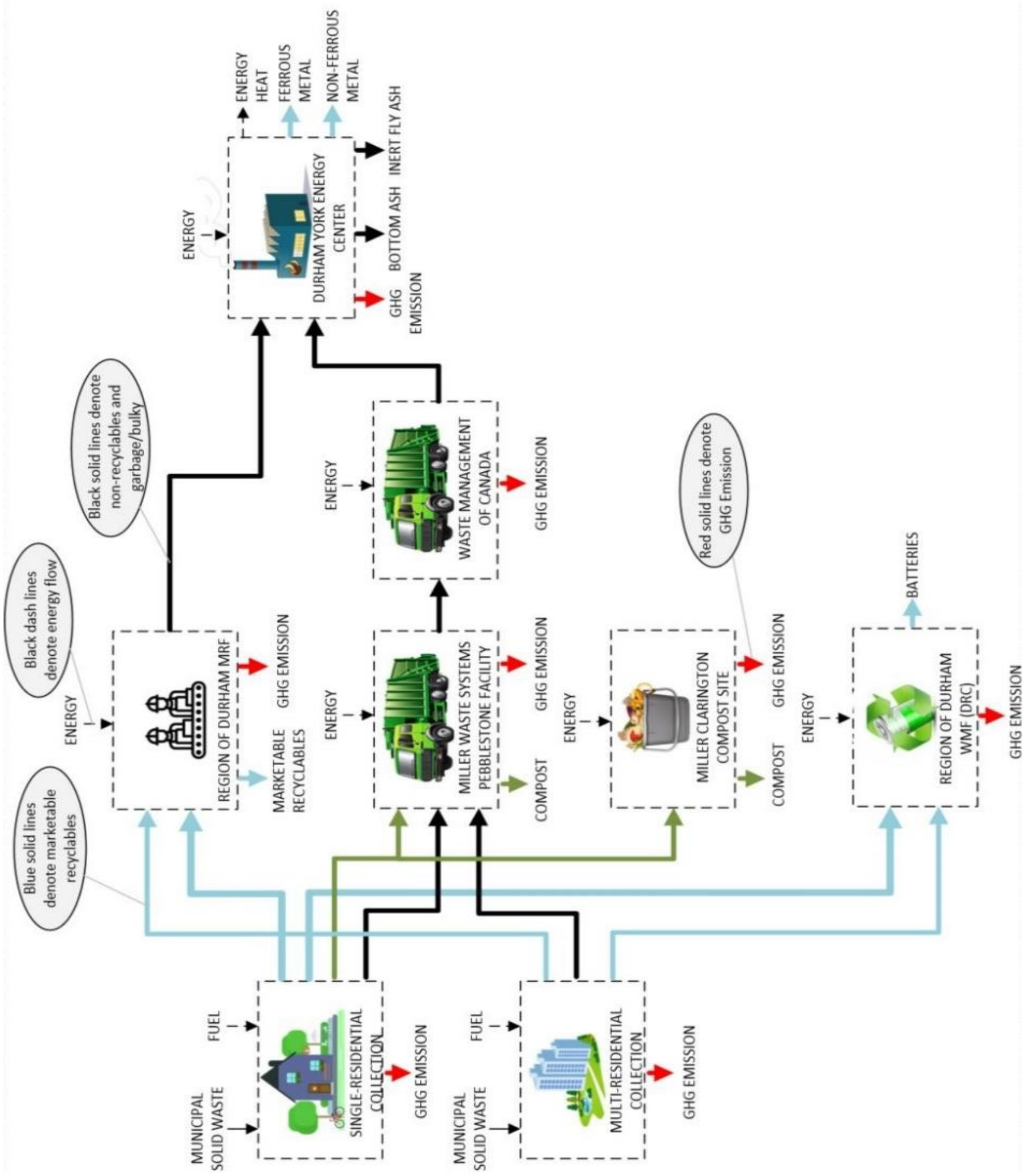

Figure 3.2: Municipal Solid Waste Collection and Management for City of Oshawa

3.1.2 Town of Whitby

In 2020, the Town of Whitby generated a total amount of 40009 tonnes of municipal solid waste. According to the waste composition of the Town of Whitby, black bag garbage accounted for 44% of the total solid waste generated. Furthermore, recyclables and organics made up approximately 22% and 34%, in that order. The composition of MSW and the existing disposal facilities are demonstrated in Table 3.5.

Table 3.5: Waste Composition and Disposal Facilities for the Town of Whitby

Waste Type	Composition(wt.%)	Waste Load (tonnes/yr)	Waste Disposal Facilities
Residential Garbage	0.37	14729.35	1. Miller Waste Pebblestone 2. WMC 3. DYEC
Multi-Res Garbage	0.06	2512.28	1. Miller Waste Pebblestone 2. WMC 3. DYEC
Other Goods Disposal	0.01	354.04	1. Miller Waste Pebblestone 2. WMC 3. DYEC
Blue Box	0.22	8898.69	1. Region of Durham MRF 2. DYEC
Food Waste	0.19	7409.05	Miller Waste Pebblestone
Yard Waste	0.15	5993.61	Miller Waste Clarington
Xmas Tree	0.00119	47.49	Miller Waste Clarington
Porcelains	0.0013	52	Durham Recycling Center
WEE	0.000001	0.2	Durham Recycling Center
Batteries	0.00025	10.2	Durham Recycling Center
Textile Pilot	0.00006	2.4	Diabetes Canada

The general curbside and multi-residential municipal solid waste collection and transportation and management are shown in Figure 3.3. The green bins collected are sent to Miller Waste Systems Pebblestone Facility along with the black bag garbage collected from the single and multi-residential houses. The organics which consist of food waste and yard waste are utilized to generate compost in Miller Waste Clarington and Miller Waste Pebblestone.

Marketable recyclables, which are collected in blue bins, are transported to MRF and sold to third party organizations. The garbage residue from MRF is sent to the incinerator along with black bag garbage for further energy utilization. E-waste, batteries, and porcelain are collected separately and transported to Durham Recycling Center to be sold to third party organizations.

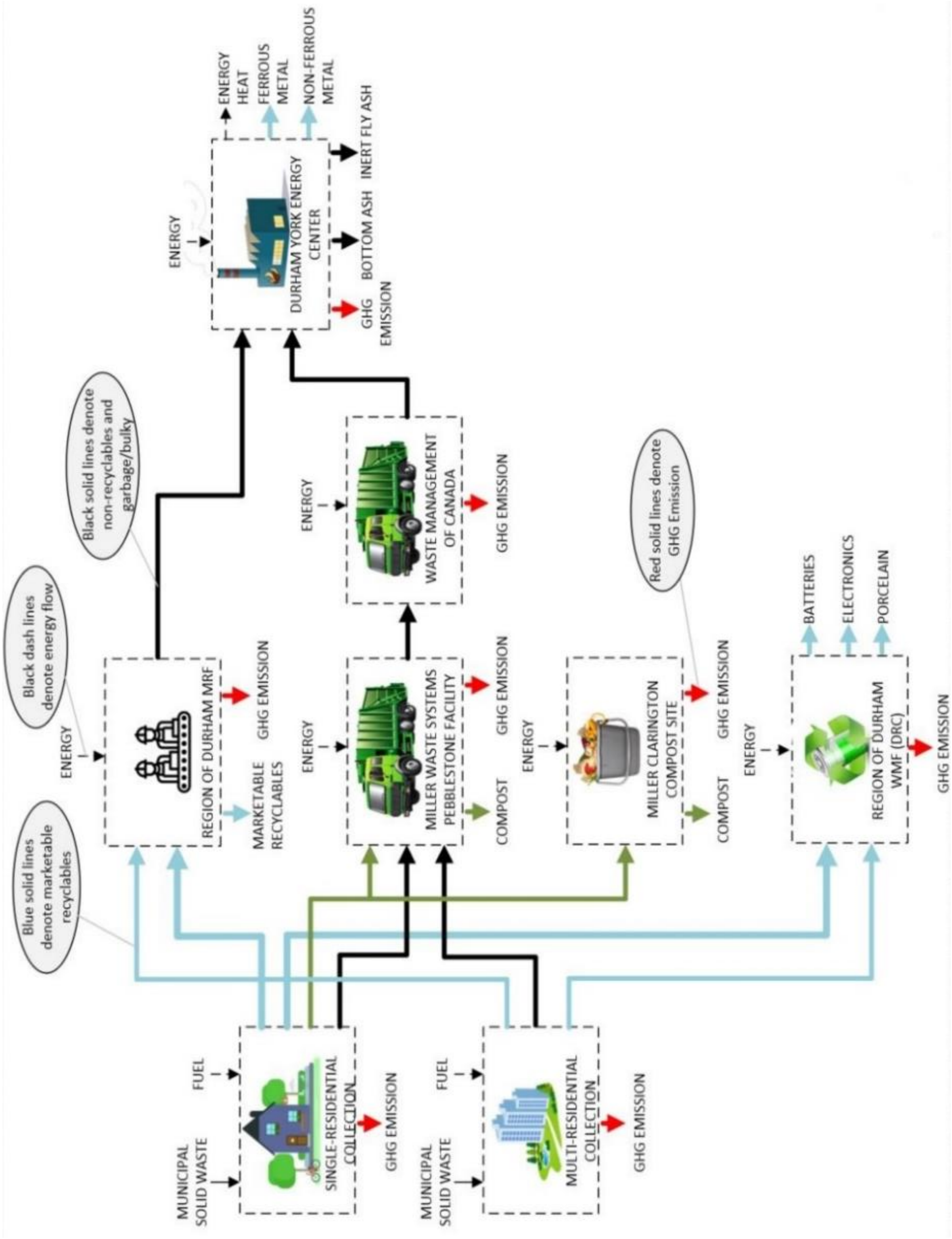

Figure 3.3: Municipal Solid Waste Collection and Management for Town of Whitby

3.1.3 Town of Ajax

In 2020, the Town of Ajax generated a total amount of 35482 tonnes of municipal solid waste. Table 3.6 demonstrates the total waste generated in the Town of Ajax according to the waste type and waste disposal facilities. According to the table, 45% of the total MSW was generated from single residential and multi-residential black bag garbage. The remaining MSW composition was made up of food waste, yard waste, and Christmas trees which was approximately 33%. Finally, marketable recyclables which are collected in blue bins accounted for 21% of the total MSW.

Table 3.6: Waste Composition and Disposal Facilities for the Town of Ajax

Waste Type	Composition(wt.%)	Waste Load (tonnes/yr)	Waste Disposal Facilities
Residential Garbage	0.41	14622.88	1. Miller Waste Systems 2. DYEC
Multi-Res Garbage	0.04	1521.80	1. Miller Waste Systems 2. DYEC
Other Goods Disposal	0.005	176.64	1. Miller Waste Systems 2. DYEC
Blue Box	0.21	7625.35	1. Region of Durham MRF 2. DYEC
Food Waste	0.20	7142.35	Miller Waste Systems
Yard Waste	0.12	4231.84	Miller Waste Systems
Xmas Tree	0.00072	25.63	Miller Waste Systems
Porcelains	0.0021	76.17	Durham Recycling Center
WEE Curbside	0.00026	9.16	Durham Recycling Center
WEE Multi-Res	0.00023	8.05	Durham Recycling Center
Batteries	0.00023	8.29	Durham Recycling Center
Textile Pilot	0.00008	2.98	Diabetes Canada
Metal Goods	0.00089	31.67	Miller Waste Systems

Figure 3.4 shows the MSW management plan used for the collection, transportation, and management of MSW in the Town of Ajax. Black bag garbage is collected by Miller Waste Systems along with the organics which consists of food waste, yard waste, and Christmas trees. These organics are further used to generate compost within this waste management facility.

Recyclables are sorted in Region of Durham MRF and marketable recyclables, which have financial value, are sold to third party organizations. The remaining garbage residue from the MRF is sent to the Durham York Energy Center along with black bag garbage for energy production and waste disposal. E-waste, batteries, and porcelain are collected within the regional recycling program in the Town of Ajax and sold to third party organizations.

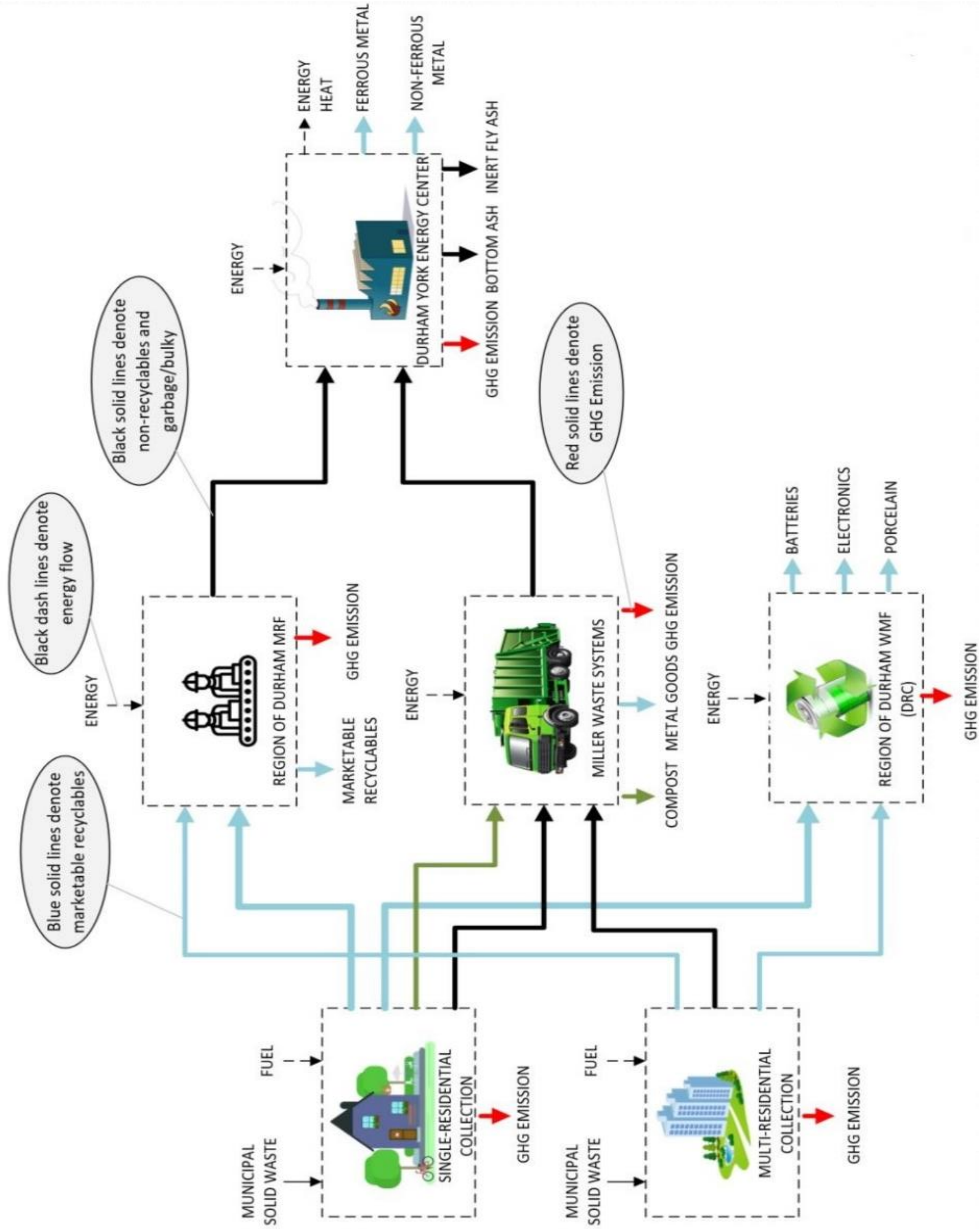

Figure 3.4: Municipal Solid Waste Collection and Management for Town of Ajax

3.1.4 City of Pickering

In 2020, in the City of Pickering generated a total amount of 28873 tonnes of municipal solid waste. Table 3.7 illustrates the total MSW in the City of Pickering and looks at the composition of the waste and the existing disposal facilities in this city.

The largest composition of the MSW was residential and multi residential garbage which accounted for about 46%. The next largest composition was seen to be blue box bins which made up about 22% of the total MSW in the City of Pickering. Finally, organics had approximately 32% of the total MSW.

Table 3.7: Waste Composition and Disposal Facilities for the City of Pickering

Waste Type	**Composition(wt.%)**	**Waste Load (tonnes/yr)**	**Waste Disposal Facilities**
Residential Garbage	0.41	11907.66	1. Miller Waste Systems 2. DYEC
Multi-Res Garbage	0.04	1037.96	1. Miller Waste Systems 2. DYEC
Other Goods Disposal	0.01	316.51	1. Miller Waste Systems 2. DYEC
Blue Box	0.22	6313.88	1. Region of Durham MRF 2. DYEC
Food Waste	0.18	5190.9	Miller Waste Systems
Yard Waste	0.14	3955.36	Miller Waste Systems
Xmas Tree	0.00095	27.54	Miller Waste Systems
Porcelains	0.00214	61.86	Durham Recycling Center
WEE Curbside	0.0004	11.54	Durham Recycling Center
WEE Multi-Res	0.00027	7.723	Durham Recycling Center
Batteries	0.00025	7.189	Durham Recycling Center
Textile Pilot	0.0001	2.79	Diabetes Canada
Metal Goods	0.0011	32.14	Miller Waste Systems

In Figure 3.5 the LCA system boundary is illustrated for the City of Pickering. Green bins, yard waste, and Christmas trees are all collected from the single residential and transported to the Miller Waste Systems along with black bag garbage generated from both single and multi-residential houses. The organics are utilized to generate compost in this facility and can be used for agricultural applications.

The blue bins are transported to the Region of Durham MRF and useful recyclables are sorted and marketed to companies. The garbage residue from the MRF facility is sent to Durham York Energy Center along with black bag garbage to generate electricity through the incineration process. E-waste and batteries are transported to Durham Recycling Center and sold to third party organizations.

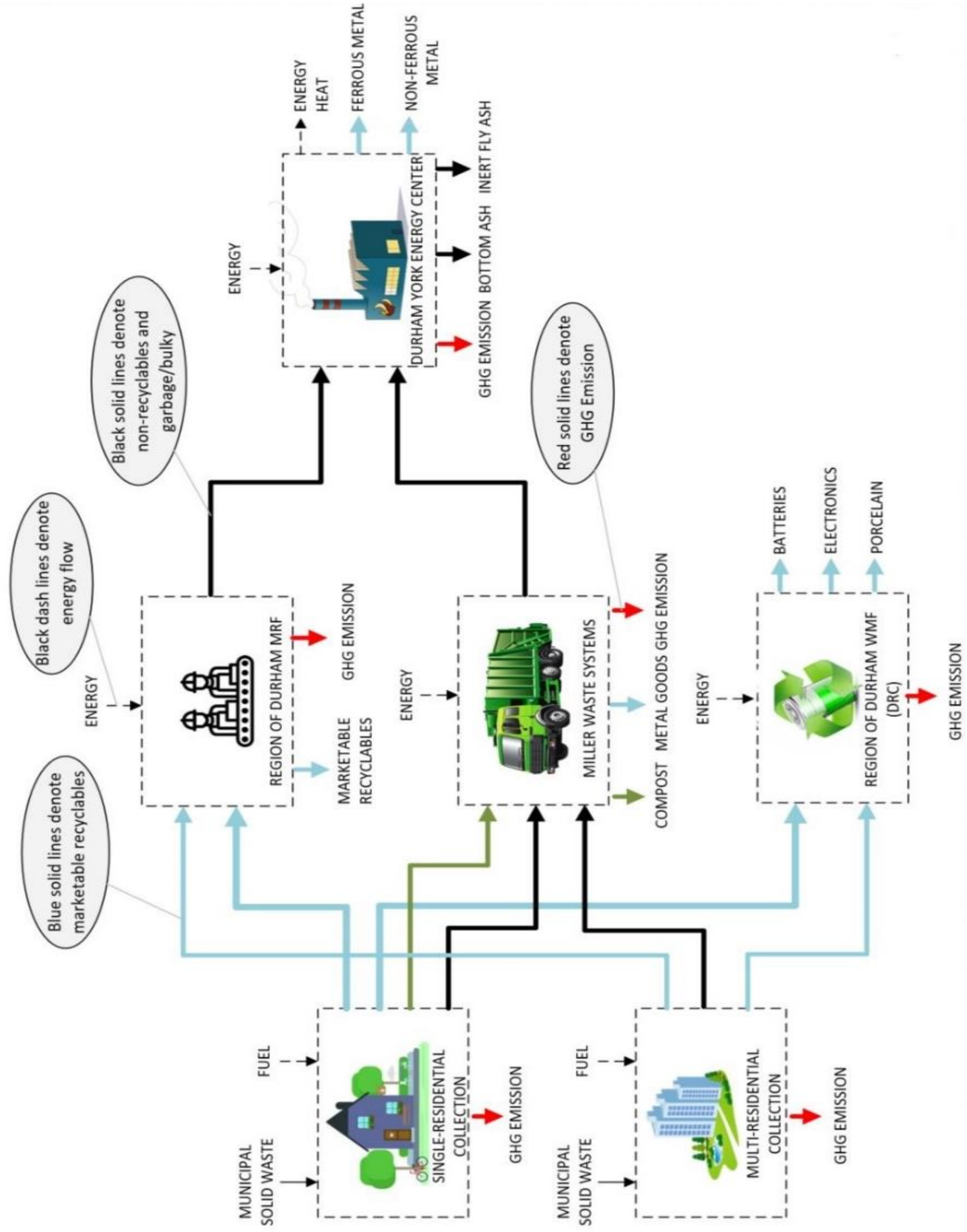

Figure 3.5: Municipal Solid Waste Collection and Management for City of Pickering

3.1.5 Municipality of Clarington

In 2020, the municipality of Clarington generated a total amount of 30700 tonnes of municipal solid waste. Approximately 48% of the solid wastes generated in the Municipality of Clarington are residential and multi-residential black bag garbage. This is followed by blue box and organics with 23% and 28% respectively. Clarington's waste composition, annual waste generated, and waste disposal facilities are given in Table 3.8 according to the waste types.

Table 3.8: Waste Composition and Disposal Facilities for the Municipality of Clarington

Waste Type	**Composition(wt.%)**	**Waste Load(tonnes/yr)**	**Waste Disposal Facilities**
Residential Garbage	0.46	14165.25	1. Waste Management Canada 2. DYEC
Multi-Res Garbage	0.01	236.43	1. Waste Management Canada 2. DYEC
Bulky Goods Disposal	0.02	524	1. Waste Management Canada 2. DYEC
Blue Box	0.23	7149.46	1. Region of Durham MRF 2. DYEC
Food Waste	0.13	4036.61	Miller Waste Systems
Yard Waste	0.14	4496.42	Miller Waste Clarington
Xmas Tree	0.0012	38.26	Miller Waste Clarington
Porcelains	0.00053	16.21	Durham Recycling Center
WEE Curbside	0.00027	8.33	Durham Recycling Center
WEE Multi-Res	0.00002	0.494	Durham Recycling Center
Batteries	0.00026	7.88	Durham Recycling Center
Metal Goods	0.0007	21.51	Miller Waste Systems

Figure 3.6 illustrates the existing waste management plan implemented in the municipality of Clarington. Black bag garbage that is generated in the municipality of Clarington, is collected from single and multi-residential houses, and directly sent to Waste Management of Canada. Recyclables in the blue bin are sorted in the Region of Durham MRF and the marketable recyclables are sold to third party organizations. The garbage residue is transported to Durham York Energy Center for energy recovery along with black bag garbage from Waste Management of Canada. In addition, green bins are collected by Miller Waste and sent to the Miller Waste Systems while yard waste and Christmas trees are transported to Miller Clarington Compost Site for organics treatment and compost

production. Finally, e-waste and batteries are transported to Durham Recycling Center and are also sold to third party organizations.

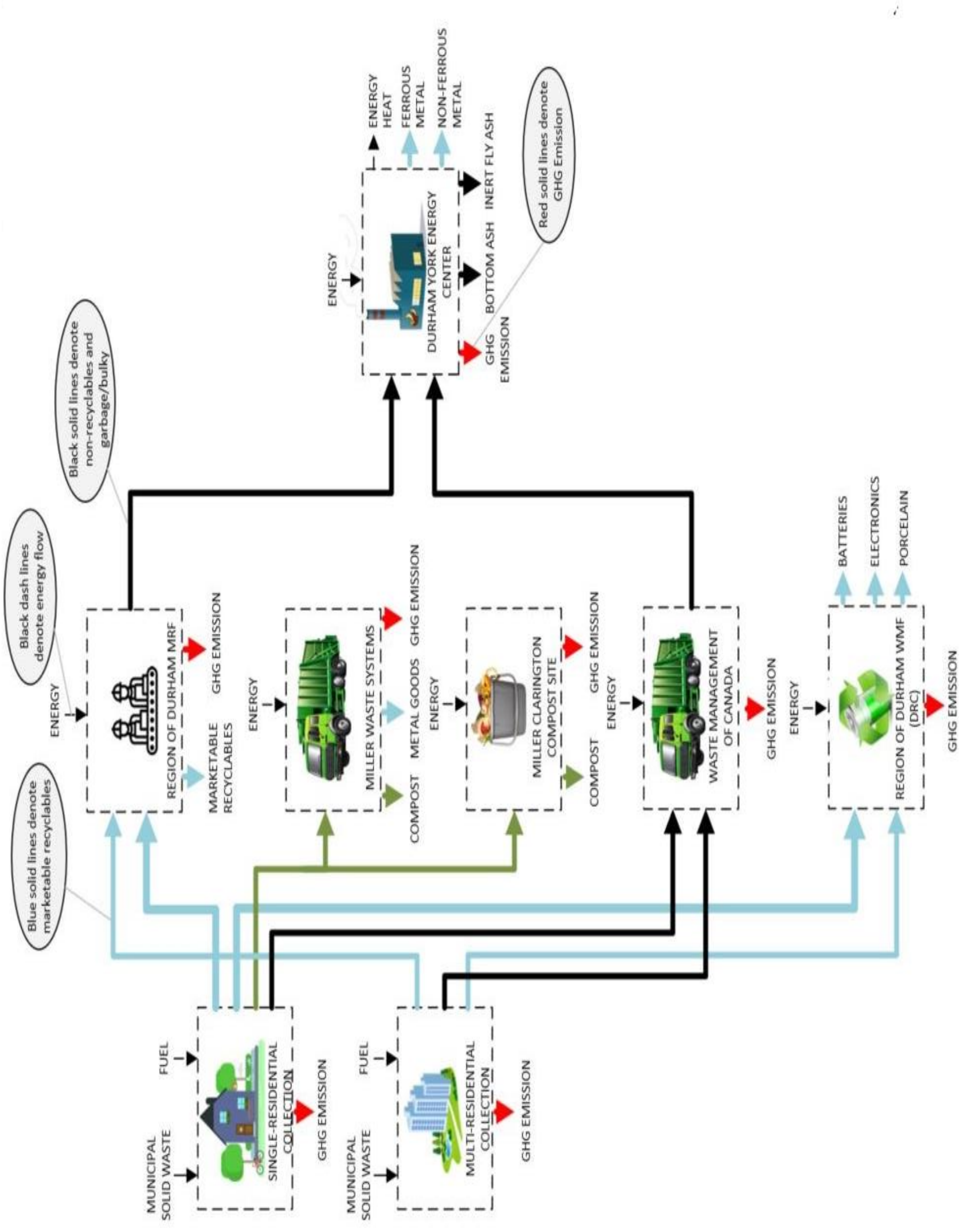

Figure 3.6: Municipal Solid Existing Waste Management Plan for Municipality of Clarington

3.1.6 Brock Township

In 2020, Brock Township generated a total amount of 4576 tonnes of municipal solid waste. Approximately 50% of the total solid waste produced consists of black bag garbage from single residential houses. Blue box and organics followed with 25% and 24% in this order. A detailed composition study for Brock Township is given in Table 3.9.

Table 3.9: Waste Composition and Disposal Facilities for Brock Township

Waste Type	Composition(wt.%)	Waste Load(tonnes/yr)	Waste Disposal Facilities
Residential Garbage	0.48	2213.76	1. Miller Waste Systems 2. MWC 3. DYEC
Bulky Goods Disposal	0.02	93.05	1. Miller Waste Systems 2. WMC 3. DYEC
Blue Box	0.25	1148.34	1. Region of Durham MRF 2. DYEC
Food Waste	0.11	487.78	Miller Waste Systems
Yard Waste	0.13	611.2	Miller Waste Clarington
Xmas Tree	0.00097	4.43	Miller Waste Clarington
Porcelains	0.00033	1.49	Durham Recycling Center
WEE Curbside	0.00031	1.42	Durham Recycling Center
Batteries	0.00027	1.23	Durham Recycling Center
Metal Goods	0.00307	14.053	Miller Waste Systems

Figure 3.7 illustrates the existing waste collection, transportation, and management plan for Brock Township. Black bag garbage is collected along with the green bins and transported to Miller Waste Systems. Some bulky items are removed from the black bag garbage and transferred to Waste Management of Canada. From this transfer station, black bag garbage is sent to the Durham York Energy Center for final disposal and energy recovery.

The blue bins collected from the single and multi-residential houses are transported to the Region of Durham MRF for the mechanical sorting process. In this facility, the marketable recyclables are separated from the garbage residue. The marketable recyclables, from the blue bins collected, are sold to third party organizations. Furthermore, the other organics, which consist of yard waste and Christmas trees, are transported to Miller Clarington Compost Site to generate compost. E-waste and batteries are collected separately under the residential recycling program and sent to Durham Recycling Center and sold to third party organizations.

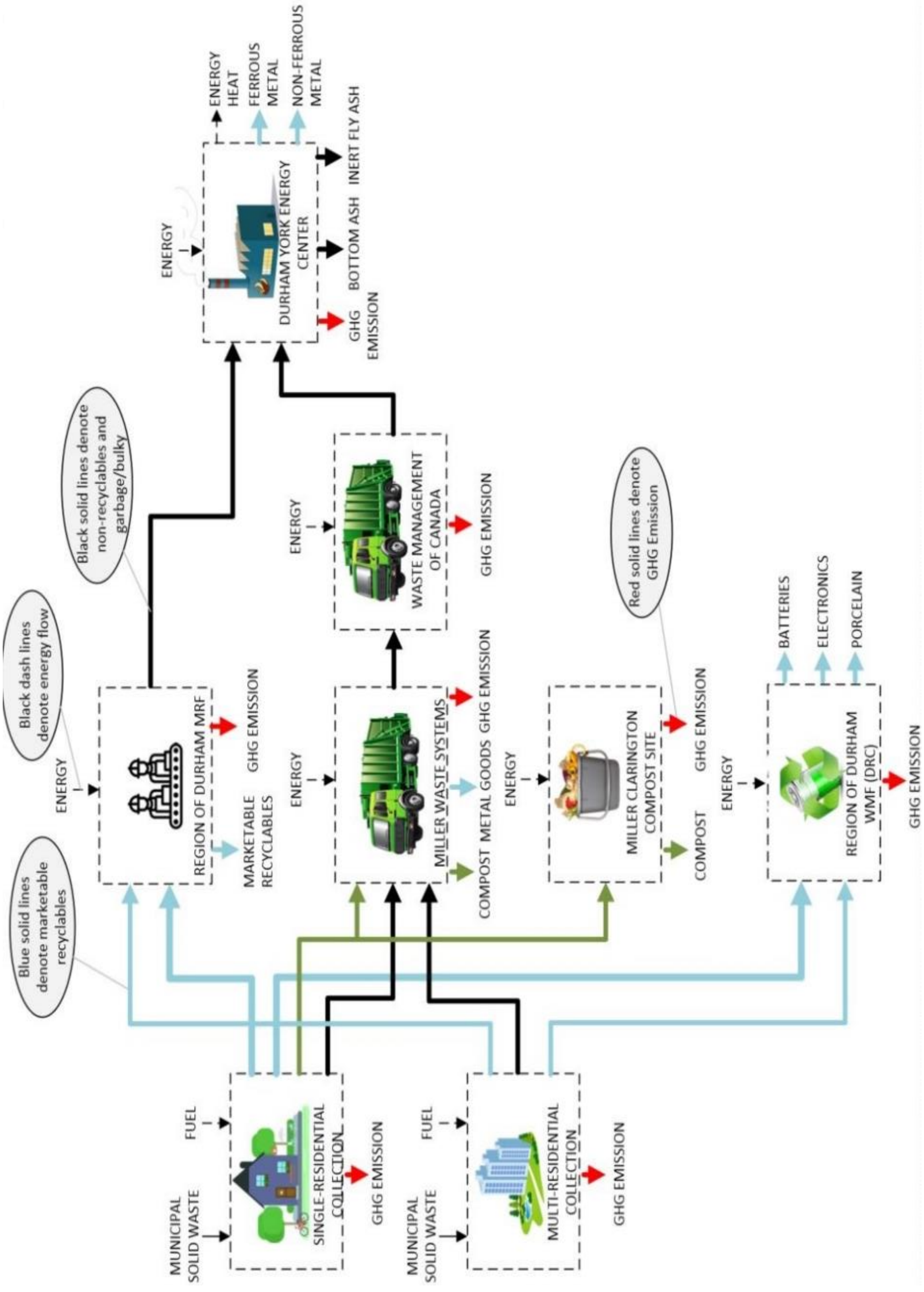

Figure 3.7: Municipal Solid Waste Collection and Management for Brock Township

3.1.7 Uxbridge Township

In 2020, Uxbridge Township generated a total amount of 6464 tonnes of municipal solid waste. Residential and multi-residential garbage was the largest amount of waste type generated at approximately 45%, while the blue box collection and organics were recorded to be 23% and 31% in that order. Table 3.10 shows the waste composition and waste disposal facilities for Uxbridge Township.

Table 3.10: Waste Composition and Disposal Facilities for Uxbridge Township

Waste Type	Composition(wt.%)	Waste Load(tonnes/yr)	Waste Disposal Facilities
Residential Garbage	0.41	2676.98	1. Miller Waste Systems 2. WMC 3. DYEC
Multi-Res Garbage	0.02	118.16	1. Miller Waste Systems 2. WMC 3. DYEC
Bulky Goods Disposal	0.02	100.56	1. Miller Waste Systems 2. WMV 3. DYEC
Blue Box	0.23	1496.33	1. Region of Durham MRF 2. DYEC
Food Waste	0.13	843.2	Miller Waste Systems
Yard Waste	0.18	1189.28	Miller Waste Clarington
Xmas Tree	0.00204	13.17	Miller Waste Clarington
Porcelains	0.00023	1.504	Durham Recycling Center
WEE Curbside	0.00022	1.45	Durham Recycling Center
Batteries	0.00026	1.65	Durham Recycling Center
Metal Goods	0.0033	21.81	Miller Waste Systems

The waste management plan of Uxbridge Township is demonstrated in Figure 3.8. Black bag garbage is collected from single and multi-residential houses and transported by Miller Waste Systems. In this facility, some bulky items are removed from the garbage, and compost is produced through the industrial composting of the organics in green bins collected.

Furthermore, blue bins are transported to the Region of Durham MRF and marketable recyclables are sorted from the garbage to be sold to other businesses. The garbage residue is sent to Durham York Energy Center along with black bag garbage from the Waste Management of Canada to generate electricity through the incineration of MSW. Moreover, yard waste and Christmas trees are sent to Miller Waste Clarington Compost

Site for further waste utilization through the industrial composting of these organics. E-waste and batteries are sent to Durham Recycling Center and sold to other organizations.

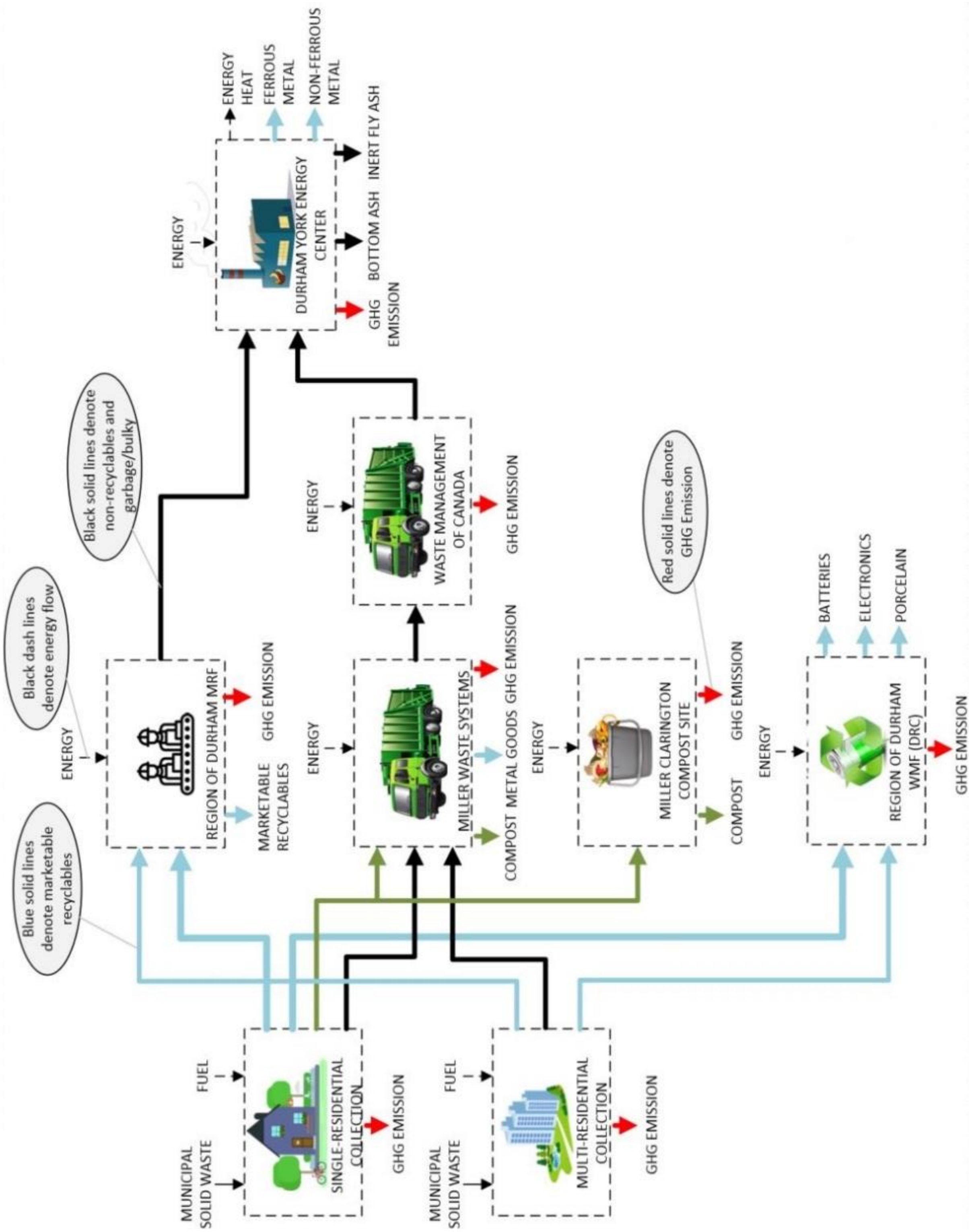

Figure 3.8: Municipal Solid Waste Collection and Management for Uxbridge Township

3.1.8 Scugog Township

In 2020, Scugog Township generated a total amount of 7156 tonnes of municipal solid waste. Black Bag garbage collected from single and multi-residential homes constitutes the majority of this total solid waste, with approximately 47%. Blue bins and organics make up about 22% and 30% of this waste composition, respectively. Table 3.11 illustrates the different waste types generated, disposal facilities, and the waste loads in Scugog Township.

Table 3.11: Waste Composition and Disposal Facilities for Scugog Township

Waste Type	Composition(wt.%)	Waste Load(tonnes/yr)	Waste Disposal Facilities
Residential Garbage	0.43	3111.29	1. Miller Waste Systems 2. WMC 3. DYEC
Multi-Res Garbage	0.03	205.26	1. Miller Waste Systems 2. WMC 3. DYEC
Bulky Goods Disposal	0.01	62.86	1. Miller Waste Systems 2. WMC 3. DYEC
Blue Box	0.22	1565.74	1. Region of Durham MRF 2. DYEC
Food Waste	0.12	894.32	Miller Waste Systems
Yard Waste	0.18	1290.19	Miller Waste Clarington
Xmas Tree	0.0012	8.91	Miller Waste Clarington
Porcelains	0.00021	1.533	Durham Recycling Center
WEE Curbside	0.0002	1.46	Durham Recycling Center
Batteries	0.00023	1.64	Durham Recycling Center
Metal Goods	0.0018	13.14	Miller Waste Systems

The waste management plan and LCA system boundary used in Scugog Township is shown in Figure 3.9. Black bag garbage is collected from single and multi-residential houses and transported to Miller Waste Systems along with green bins. In this facility, bulky items are removed from the black bag garbage, and compost is generated through the industrial composting of the food waste.

Furthermore, blue bins are transported to the Region of Durham MRF to sort marketable recyclables for re-selling and the garbage residue is sent to Durham York Energy Center along with black bag garbage from Waste Management of Canada for energy recovery. Moreover, yard waste and Christmas trees are sent to Miller Waste

Clarington Compost Site to generate compost for agricultural applications. Finally, e-waste and batteries are sent to Durham Recycling Center and sold to third party organizations.

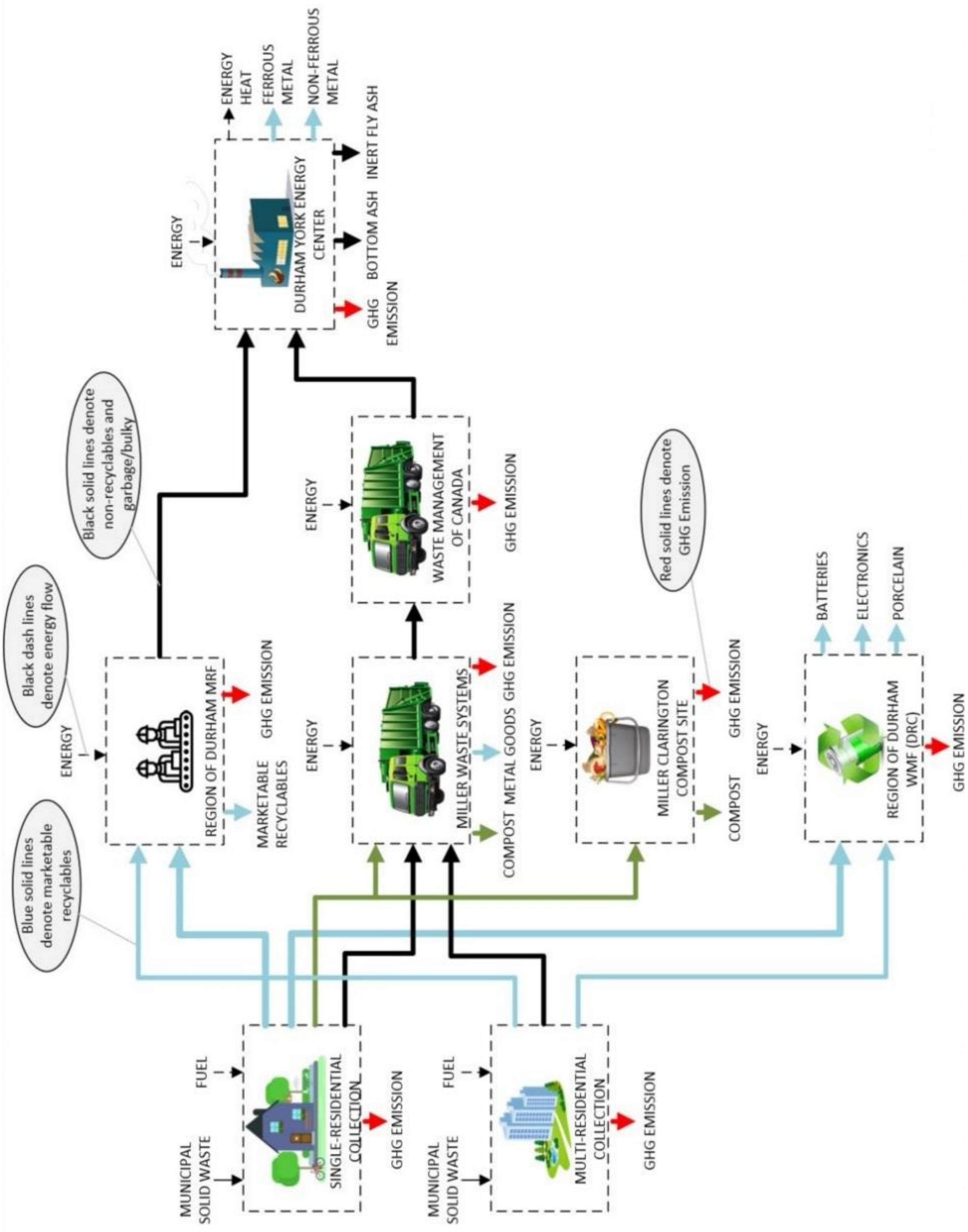

Figure 3.9: Municipal Solid Waste Collection and Management for Scugog Township

3.2 Region Owned Waste Management Facilities for Residential Visits

In this section, region owned waste management facilities where residential visits and waste collection occur, will be discussed in6 detail. There are three waste management facilities and two respective hazardous waste management facilities in Durham Region.

The three waste management facilities for Durham Region include Oshawa, Scugog, and Brock Waste Management Facility. In these mentioned waste management facilities, residential black bag garbage, cardboard and blue box, yard waste, hazardous waste, and recyclables, which are under regional re-use program, are collected.

Black bag garbage is the majority of the waste collected in these facilities. This black bag garbage is then sent to Waste Management of Canada transfer station and then transferred to Durham York Energy Center for energy recovery purposes. Blue bins and cardboard are transported to MRF to be sorted and marketable recyclables are sold to third party organizations listed in the tables below. In these mentioned facilities, hazardous waste is also collected and sent to Photech Environmental Solutions Inc. for final disposal.

There are two waste management facilities in Durham Region that specialize in collecting only hazardous waste. These facilities are Clarington and Pickering Hazardous Waste Depot. In 2020, approximately 379 tonnes of hazardous waste were collected and sent to Photech Environmental Solutions Inc. for final disposal.

3.3 Improvement Case Studies Considered for Waste Management Systems in Durham Region

Base Case Study: This case study will be used as a baseline to complete a comprehensive Life cycle assessment of the improvement case studies. This case study is based on the existing waste collection, transportation, and management of MSW in Durham Region as demonstrated in Figure 3.10. In this case study, black bag garbage collected is sent to an incinerator along with the garbage residue from waste management facilities for final disposal of the waste and energy recovery.

The total black bag garbage, which was fed to the incinerator, was observed to be approximately 146789 tonnes in 2020. Furthermore, collected organics which consist of food waste, yard waste, and Christmas trees, are utilized to generate compost. Marketable recyclables, e-waste, batteries, metal goods, and porcelain from multi-residential and single residential houses are sorted in material recovery and waste management facilities and sold to third party organizations.

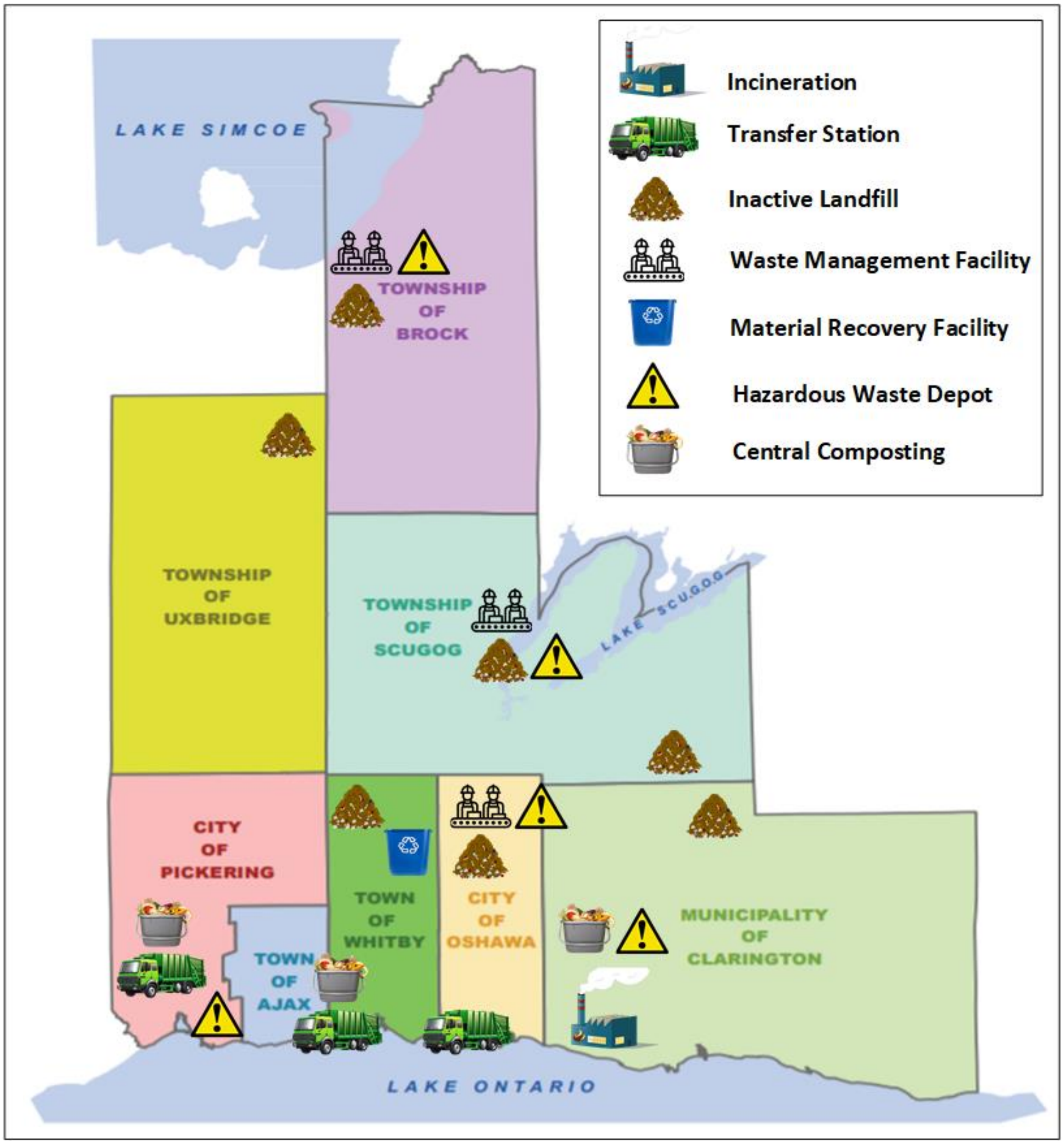

Figure 3.10: Existing Waste Management Facility Locations in Durham Region

Case study 1: In this case study, a mixed waste pre-sort and anaerobic digestion facility will be used as the main waste sorting and organics treatment process in Durham Region. Case study 1, which is implemented in the existing waste management system, is illustrated in Figure 3.11. Black bag garbage collected is pre-sorted in this facility to utilize the organic matter and sort marketable recyclables in this garbage. The composition of black bag garbage is given at Table 3.3. The garbage residue is then sent to an incinerator for energy recovery. The total garbage residue, which was fed to the incinerator, was calculated to be about 95922 tonnes per year. Biogas produced in digestors is assumed to be used for energy production. An environmental impact assessment will be completed and compared with the base case study.

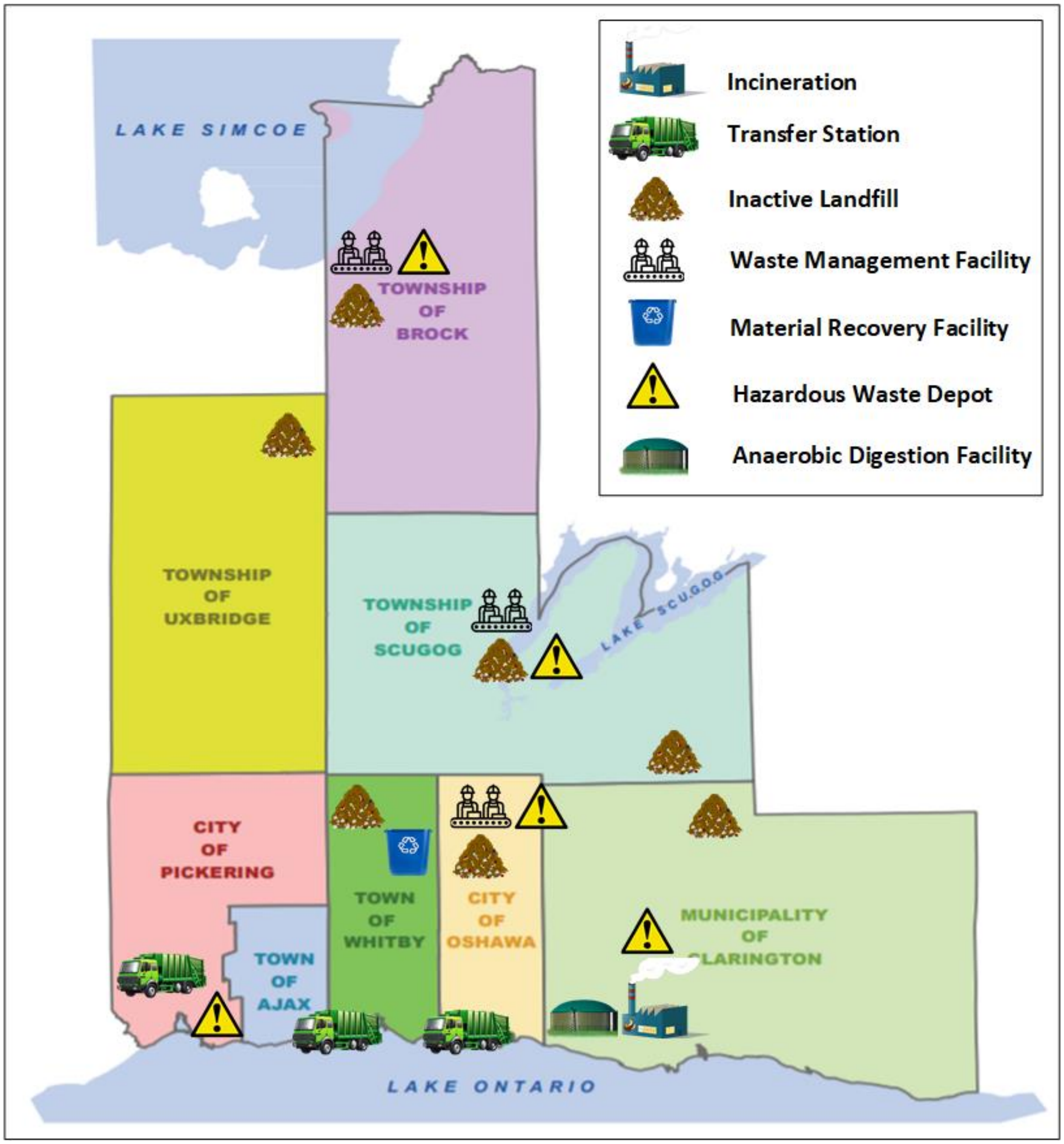

Figure 3.11: Waste Management Facility Locations in Case Study 1

Case study 2: In this case study, mixed waste pre-sort and anaerobic digestion facility will be integrated with a gasification unit. This improvement case study is demonstrated in Figure 3.12. In the pre-sort facility, black bag garbage is sorted and processable organics are sent along with green bin, yard waste, and Christmas trees collected to anaerobic digestion unit to produce biogas. Non-recyclables, unfavourable plastics and others are sent to the gasification unit along with the garbage residue for electricity production. The total feedstock, which was sent to the gasifier, was calculated to be about 95922 tonnes per year. An environmental impact assessment will be completed and compared with the base case study.

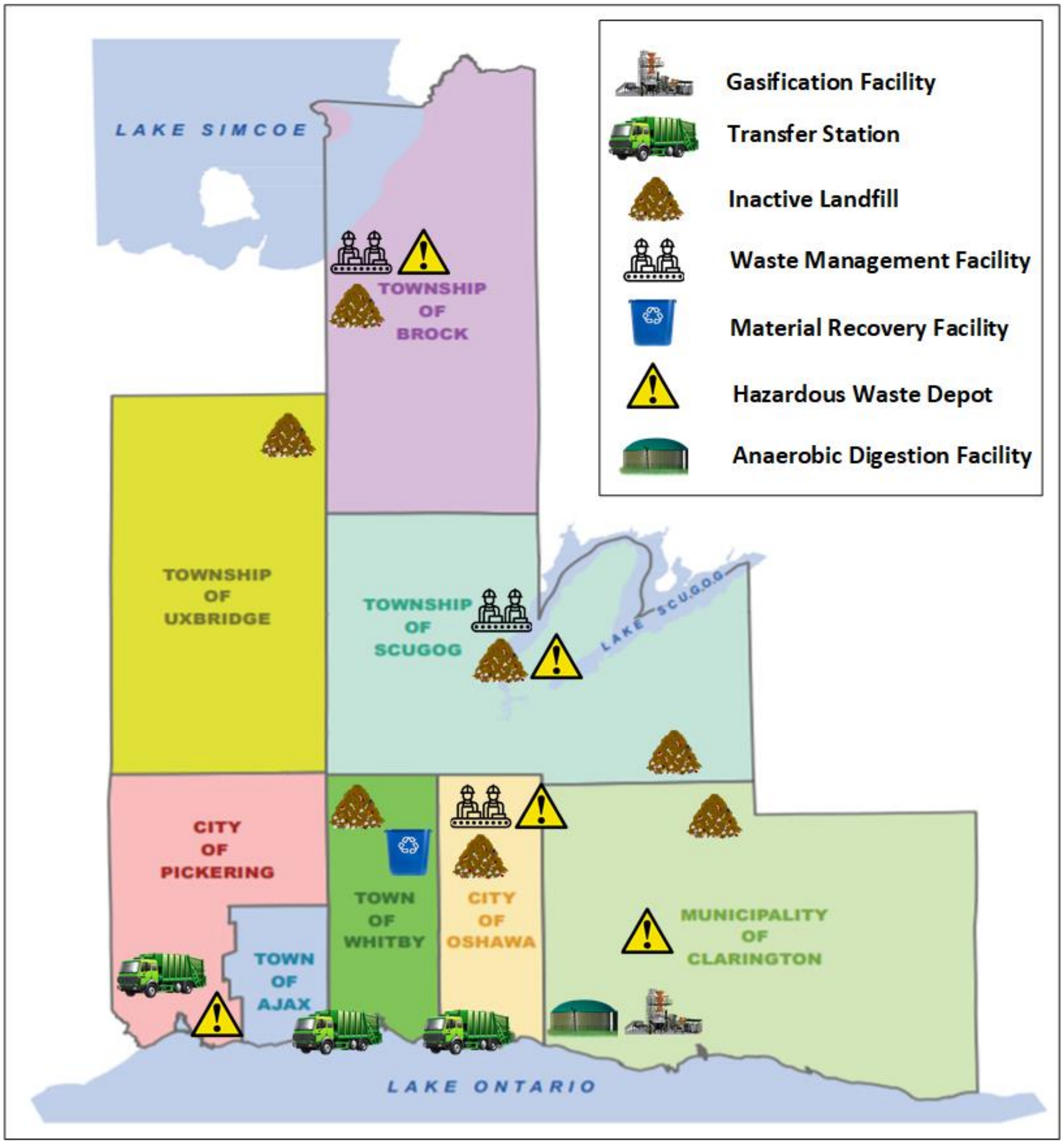

Figure 3.12: Waste Management Facility Locations in Case Study 2

Case study 3: In this case study, mixed waste pre-sort and anaerobic digestion Facility will be integrated with a pyrolysis unit. This integrated waste management system is illustrated in Figure 3.13. In the pre-sort facility, black bag garbage is sorted and processable organics are sent along with green bin, yard waste and Christmas trees collected to anaerobic digestion unit to produce biogas. Non-recyclables, unfavorable plastics, and others are sent to the pyrolysis unit along with the garbage residue for gasoline production. The total feedstock, which was sent to the pyrolysis unit, was calculated to be about 95922 tonnes per year. An environmental impact assessment will be completed and compared with the base case study.

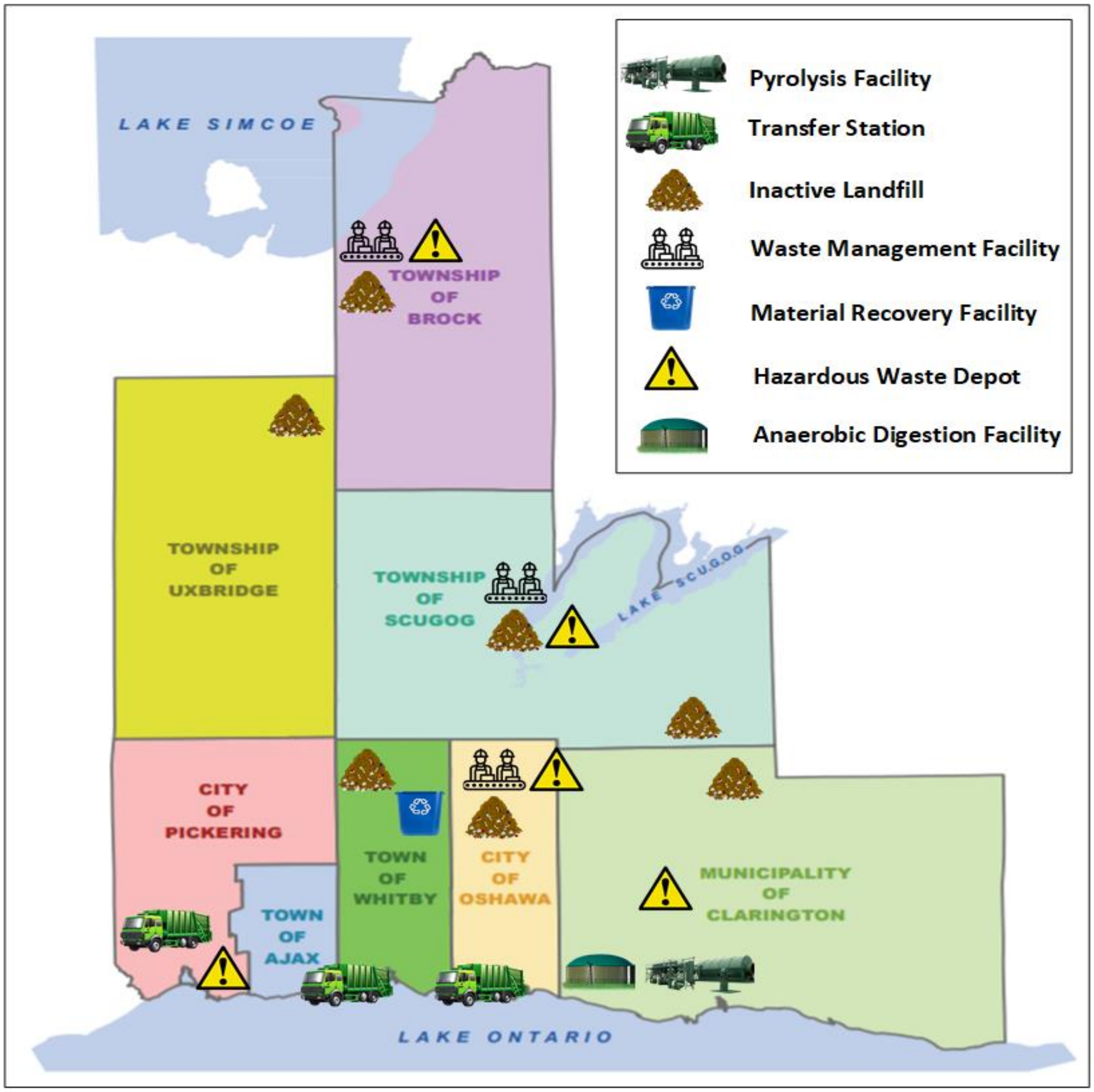

Figure 3.13: Waste Management Facility Locations in Case Study 3

3.4 Improvement Case Studies Considered for Waste Collection and Transportation in Durham Region

In this section alternatively fueled garbage collection trucks will be considered for the collection and transportation of municipal solid waste from the residential houses to waste management facilities in Durham Region. The major GHG contribution is due to the transportation of black bag garbage and organics as these waste types of account for about 90% of the total domestic solid waste generated within the region. Therefore, these case studies are conducted to investigate possible improvements in GHG emissions as a result of the black bag garbage and organics collection and transportation. The trucks considered are assumed to be using compressed natural gas, hydrogen, and electric instead of diesel fuel. An environmental impact assessment of these alternatively fueled trucks in waste transportation will be completed and compared to the existing diesel-fueled trucks. Table 3.12 demonstrates the type of diesel-fueled vehicles used for the current waste collection and transportation services in Durham Region.

Table 3.12: Current Waste Collection and Transportation Vehicles in Durham Region

Waste Type	Vehicle Type
Organics	Top Loader
Recyclables	Split Rear Loader, Side Loader
Waste/Organics	Split Rear Loader
E-waste/metal goods	Cube Van

Chapter 4: Analysis and Assessment

In this chapter, thermodynamic analysis and modeling will be defined and discussed. Furthermore, the definition of a life cycle assessment, applications of LCA in real-world settings, and LCA framework will be reviewed. Moreover, what methodology will be implemented for this study and the environmental impact assessment categories will be defined and presented in the below sections. Table 4.1 briefly explains the considered case studies for waste management, collection and transportation systems that are analyzed for Durham Region.

4.1 Thermodynamic Modelling and Analysis

A comprehensive thermodynamic analysis of the existing and improvement case study waste management systems is completed to determine the energy and exergy efficiencies of the investigated case studies. This has been demonstrated using ASPEN PLUS and Engineering Equation Solver (EES) software through mass, energy, entropy, and exergy balance equations.

Furthermore, RK-SOAVE property method is used for the simulation and analysis of the waste management systems. The electricity and fuel consumption in the facilities are observed from Durham Region. The assumptions used for the thermodynamic analysis are as follows:

- Ambient temperature is assumed to be 25°C
- Ambient pressure is assumed to be 101.325kPa
- Differences in potential and kinetic energies of the thermo fluids are not considered for the calculations.
- The isentropic efficiencies of the turbines and pumps are taken as 85% and 90%

The general mass, energy, entropy, and exergy balance equations are written for each component in the case studies considered for this study are as following

Mass Balance:

$$\sum_{i} \dot{m}_{i} = \sum_{o} \dot{m}_{o} \tag{4.1}$$

Energy Balance:

$$\sum_{net} \dot{Q}_{net} + \sum_{net} \dot{W}_{net} + \sum_{i}(h_{i} + \frac{V_{i}^{2}}{2} + gZ_{i}) = \sum_{o}(h_{o} + \frac{V_{o}^{2}}{2} + gZ_{o}) \tag{4.2}$$

Entropy Balance:

$$\sum_i \dot{m}_i s_i + \sum_{net} \frac{\dot{Q}_{net}}{T_s} + \dot{S}_{gen} = \sum_o \dot{m}_o s_o \tag{4.3}$$

Exergy Balance:

$$\sum_i \dot{Ex}_{\dot{Q}_i} + \dot{W}_i + \sum_i \dot{m}_i ex_i = \sum_o \dot{Ex}_{\dot{Q}_o} + \dot{W}_o + \sum_o \dot{m}_o ex_o + \dot{Ex}_d \tag{4.4}$$

The following equation is used to calculate the chemical exergy (CE) of the organic matters and fuels used within these integrated systems (Song et al., 2012)

$$CE_{OM} = m.\, ex_{ch,CO_2} + \frac{n}{2}.\, ex_{ch,H_2O} + \frac{q}{2}.\, ex_{ch,N_2} + r.\, ex_{ch,SO_2} - \left(m + r + \frac{n}{4} - \frac{p}{2}\right).\, ex_{ch,O_2} - \Delta G_r^0 (kj.\, kg^{-1}) \tag{4.5}$$

Where the stoichiometric equation used to calculate the coefficients is

$$C_m H_n O_q N_q S_r + \left(m + r + \frac{n}{4} + \frac{p}{2}\right) O_2 \longrightarrow mCO_2 + \frac{n}{2} H_2O + \frac{q}{2} N_2 + rSO_2 \tag{4.6}$$

4.1.1 Thermodynamic Analysis of Existing Waste Management System

In the existing waste management system, base case study, an incineration unit is used for the final disposal method of black bag garbage, which is collected from multi-residential and single residential houses. In this facility, energy recovery is achieved through the treatment of black bag garbage and sold to the grid for community use. For the organics collected in the community, which consist of food wastes, yard wastes, and Christmas trees, industrial composting is used as a main organics treatment and compost is generated as a useful output in these facilities. The compost efficiency for these industrial composting facilities is assumed to be 25%. Figure 4.1 illustrates the overall municipal solid waste flow diagram of the base case study for thermodynamic analysis.

The general composting process is shown as (Liwarska-Bizukojc & Ledakowicz, 2003):

$$OM + O_2 + nutrients \xrightarrow{Bacteria} New\ Cells + Resistant\ Organic\ Matter + H_2O + CO_2 + NH_3 + SO_4^{2-} + PO_4^{3-} + \ldots + Heat \tag{4.7}$$

The following stoichiometric reaction is for the thermodynamic analysis of the composting facilities (Liwarska-Bizukojc & Ledakowicz, 2003):

$$C_a H_b O_c N_d + \left(\frac{4a+b-2c+3d}{4}\right) O_2 \longrightarrow \left(\frac{b-3d}{2}\right) H_2O + aCO_2 + dNH_3 \tag{4.8}$$

Table 4.1: Description of Waste Management, Collection, and Transportation Case Studies

Considered Case Studies	**Description**
Base Case Study	• Black bag garbage is collected and transported to DYEC for incineration process with energy recovery while bypass garbage is sent to landfilling for final disposal. • Organics (food waste, yard waste, and Christmas trees) are transported to composting facilities for industrial composting process. • Marketable recyclables, e-waste, batteries, metal goods, and porcelain are collected and separated at MRF and WMFs to be regained into the economy.
Case Study 1	• Black bag garbage is collected and sent to a pre-sort facility along with garbage residue from MRF and WMFs to be sorted into marketable recyclables, glass, processable organics, etc. • The remaining garbage residue from this pre-sort facility is sent to DYEC for energy recovery. • Food waste, Christmas trees and yard waste are collected and transported to the AD facility along with organics from WMFs and pre-sort facility for biogas production • Marketable recyclables, e-waste, batteries, metal goods, and porcelain are collected and separated at MRF and WMFs and regained to the economy.
Case Study 2	• Black bag garbage is collected and sent to a pre-sort facility along with garbage residue from MRF and WMFs to be sorted into marketable recyclables, glass, processable organics, etc. • The remaining garbage residue from this pre-sort facility is sent to an integrated gasification combined cycle for hydrogen enriched syngas, electricity, and domestic hot water production. • Food waste, Christmas trees and yard waste are collected and transported to the AD facility along with organics from WMFs and pre-sort facility for biogas production • Marketable recyclables, e-waste, batteries, metal goods, and porcelain are collected and separated at MRF and WMFs and regained to the economy
Case Study 3	• Black bag garbage is collected and sent to a pre-sort facility along with garbage residue from MRF and WMFs to be sorted into marketable recyclables, glass, processable organics, etc. • The remaining garbage residue from this pre-sort facility is sent to a pyrolysis unit for gasoline production with energy recovery. • Food waste, Christmas trees and yard waste are collected and transported to the AD facility along with organics from WMFs and pre-sort facility for biogas production • Marketable recyclables, e-waste, batteries, metal goods, and porcelain are collected and separated at MRF and WMFs and regained to the economy
Diesel and Alternative Fueled Vehicles	• Alternative fueled vehicles (electric, hydrogen, and compressed natural gas) are compared with the diesel fueled garbage vehicles to determine possible environmental impact reductions

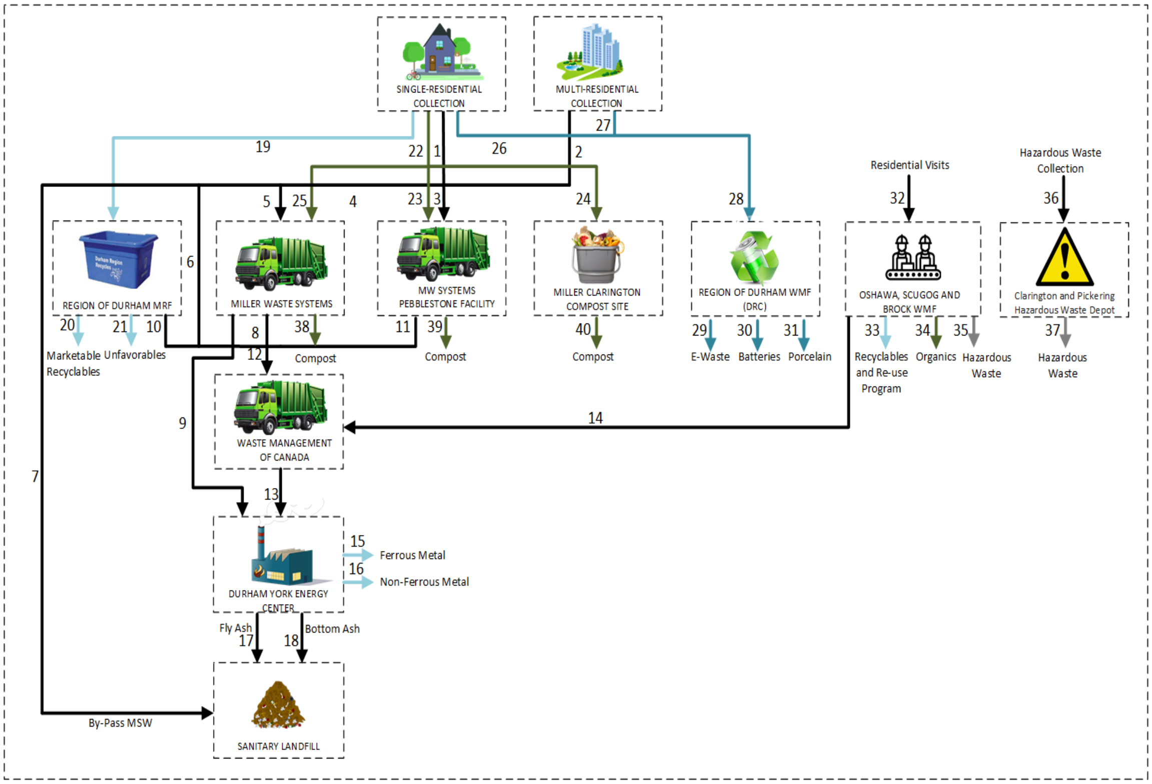

Figure 4.1: General Flow Diagram of MSW for Base Case Study

Table 4.2 demonstrates the chemical composition of food waste which is used for the thermodynamic analysis.

Table 4.2:Average Chemical Composition of food waste (Caton et al., 2010)

Element (wt.% dry)							
C	H	O	N	S	Cl	Ash	HHV (MJ/kg)
0.554	0.077	0.345	0.014	0.01	1.14	5.33	21653

The following equation is used for the energy efficiency calculation for base case study:

$$\eta = \frac{\dot{W}_{DYEC} + \dot{m}\,LHV_{c} - \sum \dot{W}_{WMF} - \sum \dot{Q}_{WMF}}{\dot{m}\,LHV_{MSW} + \dot{m}\,LHV_{NG}} \quad (4.9)$$

The below equation is used for the exergy efficiency calculation for base case study:

$$\psi = \frac{\dot{W}_{DYEC} + \dot{m}\,ex_{c} - \sum \dot{W}_{WMF} - \sum \dot{E}x_{\dot{Q}_{WMF}}}{\dot{m}\,ex_{MSW} + \dot{m}\,ex_{NG}} \quad (4.10)$$

Table 4.3 illustrates the energy, entropy, and exergy balance equations for each component within the base case study.

4.1.2 Thermodynamic Analysis and Levelized Cost Assessment of Improvement Case Studies in Waste Management Systems

In this study, three possible improvement case studies are considered to reduce overall greenhouse gas emissions and increase the energy recovery from the waste management facilities. In the improvement case studies, a mixed pre-sort and anaerobic digestion facility is implemented as the main disposal method for organics.

Black bag garbage will be mechanically separated which will allow for an increase in recycling efficiency. Furthermore, biogas will be produced through the anerobic digestion process. For the organics, the moisture content and volatile matter destruction are assumed to be 60% and 75% in the digesters.

For the energy consumption calculation in the pre-sort facility scaling approach is used which the biogas generated through the treatment of organics is calculated as follows:

$$C_aH_bO_cN_dS_e + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4} + \frac{e}{2}\right) H_2O \longrightarrow \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8} - \frac{e}{4}\right) CH_4 + \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4} + \frac{3d}{8} + \frac{e}{4}\right) CO_2 + dNH_3 + eH_2S \tag{4.11}$$

In case study 1, the pre-sort and anaerobic digestion facility is integrated with an incineration unit for the disposal of non-recyclables, unfavorable recyclables, and others. In addition, energy recovery is also achieved in this case study by the treatment of the wastes mentioned above.

Case study 1 is further explained in Section 3.4. Figure 4.2 demonstrates the overall municipal solid waste flow diagram of case study 1 for thermodynamic analysis. Table 4.4 demonstrates the energy, entropy, and exergy balance equations for each component within case study 1.

The energy efficiency of case study 1 is calculated by using the following equation:

$$\eta = \frac{\dot{W}_{DYEC} + \dot{m}\, LHV_{BG} - \Sigma\, \dot{W}_{WMF} - \Sigma\, \dot{Q}_{WMF}}{\dot{m}\, LHV_{MSW} + \dot{m}\, LHV_{NG}} \tag{4.12}$$

The exergy efficiency of case study 1 is calculated by using the equation below:

$$\psi = \frac{\dot{W}_{DYEC} + \dot{m}\, ex_{BG} - \Sigma\, \dot{W}_{WMF} - \Sigma\, \dot{Ex}_{\dot{Q}_{WMF}}}{\dot{m}\, ex_{MSW} + \dot{m}\, ex_{NG}} \tag{4.13}$$

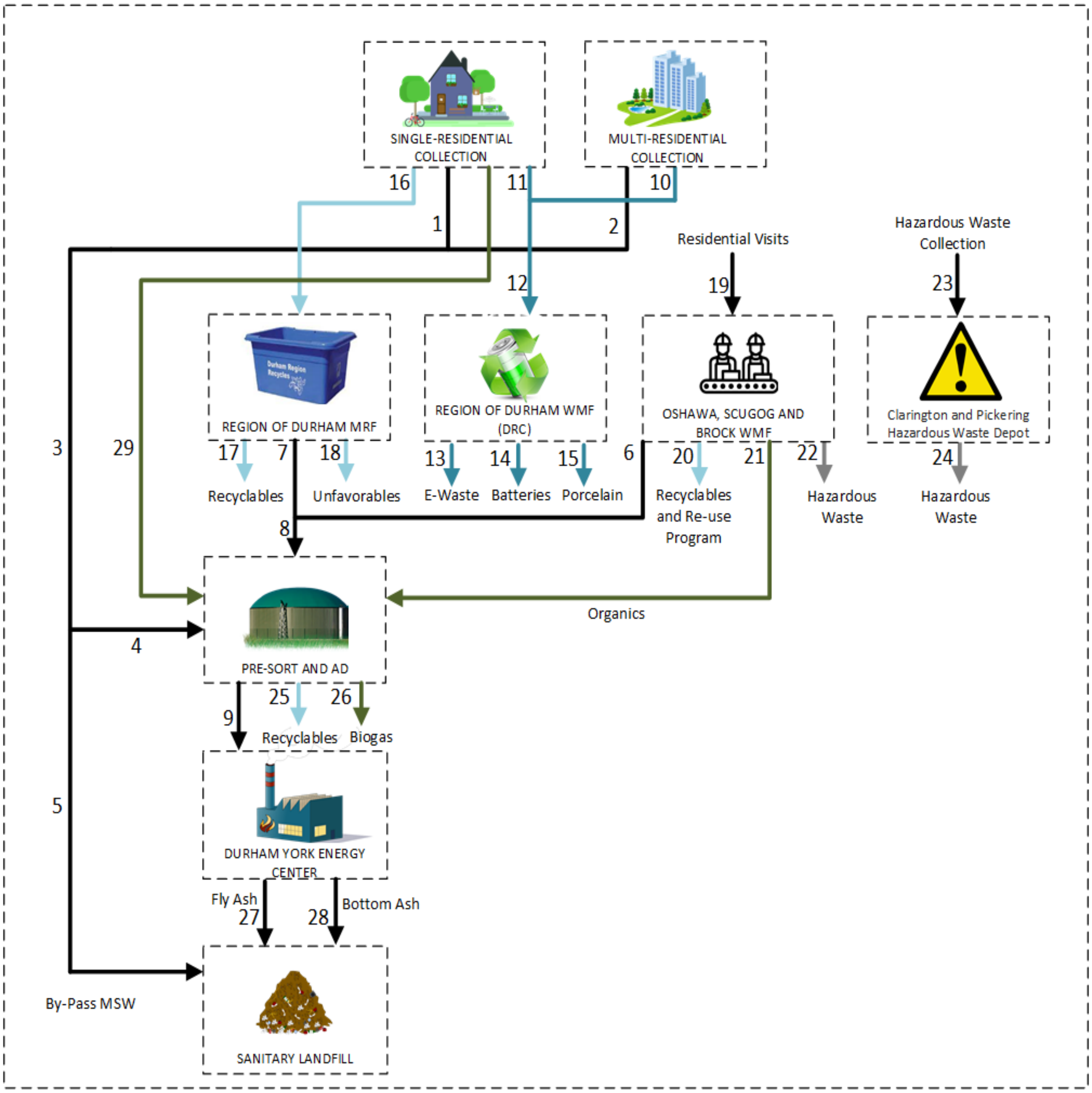

Figure 4.2: General Flow Diagram of MSW for Case Study 1

In case study 2, an integrated gasification combined cycle (IGCC) is combined with the pre-sort and anaerobic digestion unit. In this integrated gasification unit non-recyclables, unfavorable recyclables, and others are used as feedstock, which is coming from the mechanical treatment of black bag garbage, to generate hydrogen-enriched syngas. Case study 2 is further explained in Section 4.4. For this gasification reactor, the operating temperature and pressure are assumed to be 1227°C and 1650kPa. The oxygen feed ratio is chosen to be 1:10 to prevent the complete combustion of the feedstock.

Figure 4.3 demonstrate the overall municipal solid waste flow diagram of case study 2 for thermodynamic analysis. The chemical composition of the feedstock is illustrated in Table 4.3 while Table 4.6 demonstrates the energy, entropy, and exergy balance equations for each component within case study 2.

For the overall system in case study 2, the energy efficiency is found by using the equation below:

$$\eta = \frac{\dot{W}_{G} + \dot{m}\,LHV_{BG} + \dot{m}\,LHV_{SG} - \sum \dot{W}_{WMF} - \sum \dot{Q}_{WMF}}{\dot{m}\,LHV_{MSW} + \dot{m}\,LHV_{NG}} \tag{4.14}$$

Where the exergy efficiency of the system is calculated using the following equation:

$$\psi = \frac{\dot{W}_{G} + \dot{m}\,ex_{BG} + \dot{m}\,ex_{SG} - \sum \dot{W}_{WMF} - \sum \dot{Ex}_{\dot{Q}_{WMF}}}{\dot{m}\,ex_{MSW} + \dot{m}\,ex_{NG}} \tag{4.15}$$

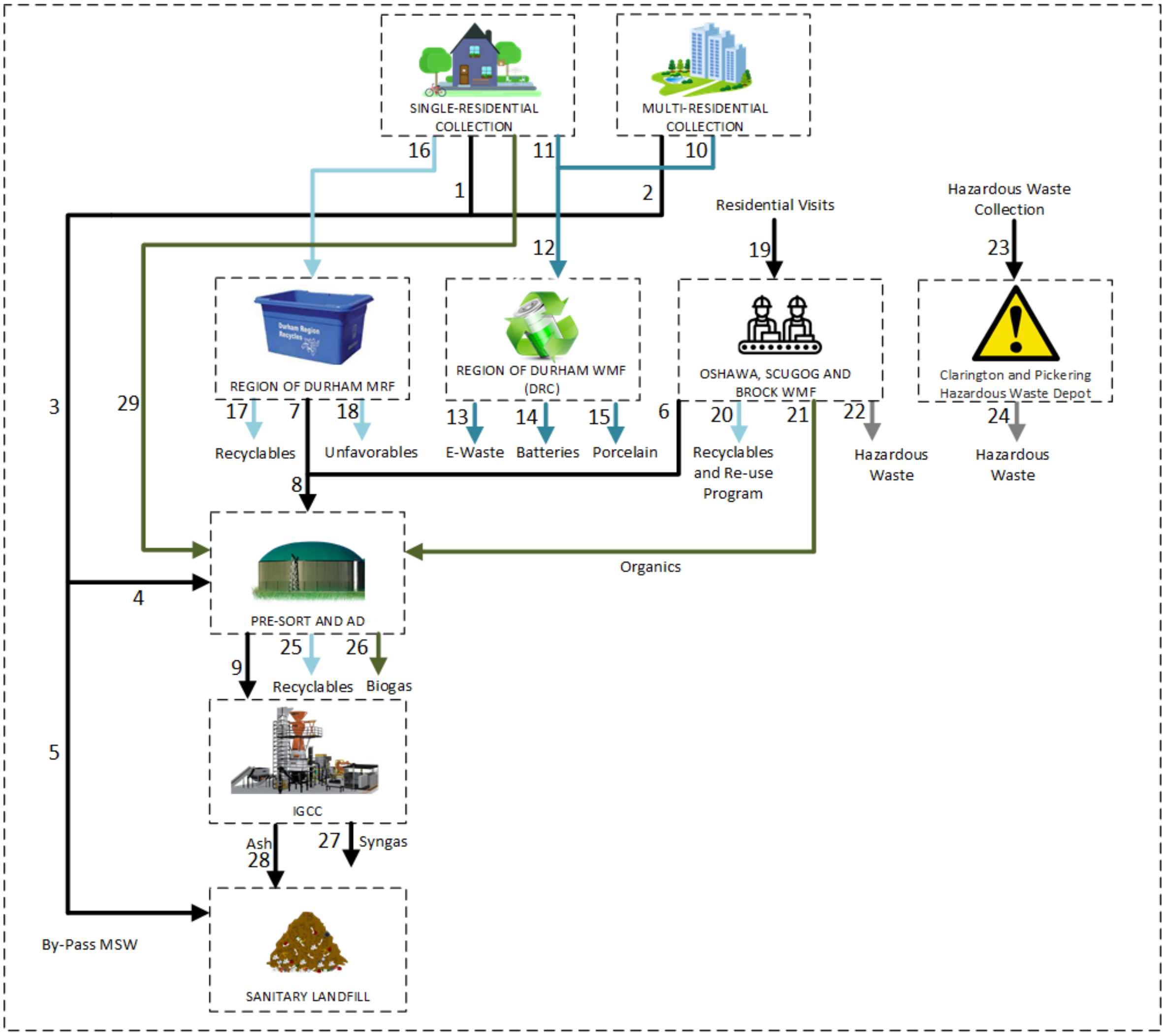

Figure 4.3:General Flow Diagram of MSW for Case Study 2

Table 4.3: Proximate and Ultimate Analysis of Mixed Non-recyclables and Unfavorable Plastics (Anuar Sharuddin et al., 2017) (Ismail et al., 2017)

		Mixed Non-Recyclables and Unfavorable plastics
Proximate Analysis	Moisture	0.22
	Fixed Carbon	6.2
	Volatile Matter	86.75
	Ash	6.83
Ultimate Analysis	C	63.94
	H	4.52
	N	0.01
	Cl	0
	S	0.04
	O	31.49
	Ash	6.83
Heating Values	HHV (MJ/kg)	24.4
	LHV (MJ/kg)	23.8

In case study 3, a pre-sort and anaerobic digestion unit is integrated with a pyrolysis unit. Non-recyclables, unfavorable plastics, and others are used as feedstock within this reactor. Case study 3 is further explained in Section 4.4. The operating temperature for this reactor is assumed to be 600°C. The gasoline range pyrolysis oil production rate is assumed to be 28% (Ben et al., 2019). Further energy is recovered from the pyrolysis gas and off-gas.

Figure 4.4 demonstrate the overall municipal solid waste flow diagram of case study 3 in this order, for thermodynamic analysis. Furthermore, Table 4.7 demonstrates the energy, entropy, and exergy balance equations for each component within case study 3.

The overall energy efficiency is calculated by the following equation:

$$\eta = \frac{\dot{W}_P + \dot{m}\,LHV_{BG} + \dot{m}\,LHV_{GN} - \sum \dot{W}_{WMF} - \sum \dot{Q}_{WMF}}{\dot{m}\,LHV_{MSW} + \dot{m}\,LHV_{NG}} \tag{4.16}$$

The overall exergy efficiency is calculated for case study 3 by using the equation below:

$$\psi = \frac{\dot{W}_P + \dot{m}\,ex_{BG} + \dot{m}\,ex_{GN} - \sum \dot{W}_{WMF} - \sum \dot{Ex}_{\dot{Q}_{WMF}}}{\dot{m}\,ex_{MSW} + \dot{m}\,ex_{NG}} \tag{4.17}$$

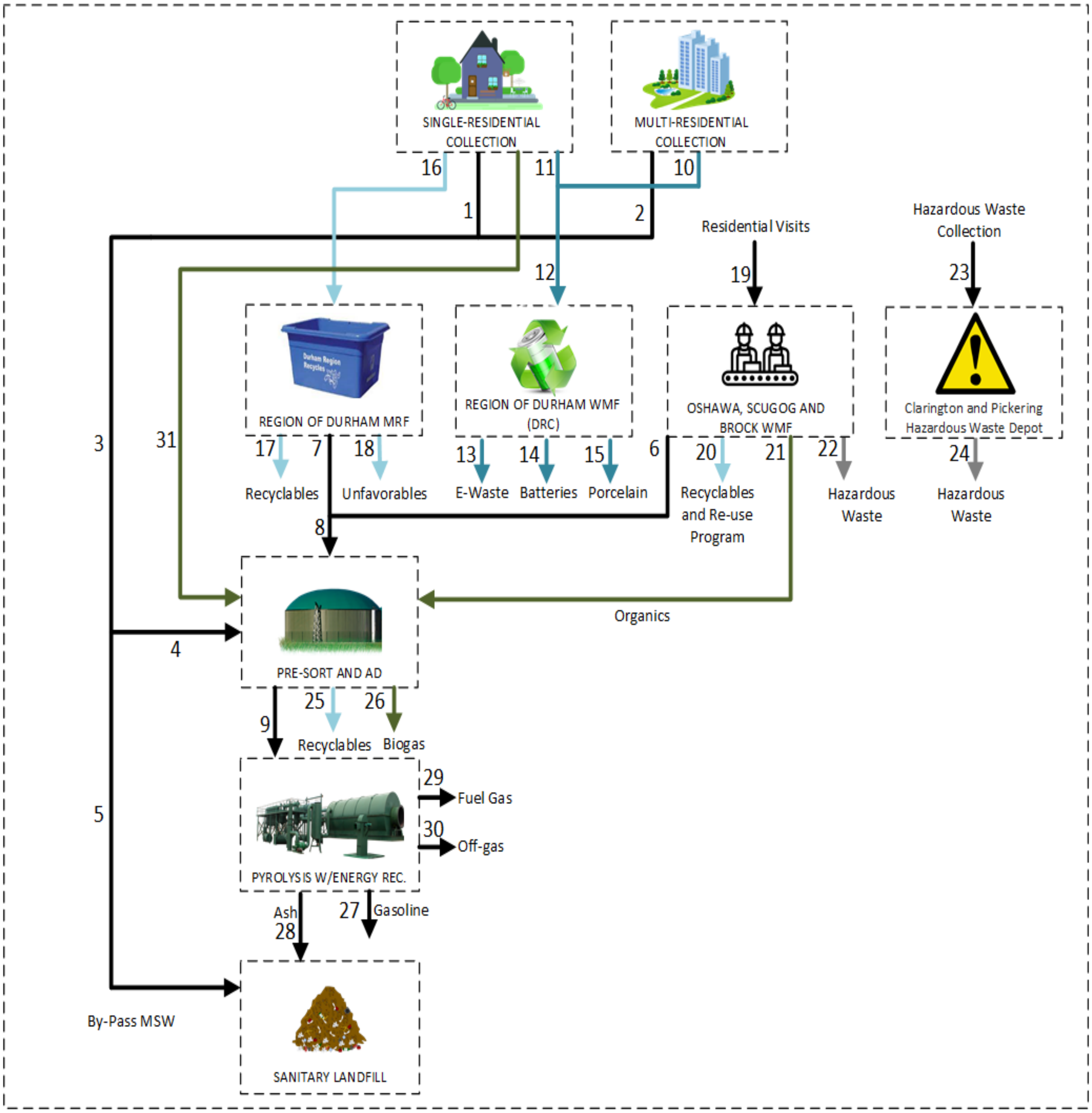

Figure 4.4: General Flow Diagram of MSW for Case Study 3

Levelized cost of electricity (LCOE) assessment of the base case study and considered improvement case studies are also conducted. Accordingly, the following equation is utilized to carry out this assessment.

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{4.18}$$

Table 4.4: Balance Equations of Each Component in Base Case Study

Component	**Energy balance equations**	**Entropy balance equations**	**Exergy balance equations**
Each pump (P)	$\dot{m}_i h_i + \dot{W}_p = \dot{m}_o h_o$	$\dot{m}_i s_i + \dot{S}_{gen,p} = \dot{m}_o s_o$	$\dot{m}_i ex_i + \dot{W}_p = \dot{m}_o ex_o + \dot{E}x_{d,p}$
Each steam turbine (ST)	$\dot{m}_i h_i = \dot{W}_{st} + \dot{m}_o h_o$	$\dot{m}_i s_i + \dot{S}_{gen,st} = \dot{m}_o s_o$	$\dot{m}_i ex_i = \dot{W}_{st} + \dot{m}_o ex_o + \dot{E}x_{d,st}$
Each expansion valve (EV)	$\dot{m}_i h_i = \dot{m}_o h_o$	$\dot{m}_i s_i + \dot{S}_{gen,XV} = \dot{m}_o s_o$	$\dot{m}_i ex_i = \dot{m}_o ex_o + \dot{E}x_{d,XV}$
Clarington and Pickering HHW	$\dot{m}_{36} h_{36} + \dot{W}_{HHW} = \dot{m}_{37} h_{37}$	$\dot{m}_{36} s_{36} + \dot{S}_{gen,HHW} = \dot{m}_{37} s_{37}$	$\dot{m}_{36} ex_{36} + \dot{W}_{HHW} = \dot{m}_{37} ex_{37} + \dot{E}x_{d,HHW}$
Durham Recycling Center (DRC)	$\dot{m}_{28} h_{28} + \dot{Q}_{DRC} + \dot{W}_{DRC} = \dot{m}_{29} h_{29} + \dot{m}_{30} h_{30} + \dot{m}_{31} h_{31}$	$\dot{m}_{28} s_{28} + \dot{Q}_{DRC}/T_s + \dot{S}_{gen,N} = \dot{m}_{29} s_{29} + \dot{m}_{30} s_{30} + \dot{m}_{31} s_{31}$	$\dot{m}_{28} ex_{28} + \dot{E}x_{\dot{Q}_{DRC}} + \dot{W}_{DRC} = \dot{m}_{29} ex_{29} + \dot{m}_{30} ex_{30} + \dot{m}_{31} ex_{31} + \dot{E}x_{d,DRC}$
Durham York Energy Center (DYEC)	$\dot{m}_9 h_9 + \dot{m}_{13} h_{13} + \dot{Q}_{DYEC} = \dot{m}_{15} h_{15} + \dot{m}_{16} h_{16} + \dot{m}_{17} h_{17} + \dot{m}_{18} h_{18} + \dot{W}_{DYEC}$	$\dot{m}_9 s_9 + \dot{m}_{13} s_{13} + \dot{Q}_{DYEC}/T_s + \dot{S}_{gen,DYEC} = \dot{m}_{15} s_{15} + \dot{m}_{16} s_{16} + \dot{m}_{17} s_{17} + \dot{m}_{18} s_{18}$	$\dot{m}_9 ex_9 + \dot{m}_{13} ex_{13} + \dot{E}x_{\dot{Q}_{DYEC}} = \dot{m}_{15} ex_{15} + \dot{m}_{16} ex_{16} + \dot{m}_{17} ex_{17} + \dot{m}_{18} ex_{18} + \dot{W}_{DYEC} + \dot{E}x_{d,DYEC}$
Durham Waste Management Facilities (WMF)	$\dot{m}_{32} h_{32} + \dot{Q}_{WMF} + \dot{W}_{WMF} = \dot{m}_{14} h_{14} + \dot{m}_{33} h_{33} + \dot{m}_{34} h_{34} + \dot{m}_{35} h_{35}$	$\dot{m}_{32} s_{32} + \dot{Q}_{WMF}/T_s + \dot{S}_{gen,WMF} = \dot{m}_{14} s_{14} + \dot{m}_{33} s_{33} + \dot{m}_{34} s_{34} + \dot{m}_{35} s_{35}$	$\dot{m}_{32} ex_{32} + \dot{E}x_{\dot{Q}_{WMF}} + \dot{W}_{WMF} = \dot{m}_{14} ex_{14} + \dot{m}_{33} ex_{33} + \dot{m}_{34} ex_{34} + \dot{m}_{35} ex_{35} + \dot{E}x_{d,WMF}$
Miller Waste	$\dot{m}_5 h_5 + \dot{m}_{25} h_{25} + \dot{W}_{MW} = \dot{m}_8 h_8 + \dot{m}_{38} h_{38} + \dot{Q}_{MW}$	$\dot{m}_5 s_5 + \dot{m}_{25} s_{25} + \dot{S}_{gen,MW} = \dot{m}_8 s_8 + \dot{m}_{38} s_{38} + \dot{Q}_{MW}/T_s$	$\dot{m}_5 ex_5 + \dot{m}_{25} ex_{25} + \dot{W}_{MW} = \dot{m}_8 ex_8 + \dot{m}_{38} ex_{38} + \dot{E}x_{\dot{Q}_{MW}} + \dot{E}x_{d,MW}$
Miller Waste Clarington	$\dot{m}_{24} h_{24} + \dot{W}_{MWC} = \dot{m}_{40} h_{40} + \dot{Q}_{MWC}$	$\dot{m}_{24} s_{24} + \dot{S}_{gen,MWC} = \dot{m}_{40} s_{40} + \dot{Q}_{MWC}/T_s$	$\dot{m}_{24} ex_{24} + \dot{W}_{MWC} = \dot{m}_{40} ex_{40} + \dot{E}x_{\dot{Q}_{MWC}} + \dot{E}x_{d,MWC}$
Miller Waste Pebblestone	$\dot{m}_{23} h_{23} + \dot{m}_3 h_3 + \dot{W}_{MWP} = \dot{m}_{11} h_{11} + \dot{m}_{39} h_{39} + \dot{Q}_{MWP}$	$\dot{m}_{23} s_{23} + \dot{m}_3 s_3 + \dot{S}_{gen,MWP} = \dot{m}_{11} s_{11} + \dot{m}_{39} s_{39} + \dot{Q}_{MWP}/T_s$	$\dot{m}_{23} ex_{23} + \dot{m}_3 ex_3 + \dot{W}_{MWP} = \dot{m}_{11} ex_{11} + \dot{m}_{39} ex_{39} + \dot{E}x_{\dot{Q}_{MWP}} + \dot{E}x_{d,MWP}$
Material Recovery Facility (MRF)	$\dot{m}_{19} h_{19} + \dot{W}_{MRF} = \dot{m}_{20} h_{20} + \dot{m}_{21} h_{21} + \dot{m}_{10} h_{10}$	$\dot{m}_{19} s_{19} + \dot{S}_{gen,MRF} = \dot{m}_{20} s_{20} + \dot{m}_{21} s_{21} + \dot{m}_{10} s_{10}$	$\dot{m}_{19} ex_{19} + \dot{W}_{MRF} = \dot{m}_{20} ex_{20} + \dot{m}_{21} ex_{21} + \dot{m}_{10} ex_{10} + \dot{E}x_{d,MRF}$
Heat recovery heat exchangers (HR)	$\sum \dot{m}_i h_i + \dot{Q}_{HR} = \sum \dot{m}_o h_o$	$\sum \dot{m}_i s_i + \dot{Q}_{HR}/T_s + \dot{S}_{gen,HR} = \sum \dot{m}_o s_o$	$\sum \dot{m}_i ex_i + \dot{E}x_{\dot{Q}_{HR}} = \sum \dot{m}_o ex_o + \dot{E}x_{d,HR}$
Each boiler (B)	$\sum \dot{m}_i h_i + \dot{Q}_B = \sum \dot{m}_o h_o$	$\sum \dot{m}_i s_i + \dot{Q}_B/T_s + \dot{S}_{gen,B} = \sum \dot{m}_o s_o$	$\sum \dot{m}_i ex_i + \dot{E}x_{\dot{Q}_B} = \sum \dot{m}_o ex_o + \dot{E}x_{d,B}$

Table 4.5: Balance Equations of Each Component in Case Study 1

Component	**Energy balance equations**	**Entropy balance equations**	**Exergy balance equations**
Each pump	$\dot{m}_i h_i + \dot{W}_p = \dot{m}_o h_o$	$\dot{m}_i s_i + \dot{S}_{gen,p} = \dot{m}_o s_o$	$\dot{m}_i ex_i + \dot{W}_p = \dot{m}_o ex_o + \dot{Ex}_{d,p}$
Each steam turbine	$\dot{m}_i h_i = \dot{W}_{st} + \dot{m}_o h_o$	$\dot{m}_i s_i + \dot{S}_{gen,st} = \dot{m}_o s_o$	$\dot{m}_i ex_i = \dot{W}_{st} + \dot{m}_o ex_o + \dot{Ex}_{d,st}$
Each expansion valve	$\dot{m}_i h_i = \dot{m}_o h_o$	$\dot{m}_i s_i + \dot{S}_{gen,XV} = \dot{m}_o s_o$	$\dot{m}_i ex_i = \dot{m}_o ex_o + \dot{Ex}_{d,XV}$
Pre-Sort and Anaerobic Digestion	$\dot{m}_{29} h_{29} + \dot{m}_8 h_8 + \dot{m}_4 h_4 + \dot{m}_{21} h_{21} + \dot{W}_{AD} = \dot{m}_9 h_9 + \dot{m}_{25} h_{25} + \dot{m}_{26} h_{26}$	$\dot{m}_{29} s_{29} + \dot{m}_8 s_8 + \dot{m}_4 s_4 + \dot{m}_{21} s_{21} + \dot{S}_{gen,AD} = \dot{m}_9 s_9 + \dot{m}_{25} s_{25} + \dot{m}_{26} s_{26}$	$\dot{m}_{29} ex_{29} + \dot{m}_8 ex_8 + \dot{m}_4 ex_4 + \dot{m}_{21} ex_{21} + \dot{W}_{AD} = \dot{m}_9 ex_9 + \dot{m}_{25} ex_{25} + \dot{m}_{26} ex_{26} + \dot{Ex}_{d,AD}$
Clarington and Pickering HHW	$\dot{m}_{23} h_{23} + \dot{W}_{HHW} = \dot{m}_{24} h_{24}$	$\dot{m}_{23} s_{23} + \dot{S}_{gen,HHW} = \dot{m}_{24} s_{24}$	$\dot{m}_{23} ex_{23} + \dot{W}_{HHW} = \dot{m}_{24} ex_{24} + \dot{Ex}_{d,HHW}$
Durham Recycling Center (DRC)	$\dot{m}_{12} h_{12} + \dot{Q}_{DRC} + \dot{W}_{DRC} = \dot{m}_{13} h_{13} + \dot{m}_{14} h_{14} + \dot{m}_{15} h_{15}$	$\dot{m}_{12} s_{12} + \dot{Q}_{DRC}/T_s + \dot{S}_{gen,DRC} = \dot{m}_{13} s_{13} + \dot{m}_{14} s_{14} + \dot{m}_{15} s_{15}$	$\dot{m}_{12} ex_{12} + \dot{Ex}_{\dot{Q}_{DRC}} + \dot{W}_{DRC} = \dot{m}_{13} ex_{13} + \dot{m}_{14} ex_{14} + \dot{m}_{15} ex_{15} + \dot{Ex}_{d,DRC}$
Durham York Energy Center (DYEC)	$\dot{m}_9 h_9 + \dot{Q}_{DYEC} = \dot{m}_{27} h_{27} + \dot{m}_{28} h_{28} + \dot{W}_{DYEC}$	$\dot{m}_9 s_9 + \dot{Q}_{DYEC}/T_s + \dot{S}_{gen,DYEC} = \dot{m}_{27} s_{27} + \dot{m}_{28} s_{28}$	$\dot{m}_9 ex_9 + \dot{Ex}_{\dot{Q}_{DYEC}} = \dot{m}_{27} ex_{27} + \dot{m}_{28} ex_{28} + \dot{W}_{DYEC} + \dot{Ex}_{d,DYEC}$
Durham Waste Management Facilities (WMF)	$\dot{m}_{19} h_{19} + \dot{Q}_{WMF} + \dot{W}_{WMF} = \dot{m}_6 h_6 + \dot{m}_{20} h_{20} + \dot{m}_{21} h_{21} + \dot{m}_{22} h_{22}$	$\dot{m}_{19} s_{19} + \dot{Q}_{WMF}/T_s + \dot{S}_{gen,WMF} = \dot{m}_6 s_6 + \dot{m}_{20} s_{20} + \dot{m}_{21} s_{21} + \dot{m}_{22} s_{22}$	$\dot{m}_{19} ex_{19} + \dot{Ex}_{\dot{Q}_{WMF}} + \dot{W}_{WMF} = \dot{m}_6 ex_6 + \dot{m}_{20} ex_{20} + \dot{m}_{21} ex_{21} + \dot{m}_{22} ex_{22} + \dot{Ex}_{d,WMF}$
Material Recovery Facility (MRF)	$\dot{m}_{16} h_{16} + \dot{W}_{MRF} = \dot{m}_{17} h_{17} + \dot{m}_7 h_7 + \dot{m}_{18} h_{18}$	$\dot{m}_{16} s_{16} + \dot{S}_{gen,MRF} = \dot{m}_{17} s_{17} + \dot{m}_7 s_7 + \dot{m}_{18} s_{18}$	$\dot{m}_{16} ex_{16} + \dot{W}_{MRF} = \dot{m}_{17} ex_{17} + \dot{m}_7 ex_7 + \dot{m}_{18} ex_{18} + \dot{Ex}_{d,MRF}$
Heat recovery heat exchangers	$\sum \dot{m}_i h_i + \dot{Q}_{HR} = \sum \dot{m}_o h_o$	$\sum \dot{m}_i s_i + \dot{Q}_{HR}/T_s + \dot{S}_{gen,HR} = \sum \dot{m}_o s_o$	$\sum \dot{m}_i ex_i + \dot{Ex}_{\dot{Q}_{HR}} = \sum \dot{m}_o ex_o + \dot{Ex}_{d,HR}$
Each boiler	$\sum \dot{m}_i h_i + \dot{Q}_B = \sum \dot{m}_o h_o$	$\sum \dot{m}_i s_i + \dot{Q}_B/T_s + \dot{S}_{gen,B} = \sum \dot{m}_o s_o$	$\sum \dot{m}_i ex_i + \dot{Ex}_{\dot{Q}_B} = \sum \dot{m}_o ex_o + \dot{Ex}_{d,B}$

Table 4.6: Balance Equations of Each Component in Case Study 2

Component	**Energy balance equations**	**Entropy balance equations**	**Exergy balance equations**
Each pump	$\dot{m}_i h_i + \dot{W}_p = \dot{m}_o h_o$	$\dot{m}_i s_i + \dot{S}_{gen,p} = \dot{m}_o s_o$	$\dot{m}_i ex_i + \dot{W}_p = \dot{m}_o ex_o + \dot{E}x_{d,p}$
Each steam turbine	$\dot{m}_{\imath} h_i = \dot{W}_{st} + \dot{m}_o h_o$	$\dot{m}_i s_i + \dot{S}_{gen,st} = \dot{m}_o s_o$	$\dot{m}_i ex_i = \dot{W}_{st} + \dot{m}_o ex_o + \dot{E}x_{d,st}$
Each expansion valve	$\dot{m}_i h_i = \dot{m}_o h_o$	$\dot{m}_i s_i + \dot{S}_{gen,XV} = \dot{m}_o s_o$	$\dot{m}_i ex_i = \dot{m}_o ex_o + \dot{E}x_{d,XV}$
Pre-Sort and Anaerobic Digestion	$\dot{m}_{29} h_{29} + \dot{m}_8 h_8 + \dot{m}_4 h_4 + \dot{m}_{21} h_{21} + \dot{W}_{AD} = \dot{m}_9 h_9 + \dot{m}_{25} h_{25} + \dot{m}_{26} h_{26}$	$\dot{m}_{29} s_{29} + \dot{m}_8 s_8 + \dot{m}_4 s_4 + \dot{m}_{21} s_{21} + \dot{S}_{gen,AD} = \dot{m}_9 s_9 + \dot{m}_{25} s_{25} + \dot{m}_{26} s_{26}$	$\dot{m}_{29} ex_{29} + \dot{m}_8 ex_8 + \dot{m}_4 ex_4 + \dot{m}_{21} ex_{21} + \dot{W}_{AD} = \dot{m}_9 ex_9 + \dot{m}_{25} ex_{25} + \dot{m}_{26} ex_{26} + \dot{E}x_{d,AD}$
Clarington and Pickering HHW	$\dot{m}_{23} h_{23} + \dot{W}_{HHW} = \dot{m}_{24} h_{24}$	$\dot{m}_{23} s_{23} + \dot{S}_{gen,HHW} = \dot{m}_{24} s_{24}$	$\dot{m}_{23} ex_{23} + \dot{W}_{HHW} = \dot{m}_{24} ex_{24} + \dot{E}x_{d,HHW}$
Durham Recycling Center (DRC)	$\dot{m}_{12} h_{12} + \dot{Q}_{DRC} + \dot{W}_{DRC} = \dot{m}_{13} h_{13} + \dot{m}_{14} h_{14} + \dot{m}_{15} h_{15}$	$\dot{m}_{12} s_{12} + \dot{Q}_{DRC}/T_s + \dot{S}_{gen,DRC} = \dot{m}_{13} s_{13} + \dot{m}_{14} s_{14} + \dot{m}_{15} s_{15}$	$\dot{m}_{12} ex_{12} + \dot{E}x_{\dot{Q}_{DRC}} + \dot{W}_{DRC} = \dot{m}_{13} ex_{13} + \dot{m}_{14} ex_{14} + \dot{m}_{15} ex_{15} + \dot{E}x_{d,DRC}$
Integrated Gasification Combined Cycle (IGCC)	$\dot{m}_9 h_9 + \dot{m}_{18} h_{18} + \dot{Q}_{IGCC} = \dot{m}_{27} h_{27} + \dot{m}_{28} h_{28} + \dot{W}_{IGCC}$	$\dot{m}_9 s_9 + \dot{m}_{18} h_{18} + \dot{Q}_{IGCC}/T_s + \dot{S}_{gen,IGCC} = \dot{m}_{27} s_{27} + \dot{m}_{28} s_{28}$	$\dot{m}_9 ex_9 + \dot{m}_{18} ex_{18} + \dot{E}x_{\dot{Q}_{IGCC}} = \dot{m}_{27} ex_{27} + \dot{m}_{28} ex_{28} + \dot{W}_{IGCC} + \dot{E}x_{d,IGCC}$
Durham Waste Management Facilities (WMF)	$\dot{m}_{19} h_{19} + \dot{Q}_{WMF} + \dot{W}_{WMF} = \dot{m}_6 h_6 + \dot{m}_{20} h_{20} + \dot{m}_{21} h_{21} + \dot{m}_{22} h_{22}$	$\dot{m}_{19} s_{19} + \dot{Q}_{WMF}/T_s + \dot{S}_{gen,WMF} = \dot{m}_6 s_6 + \dot{m}_{20} s_{20} + \dot{m}_{21} s_{21} + \dot{m}_{22} s_{22}$	$\dot{m}_{19} ex_{19} + \dot{E}x_{\dot{Q}_{WMF}} + \dot{W}_{WMF} = \dot{m}_6 ex_6 + \dot{m}_{20} ex_{20} + \dot{m}_{21} ex_{21} + \dot{m}_{22} ex_{22} + \dot{E}x_{d,WMF}$
Material Recovery Facility (MRF)	$\dot{m}_{16} h_{16} + \dot{W}_{MRF} = \dot{m}_{17} h_{17} + \dot{m}_7 h_7 + \dot{m}_{18} h_{18}$	$\dot{m}_{16} s_{16} + \dot{S}_{gen,MRF} = \dot{m}_{17} s_{17} + \dot{m}_7 s_7 + \dot{m}_{18} s_{18}$	$\dot{m}_{16} ex_{16} + \dot{W}_{MRF} = \dot{m}_{17} ex_{17} + \dot{m}_7 ex_7 + \dot{m}_{18} ex_{18} + \dot{E}x_{d,MRF}$
Heat recovery heat exchangers	$\sum \dot{m}_i h_i + \dot{Q}_{HR} = \sum \dot{m}_o h_o$	$\sum \dot{m}_i s_i + \dot{Q}_{HR}/T_s + \dot{S}_{gen,HR} = \sum \dot{m}_o s_o$	$\sum \dot{m}_i ex_i + \dot{E}x_{\dot{Q}_{HR}} = \sum \dot{m}_o ex_o + \dot{E}x_{d,HR}$
Each boiler	$\sum \dot{m}_i h_i + \dot{Q}_B = \sum \dot{m}_o h_o$	$\sum \dot{m}_i s_i + \dot{Q}_B/T_s + \dot{S}_{gen,B} = \sum \dot{m}_o s_o$	$\sum \dot{m}_i ex_i + \dot{E}x_{\dot{Q}_B} = \sum \dot{m}_o ex_o + \dot{E}x_{d,B}$

Table 4.7: Balance Equations of Each Component in Case Study 3

Component	**Energy balance equations**	**Entropy balance equations**	**Exergy balance equations**
Each pump	$\dot{m}_i h_i + \dot{W}_p = \dot{m}_o h_o$	$\dot{m}_i s_i + \dot{S}_{gen,p} = \dot{m}_o s_o$	$\dot{m}_i ex_i + \dot{W}_p = \dot{m}_o ex_o + \dot{E}x_{d,p}$
Each steam turbine	$\dot{m}_i h_i = \dot{W}_{st} + \dot{m}_o h_o$	$\dot{m}_i s_i + \dot{S}_{gen,st} = \dot{m}_o s_o$	$\dot{m}_i ex_i = \dot{W}_{st} + \dot{m}_o ex_o + \dot{E}x_{d,st}$
Each expansion valve	$\dot{m}_i h_i = \dot{m}_o h_o$	$\dot{m}_i s_i + \dot{S}_{gen,XV} = \dot{m}_o s_o$	$\dot{m}_i ex_i = \dot{m}_o ex_o + \dot{E}x_{d,XV}$
Pre-Sort and Anaerobic Digestion	$\dot{m}_{31} h_{31} + \dot{m}_8 h_8 + \dot{m}_4 h_4 + \dot{m}_{21} h_{21} + \dot{W}_{AD} = \dot{m}_9 h_9 + \dot{m}_{25} h_{25} + \dot{m}_{26} h_{26}$	$\dot{m}_{31} s_{31} + \dot{m}_8 s_8 + \dot{m}_4 s_4 + \dot{m}_{21} s_{21} + \dot{S}_{gen,AD} = \dot{m}_9 s_9 + \dot{m}_{25} s_{25} + \dot{m}_{26} s_{26}$	$\dot{m}_{31} ex_{31} + \dot{m}_8 ex_8 + \dot{m}_4 ex_4 + \dot{m}_{21} ex_{21} + \dot{W}_{AD} = \dot{m}_9 ex_9 + \dot{m}_{25} ex_{25} + \dot{m}_{26} ex_{26} + \dot{E}x_{d,AD}$
Clarington and Pickering HHW	$\dot{m}_{23} h_{23} + \dot{W}_{HHW} = \dot{m}_{24} h_{24}$	$\dot{m}_{23} s_{23} + \dot{S}_{gen,HHW} = \dot{m}_{24} s_{24}$	$\dot{m}_{23} ex_{23} + \dot{W}_{HHW} = \dot{m}_{24} ex_{24} + \dot{E}x_{d,HHW}$
Durham Recycling Center (DRC)	$\dot{m}_{12} h_{12} + \dot{Q}_{DRC} + \dot{W}_{DRC} = \dot{m}_{13} h_{13} + \dot{m}_{14} h_{14} + \dot{m}_{15} h_{15}$	$\dot{m}_{12} s_{12} + \dot{Q}_{DRC}/T_s + \dot{S}_{gen,DRC} = \dot{m}_{13} s_{13} + \dot{m}_{14} s_{14} + \dot{m}_{15} s_{15}$	$\dot{m}_{12} ex_{12} + \dot{E}x_{\dot{Q}_{DRC}} + \dot{W}_{DRC} = \dot{m}_{13} ex_{13} + \dot{m}_{14} ex_{14} + \dot{m}_{15} ex_{15} + \dot{E}x_{d,DRC}$
Pyrolysis Reactor with Energy Recovery (PR)	$\dot{m}_9 h_9 + \dot{m}_{18} h_{18} + \dot{Q}_{PR} = \dot{m}_{27} h_{27} + \dot{m}_{28} h_{28} + \dot{m}_{29} h_{29} + \dot{m}_{30} h_{30} + \dot{W}_{PR}$	$\dot{m}_9 s_9 + \dot{m}_{18} h_{18} + \dot{Q}_{PR}/T_s + \dot{S}_{gen,IGCC} = \dot{m}_{27} s_{27} + \dot{m}_{28} s_{28} + \dot{m}_{29} s_{29} + \dot{m}_{30} s_{30}$	$\dot{m}_9 ex_9 + \dot{m}_{18} ex_{18} + \dot{E}x_{\dot{Q}_{PR}} = \dot{m}_{27} ex_{27} + \dot{m}_{28} ex_{28} + \dot{m}_{29} ex_{29} + \dot{m}_{30} ex_{30} + \dot{W}_{PR} + \dot{E}x_{d,PR}$
Durham Waste Management Facilities (WMF)	$\dot{m}_{19} h_{19} + \dot{Q}_{WMF} + \dot{W}_{WMF} = \dot{m}_6 h_6 + \dot{m}_{20} h_{20} + \dot{m}_{21} h_{21} + \dot{m}_{22} h_{22}$	$\dot{m}_{19} s_{19} + \dot{Q}_{WMF}/T_s + \dot{S}_{gen,WMF} = \dot{m}_6 s_6 + \dot{m}_{20} s_{20} + \dot{m}_{21} s_{21} + \dot{m}_{22} s_{22}$	$\dot{m}_{19} ex_{19} + \dot{E}x_{\dot{Q}_{WMF}} + \dot{W}_{WMF} = \dot{m}_6 ex_6 + \dot{m}_{20} ex_{20} + \dot{m}_{21} ex_{21} + \dot{m}_{22} ex_{22} + \dot{E}x_{d,WMF}$
Material Recovery Facility (MRF)	$\dot{m}_{16} h_{16} + \dot{W}_{MRF} = \dot{m}_{17} h_{17} + \dot{m}_7 h_7 + \dot{m}_{18} h_{18}$	$\dot{m}_{16} s_{16} + \dot{S}_{gen,MRF} = \dot{m}_{17} s_{17} + \dot{m}_7 s_7 + \dot{m}_{18} s_{18}$	$\dot{m}_{16} ex_{16} + \dot{W}_{MRF} = \dot{m}_{17} ex_{17} + \dot{m}_7 ex_7 + \dot{m}_{18} ex_{18} + \dot{E}x_{d,MRF}$
Heat recovery heat exchangers	$\sum \dot{m}_i h_i + \dot{Q}_{HR} = \sum \dot{m}_o h_o$	$\sum \dot{m}_i s_i + \dot{Q}_{HR}/T_s + \dot{S}_{gen,HR} = \sum \dot{m}_o s_o$	$\sum \dot{m}_i ex_i + \dot{E}x_{\dot{Q}_{HR}} = \sum \dot{m}_o ex_o + \dot{E}x_{d,HR}$
Each boiler	$\sum \dot{m}_i h_i + \dot{Q}_B = \sum \dot{m}_o h_o$	$\sum \dot{m}_i s_i + \dot{Q}_B/T_s + \dot{S}_{gen,B} = \sum \dot{m}_o s_o$	$\sum \dot{m}_i ex_i + \dot{E}x_{\dot{Q}_B} = \sum \dot{m}_o ex_o + \dot{E}x_{d,B}$

4.2 Definition of Life Cycle Assessment

The traditional environmental management tools evaluate the environmental impact using a single point of view. However, environmental problems are caused by various factors which are all interconnected with each other. When using LCA as an environmental management tool, analysis of the product's entire life cycle is considered with a multi-dimensional view to be able to make critical environmental decisions (Hoekstra & Wiedmann, 2014) (Ren & Toniolo, 2019).

Life cycle assessment is a useful decision-making tool to investigate and interpret possible environmental impacts of a product, a process, or an activity with a holistic approach. The complete life cycle assessment includes raw material mining, transportation, production, product use, maintenance, recycling, and final treatment processes within the product's life cycle (Ren & Toniolo, 2019). LCA adapts the cradle-to-grave approach to evaluate the processes holistically to reduce environmental impacts caused by the above processes of a product, process, or activity.

LCA has evolved throughout the years, it began as a simple environmental approach to assess the environmental impacts of a product, process, or activity. LCA has now developed into standardized environmental management that is widely used as a decision-making tool for new products, systems, and technologies. Furthermore, by implementing LCA the indirect environmental effects through the life cycle of a product can be investigated and evaluated (Curran, 2012).

4.3 Applications of Life Cycle Assessment

LCA is an environmental decision-making technique that is standardized according to ISO 14040 and is associated with the cradle-to-grave approach. LCA has become an important tool because of increased environmental awareness on the public, industry, and government side. The most significant applications within LCA include the evaluation of the life cycle stages to decrease the environmental burden of products, processes, or activities and to internally compare between each product, process, and activity (Muralikrishna & Manickam, 2017). LCA can be used in different areas including industry and enterprise sectors, and government administration and international organizations. Sections 3.2.1 and

3.2.2 further describe the use of LCA in these various sectors and organizations (Ren & Toniolo, 2019).

4.3.1 LCA in Industry and Enterprise Sectors

LCA is used regularly in industrial applications and businesses for production processes, long terms planning, and logistic analysis. The areas where the LCA is implemented include:

- Determining and analyzing the products and their overall system
- Interpreting the environmental impact assessment results and comparing the life cycle assessment of the products and processes
- Considering possible improvements in the products and investigating their possible environmental effects
- Evaluating waste management and creating cleaner processes for the products life cycle (Houillon & Jolliet, 2005) (Perugini et al., 2004) (Lopes et al., 2002)

4.3.2 LCA in Government Administration and International Organizations

LCA can shape environmental guidelines, policies, and legislations implemented by government administrations and international organizations. The major ways in which LCA effect these policies include:

- Recognizing the regional and global environmental issues to create sustainable economies.
- Setting environmental product standards
- Prioritizing waste recovery and recycling and implementing tax, credit, investment, and environmental policies.
- Minimizing energy consumption caused by improper waste management systems (i.e., transportation, fuel consumption, electricity, etc.)
- Increasing environmental awareness by developing green policies and guidelines. (Reich, 2005) (Funazaki et al., 2003) (Park et al., 2003) (Chevalier et al., 2003)

4.4 Life Cycle Assessment Framework

This section focuses on the general framework of the LCA process which is standardized by ISO 14040. There are four stages in a complete LCA, to generate accurate results individuals should follow these stages accordingly. These four main stages for the LCA process consist of:

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

Sections 4.4.1, 4.4.2, 4.4.3, and 4.4.4 further describe the above stages of the LCA analysis. Figure 4.5 demonstrates the framework of LCA according to EN ISO 14040.

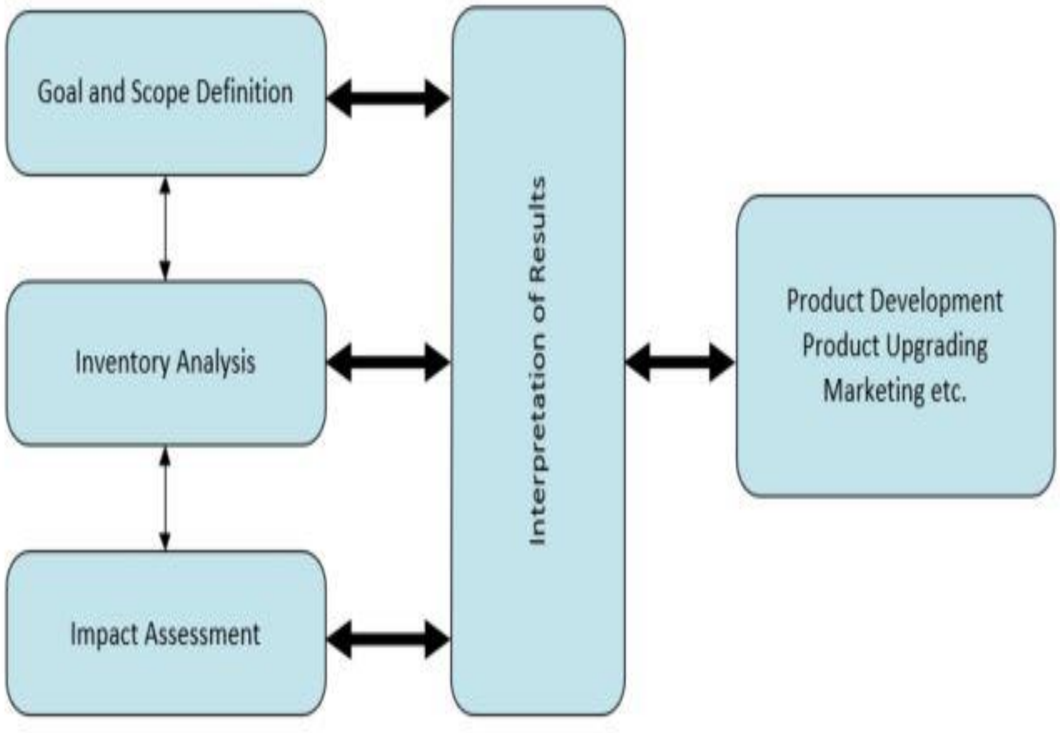

Figure 4.5: LCA Framework according to EN ISO 14040

4.4.1 Goal and Scope Definition

This stage defines the study's objectives, systems boundaries, functional units, methodology, and assumptions made while completing the study. Furthermore, it identifies the life cycle of the specific product, process, or activity and how the LCA will assess and address the overall environmental impact assessment. This is a critical step as these definitions influence the objective and outcome of the study (Muralikrishna & Manickam, 2017) (Yue et al., 2013) (Guinée, 2001).

4.4.2 Inventory Analysis

The next stage of the LCA framework is the inventory analysis. This phase describes the material and energy flows that occur in the system. All inputs and outputs within the system, according to the functional units, are entered in this phase. Some examples of inputs and outputs necessary for the life cycle inventory (LCI) include materials, energy, chemicals, air/water emissions, solid waste, etc. The use of site-specific data is a significant measure for the correctness of a life cycle assessment study (Muralikrishna & Manickam, 2017) (International organization for standardization, 2004).

4.4.3 Impact Assessment

In this stage of the LCA framework, the data entered from the previous stage is used to complete an impact assessment. Impact assessment is made up of various components including classification, characterization, normalization, and valuation. The results calculated are given in detail according to the impact categories based on the selected methodology. In this study, CML-IA is selected as a life cycle impact assessment method (Muralikrishna & Manickam, 2017) (Ren & Toniolo, 2019).

4.4.4 Interpretation

The last stage of the LCA framework is interpretation, summary, and discussion of the collected and analyzed data. Furthermore, the limits and possible improvement case studies of the study are discussed (Muralikrishna & Manickam, 2017) (Ren & Toniolo, 2019).

4.5 Environmental Impact Assessment Methodology

A complete life cycle of a product includes substance emissions and resource extractions depending on their environmental relevance. Life cycle impact assessment (LCIA) is used to interpret the product's emissions and resources extractions by categorizing and scoring them according to the impact assessment category in the selected method. LCIA is completed using characterization factors and the functional unit is selected to be kilogram kilometers (kg km). for this study (Hauschild & Huijbregts, 2015). In this study, CML-IA is selected as a life cycle impact assessment method. The following sections describe each impact category used in the CML-IA method.

4.5.1 CML-IA Method

CML-IA was developed by the Center of Environmental (CML) of Leiden University in the Netherlands. This software is an updated version of the CML-IA and uses a problem-oriented approach. A baseline indicator was selected to ensure the best problem-oriented approach when looking at the impact categories. Due to CML-IA being a problem-focused approach it is widely used when completing LCA studies. The following sections below describe each impact category within the considered methodology. The impact categories and their units for this study are demonstrated in Table 4.8..

Table 4.8: CML-IA Environmental Impact Categories and Unit Definitions

Impact Category	**Unit Definition**
Abiotic depletion potential (ADP) (kg Sb-eq)	Kilogram of Antimony equivalent
Acidification potential (AP) (kg SO_2-eq)	Kilogram of Sulphur dioxide equivalent
Global warming potential (GWP) (kg CO_2-eq)	Kilogram of Carbon dioxide equivalent
Ozone layer depletion potential (ODP) (kg CFC-11-eq)	Kilogram of Trichlorofluoromethane equivalent
Human toxicity potential (HTP) (kg 1,4-DB-eq)	Kilogram of 1,4-dichlorobenzene equivalent

4.5.2 Abiotic Depletion Potential (ADP)

This impact category investigates any possible effects on human welfare, human health, and ecosystem health. This impact category is directly connected to the extraction of minerals and fossil fuels as a result of the inputs within the boundary layer in the system. The ADP is calculated based on kg antimony equivalents/kg extraction, meaning it looks at the extraction of the above inputs based on concentration reserves and its depletion rate (SimaPro, 2014).

4.5.3 Acidification Potential (AP)

Acidification potential indicates impacts on soil, groundwater, surface water, organisms, ecosystems, and materials. This impact category is calculated with RAINS 10 model which is based on the fate and deposition of acidifying substances. The AP unit is shown as kg SO_2 equivalent/kg emission (SimaPro, 2014).

4.5.4 Global Warming Potential (GWP)

Climate change is caused by greenhouse gases emitted into the air which can have negative effects on ecosystem health, human health, and human welfare. This model was developed by Intergovernmental Panel on Climate Change (IPCC). This impact category is defined as global warming potential for time horizon 100 years (GWP100) and is expressed as kg carbon dioxide/kg emission (SimaPro, 2014).

4.5.5 Ozone Layer Depletion Potential (ODP)

As a result of stratospheric ozone depletion, a large amount of UV-B radiation penetrates the earth's surface and this can result in negative effects on human health, animal health, terrestrial and aquatic ecosystems, biochemical cycles, etc. This impact category was created by the World Meteorological Organization (WMO) and defined as kg CFC-11 equivalent/kg emission (SimaPro, 2014).

4.5.6 Human Toxicity Potential (HTP)

Human toxicity potential focuses on the effects of toxic substances on the human environment. This impact category uses USES-LCA, describing the fate, exposure, and effects of toxic substances for an infinite time span. HTP is expressed as 1,4-dichlorobenzene equivalents/kg emission (SimaPro, 2014).

Chapter 5: Results and Discussion

In this study, a comprehensive thermodynamics analysis, section 5.1, of the existing waste management system and proposed waste-to-energy systems is completed to determine the energy and exergy efficiencies of each case study. Furthermore, a life cycle assessment is also completed to improve GHG emissions caused by the management of municipal solid waste in Durham Region. In this chapter, the LCA modeling of the existing waste management system in Durham Region and possible improvement case studies are completed via SimaPro software. CML-IA method is selected to carry out this LCA modeling, as further explained in section 5.2.

The existing waste management system is compared with possible improvement waste management systems based on the environmental impact categories which will be further discussed in section 5.3. In section 5.4, the existing collection and transportation trucks are investigated according to the environmental impact categories and compared with alternative fueled trucks.

5.1 Thermodynamic Analysis and Levelized Cost Assessment of Considered Improvement Case Studies for Waste Management Systems in Durham Region

A comprehensive thermodynamic analysis is completed for the existing waste management system in Durham Region and possible improvement case studies in addition to their LCA to investigate the systems' feasibilities. In this section, the analytic results of the integrated systems and their subsystems are discussed in detail. ASPEN PLUS and Engineering Equation Solver software are used for the thermodynamic calculations through simulations and stoichiometric equations. The results are generated based on RK-SOAVE property method and the overall energy and exergy efficiencies for the base case study, case study 1, case study 2, and case study 3 are given in Figure 5.1.

Furthermore, a levelized cost of electricity assessment is completed for the base case study and proposed case studies. The base case study is found to have the highest cost per kilowatt hour among all case studies with the value of 0.24$/kWh while case study 1 is observed to be the most cost-efficient case study with 0.16$/kWh due to the integration of a mixed pre-sort and anaerobic digestion facility. These values are followed by case study 3 and case study 2 with 0.18$/kWh and 0.23$/kWh.

As illustrated in Figure 5.1, case study 2 has the highest energy and exergy efficiency with 58% and 56%, respectively, due to the higher energy recovery through an integrated gasification system. This is followed by case study 3, where gasoline is generated as a useful output, with 40% and 39%, in this order while the existing waste management case study is observed to have the least energy and exergy efficiency with 23% and 22%, respectively. A thermodynamic analysis is also completed for each municipal solid waste management process, which is used in the above case studies. Figure 5.2 demonstrates these processes' overall energy and exergy efficiencies.

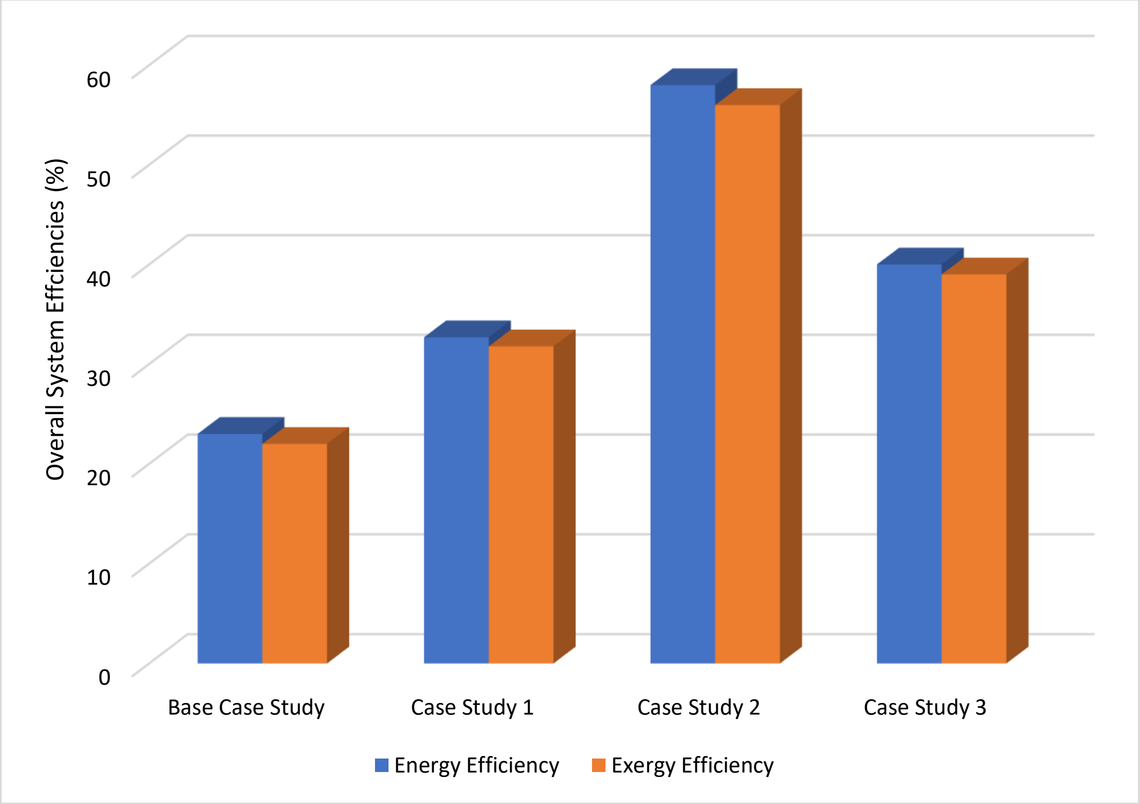

Figure 5.1: Overall Energy and Exergy Efficiencies for Waste Management Systems

As seen in Figure 5.2, the gasification process is calculated to have the highest energy and exergy efficiency among all the municipal solid waste processes with 74% and 72%, respectively. This is followed by the anaerobic digestion of organics, pyrolysis of non-recyclables and unfavorable plastics and composting of organics processes. However, the existing incineration system is observed to be the least energy and exergy efficiencies with 22.5% and 21.3%, in this order. The following sections discuss the thermodynamic analysis of these systems in more detail.

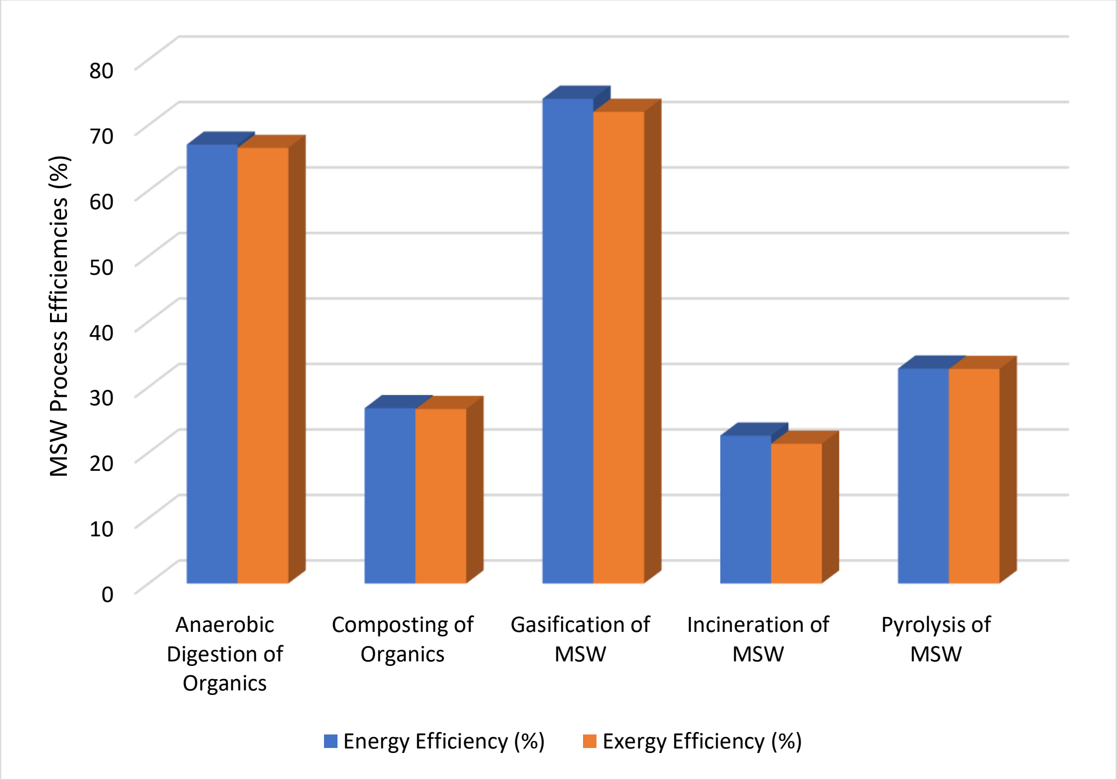

Figure 5.2: Municipal Solid Waste Processes Energy and Exergy Efficiencies

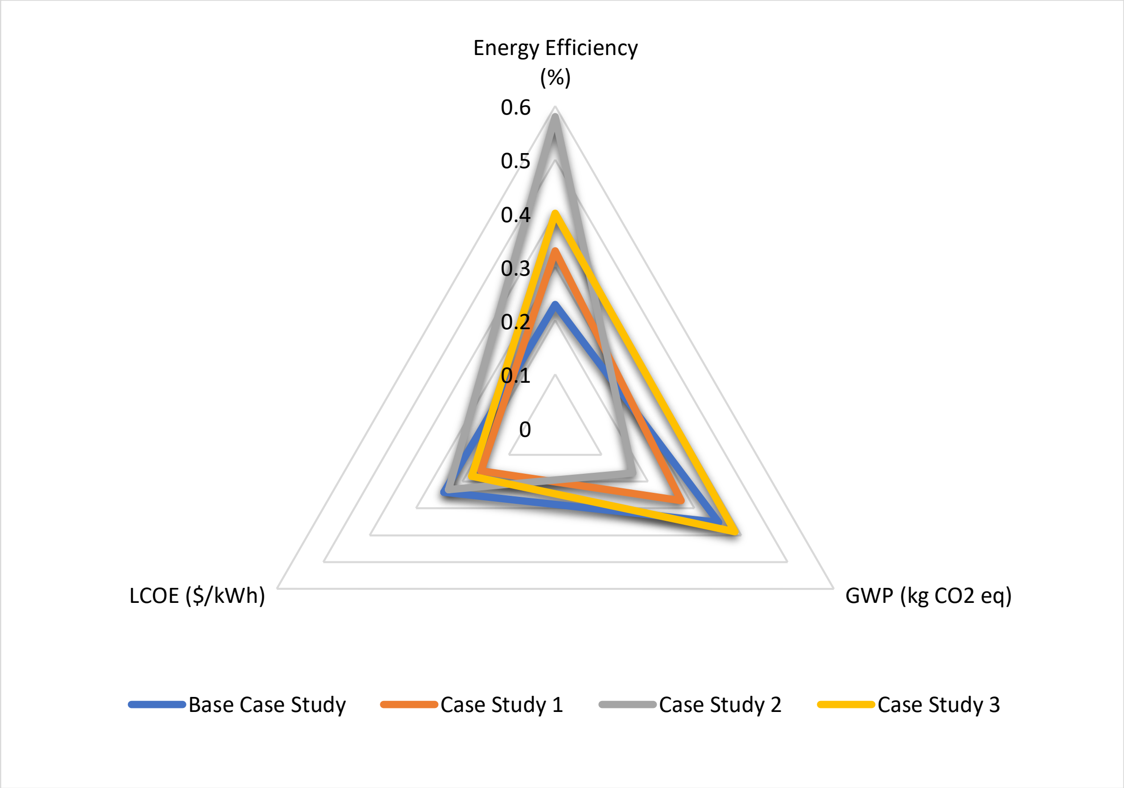

Figure 5.3: Sustainability Perspective of Baseline and Improvement Case Studies

The base case study and proposed case studies are investigated based on the correlation between their energy efficiency, levelized cost of electricity, and global warming potential to determine overall sustainability. As seen in the figure above, case study 2 where a mixed pre-sort and anaerobic digestion facility is integrated with an IGCC, shows much higher sustainability compared to the base case study and other case studies. This is because this case study has the highest energy efficiency with the least global warming potential and a competitive levelized cost of electricity compared to the other case studies.

5.1.1 Thermodynamic Analysis of Base Case Study

Thermodynamic analysis of the existing waste management system in Durham Region is completed according to the data obtained from the Region. In this case study, composting facilities are used as the main treatment method for organics while an incinerator is used for the black bag garbage disposal process where the energy recovery rate was observed to be 14363 kW.

In Durham Region, there are three industrial composting facilities, Miller Waste, Miller Waste Pebblestone, and Miller Waste Clarington. In these facilities, the total compost production rate is calculated to be 0.49 kg/s by the treatment of the organic matter.

The exergy destruction rates are also calculated for each waste management facility in Durham Region, and as expected, Durham York Energy Center has the highest exergy destruction with 50124 kW. This is followed by Miller Waste, Miller Waste Clarington, and Miller Waste Pebblestone with 4836 kW, 3930 kW, and 2568 kW, in this order. The detailed exergy destruction rates for each waste management facility in this case study are illustrated in Figure 5.4.

According to the thermodynamic analysis, the energy and exergy efficiencies of the composting facilities are calculated to be 27% and 28%, respectively. For the incinerator, Durham York Energy Center, the energy, and exergy efficiencies are observed to be 23% and 21%, respectively. The overall waste management system efficiency was the lowest compared to other case studies with 23% and 22%, in that order.

A parametric study is also conducted to investigate possible improvements in the overall energy and exergy efficiencies by varying the composting process efficiency in the industrial composting facilities. The composting efficiency is varied from 10% to 40% and the results are shown in Figure 5.5. Expectedly, as the composting efficiency increases, both energy and exergy efficiency show an increasing trend. The highest energy and exergy efficiency are observed as 26.65% and 25.75% when the composting efficiency is 40%.

Another parametric study is completed to investigate seasonal energy and exergy efficiencies of the base case study by changing ambient temperature. The ambient temperature varied based on the monthly average air temperature in Durham Region. As demonstrated in Figure 5.6, the baseline shows the greatest energy and exergy efficiencies in the summer months with the highest value of 22.1% and 21.1%, respectively in the month of July.

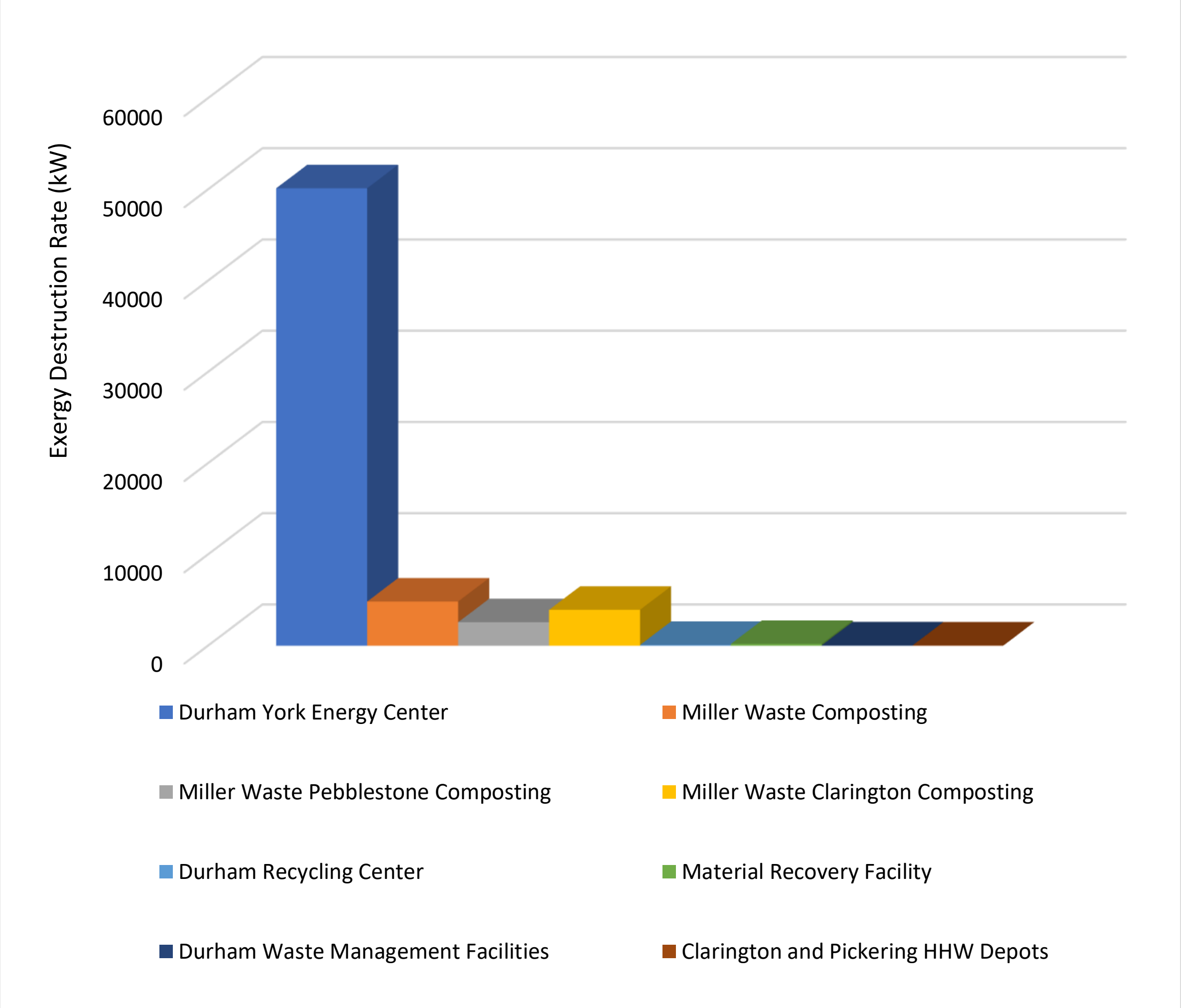

Figure 5.4: Exergy Destruction Analysis of Waste Management Facilities for Base Case Study

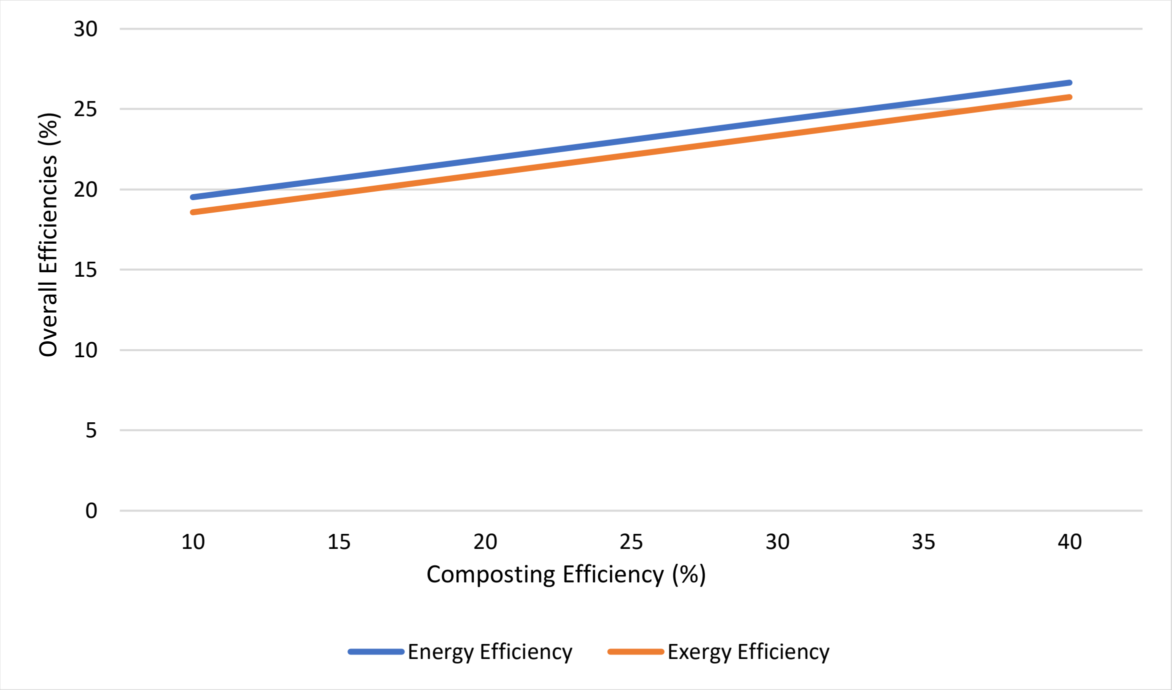

Figure 5.5: Impact of Varying Composting Efficiency on Energy and Exergy Efficiencies

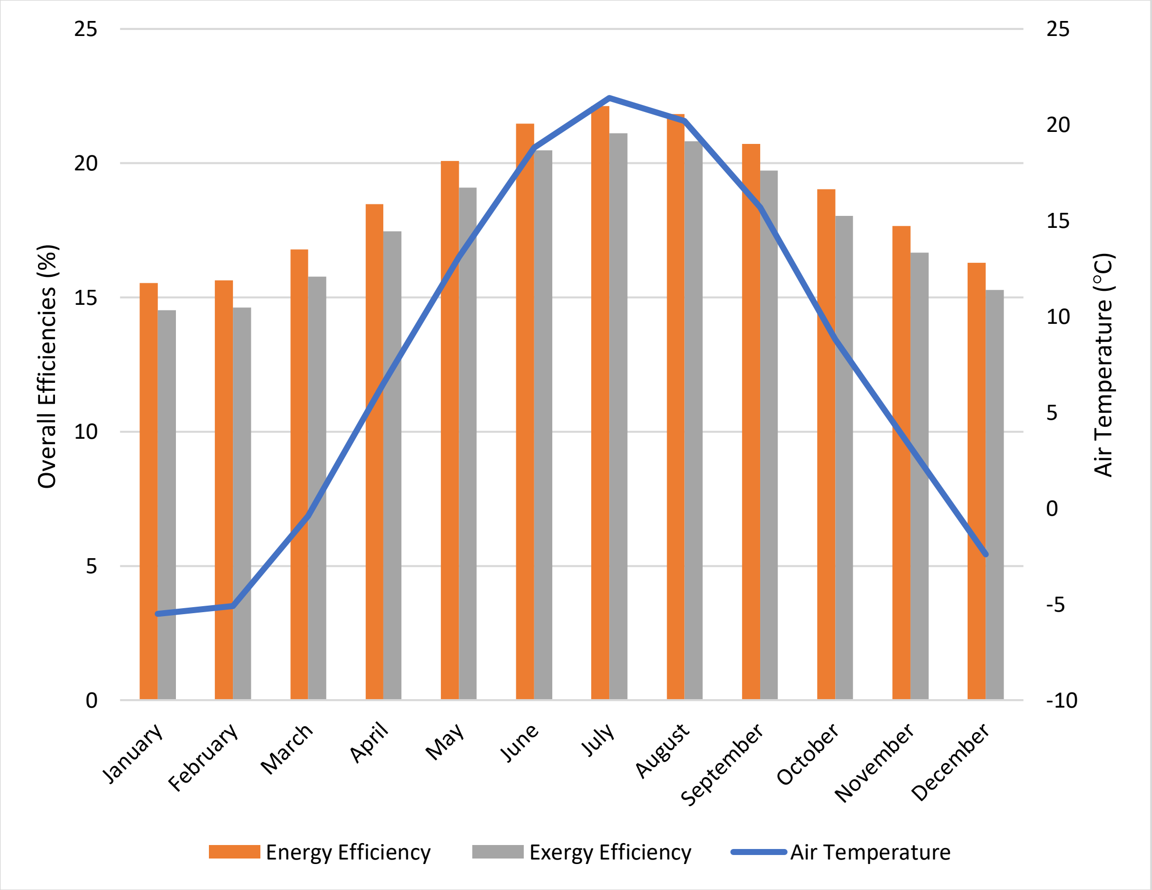

Figure 5.6: Impact of Varying Air Temperature on Overall Efficiencies for Base Case Study

5.1.2 Thermodynamic Analysis of Case Study 1

In case study 1, a pre-sort and anaerobic digestion facility is integrated with an incinerator, Durham York Energy Center, to increase energy recovery through the utilization of waste. In the pre-sort facility, black bag garbage is mechanically sorted, and the recyclable components are regained and processable organics with the rest of the organics are sent to an anaerobic digestion facility. The total biogas production rate in the digestors is calculated to be 8253.66 m^3/h and the net heating value of this biogas is observed to be 16855.1 kJ/kg from ASPEN PLUS.

The volumetric biogas composition is given in Figure 5.7. Non-recyclables and unfavorable plastics are sent to Durham York Energy Center as a final disposal method. The energy output rate is calculated to be 17070 kW in the above facility.

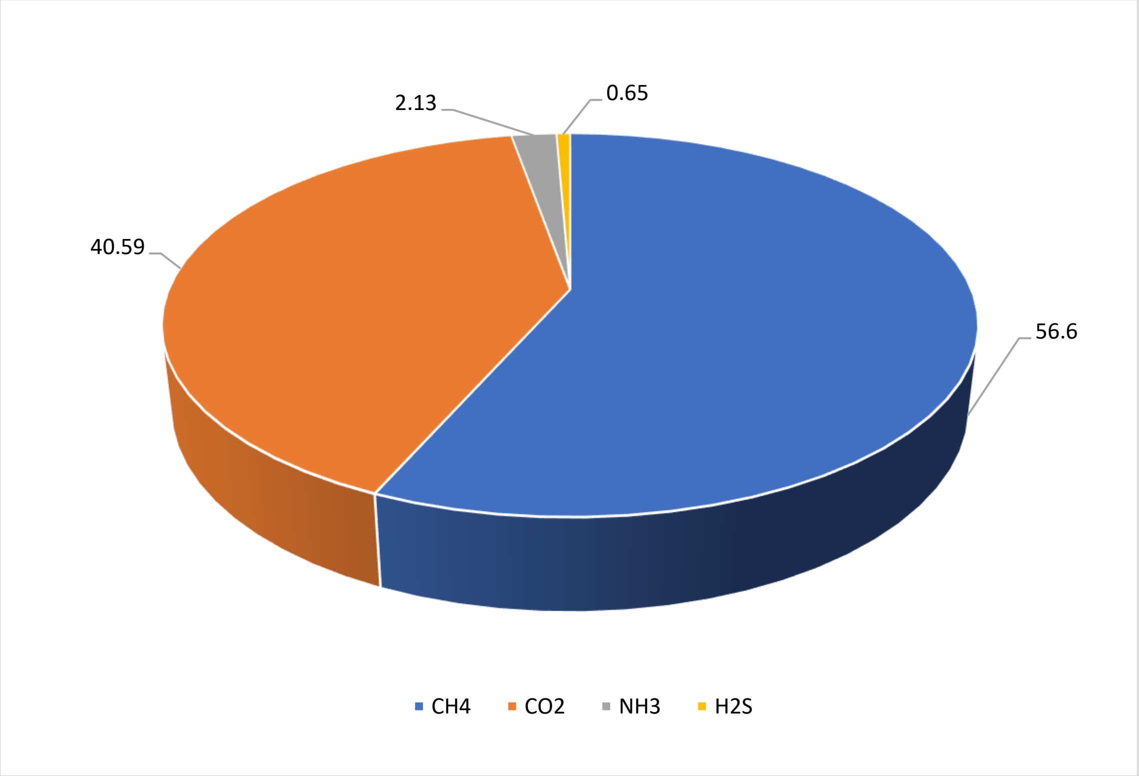

Figure 5.7: Volumetric Biogas Composition in AD

Exergy destruction rates are also calculated for the waste management facilities for case study 1. As seen in Figure 5.8, Durham York Energy Center has the highest exergy rate of 62135 kW and this followed by an anaerobic digestion facility and pre-sort facility with an exergy destruction rate of 2999 kW and 452.53 kW, respectively.

According to the thermodynamic analysis, the energy efficiencies of Durham York Energy Center and the anaerobic digestion facility are observed to be 23% and 67%, respectively. Furthermore, the exergy efficiencies of these two facilities are calculated to be 21% and 66.5%, in this order. Finally, the overall energy and exergy efficiency of this integrated system are found to be 32.7% and 31.8%, respectively.

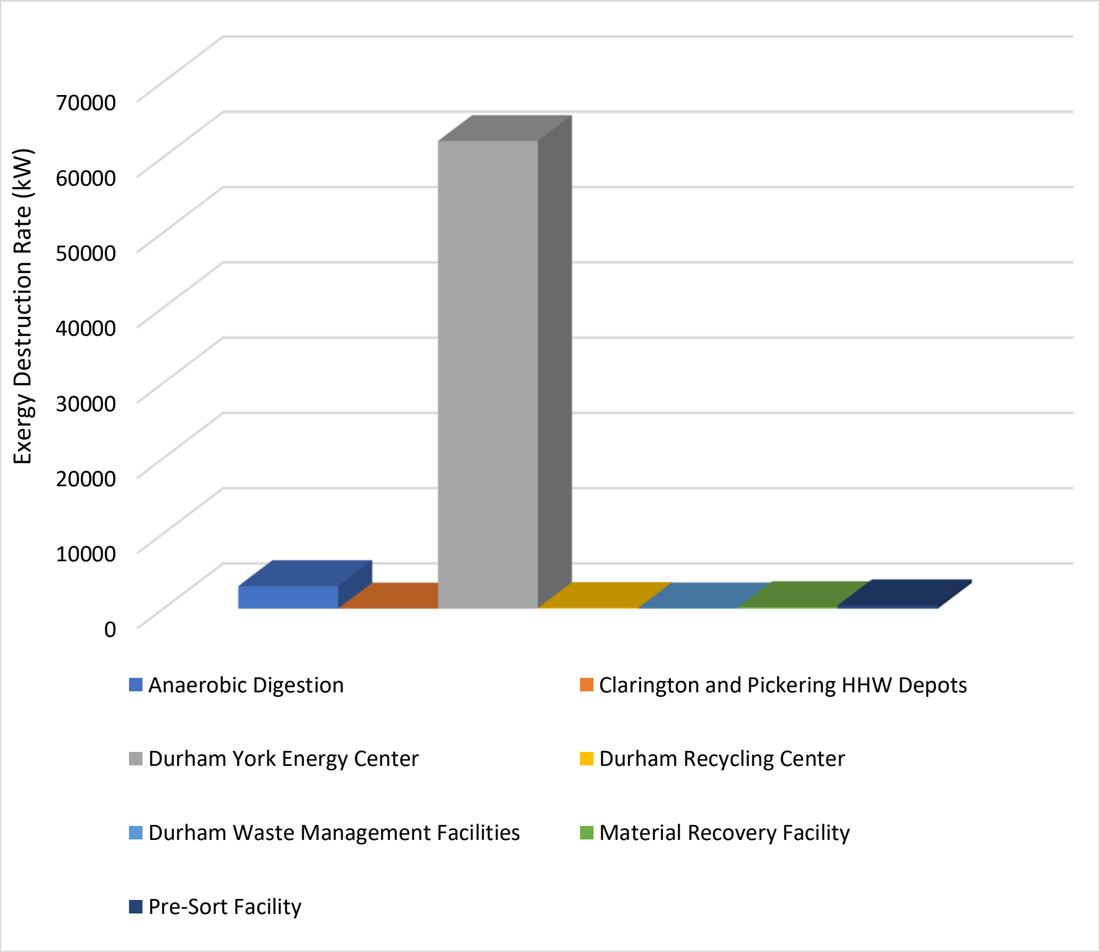

Figure 5.8: Exergy Destruction Analysis of Waste Management Facilities for Case Study 1

A parametric study is conducted to examine monthly energy and exergy efficiencies of case study 1 by varying ambient temperature. The ambient temperature varied based on monthly average air temperature in Durham Region. As seen in Figure 5.9, the highest energy and exergy efficiencies are observed to be 31.8% and 30.9% in July. Furthermore, lower energy and exergy efficiencies are seen in the winter months. The least energy and exergy efficiencies are observed in the month of January with values of 25.2% and 24.3%, respectively.

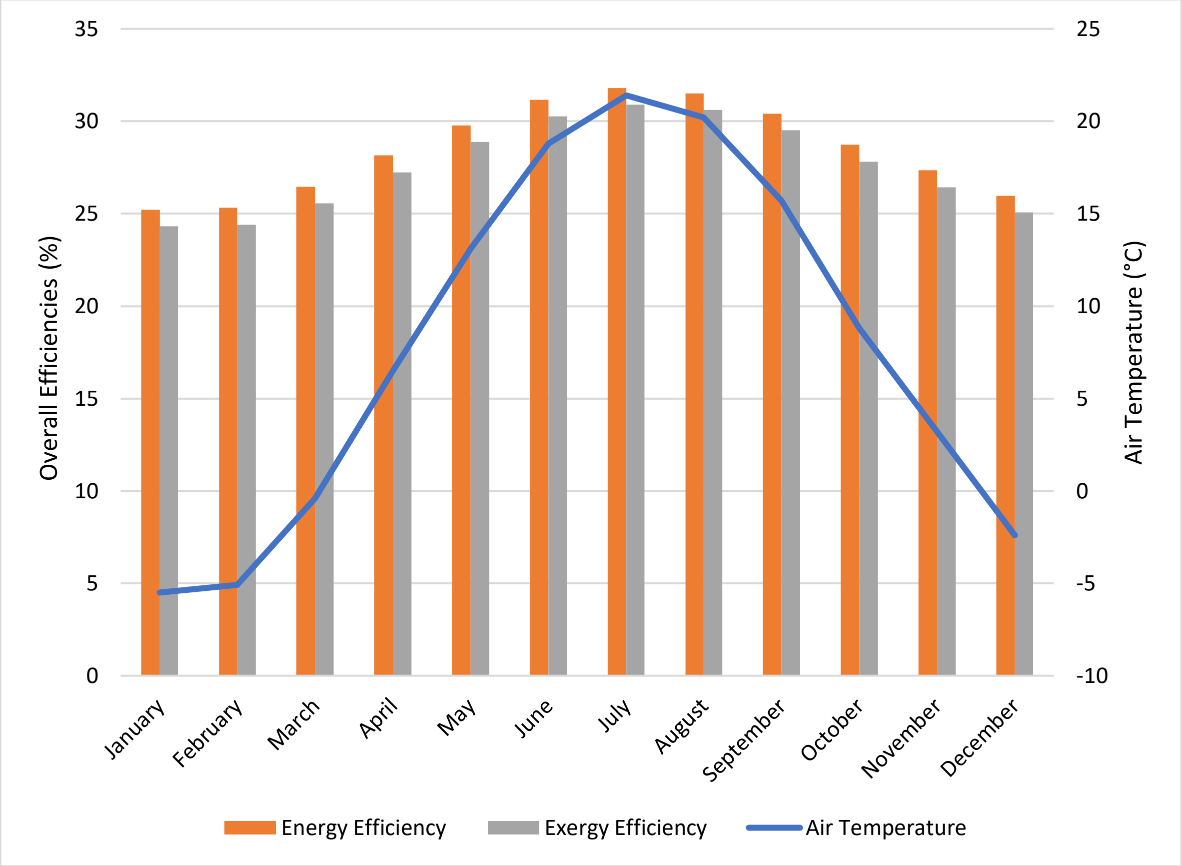

Figure 5.9: Impact of Varying Air Temperature on Overall Efficiencies for Case Study 1

5.1.3 Thermodynamic Analysis of Case Study 2

In case study 2, an integrated combined gasification unit is implemented in the existing waste management system with a pre-sort and anaerobic digestion unit. In this pre-sort facility, black bag garbage is mechanically sorted, and non-recyclables and unfavourable plastics are used as a feedstock in the gasifier (G) to produce hydrogen enriched syngas. Furthermore, this syngas is used to run a Rankine cycle to produce electricity from the waste heat recovery. Organics are treated in the anerobic digestion unit for biogas production. The total biogas production is found to be the same with case study 1 as 8253.66 m^3/h.

The syngas production rate is calculated to be 5.49 kg/s. The hydrogen flow rate in the syngas at the gasifier is calculated to be 0.44 kg/s while the net heating value of this syngas is observed to be 17574 kJ/kg from ASPEN PLUS. The volumetric syngas composition at the exit of the gasifier is given in Figure 5.10. The total electricity production rate from energy recovery for this case study is calculated to be 1420.7 kW and the total waste heat recovery rate in the steam cycle, which is used for domestic heat water application, is found to be 500 kW.

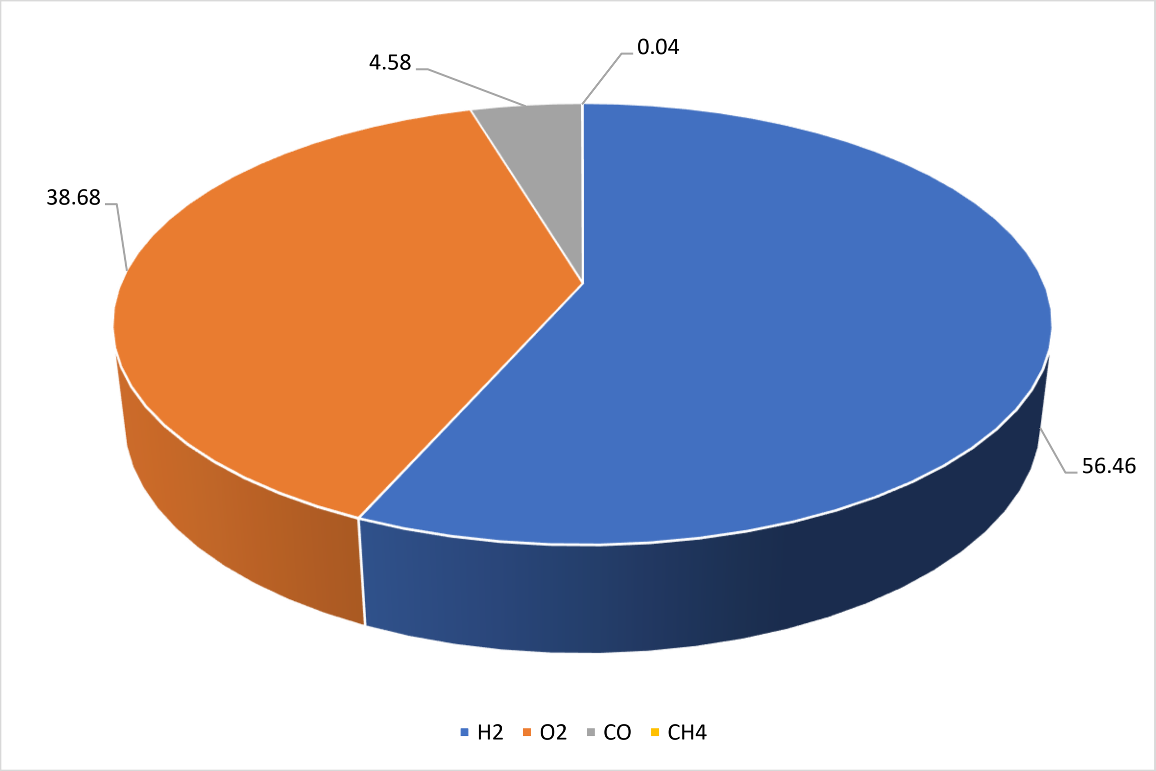

Figure 5.10: Volumetric Syngas Composition at the Exit of Gasifier

Exergy destruction rates for each system and subsystems within this case study are calculated and demonstrated in Figure 5.11. As seen in the below figure, the gasifier has the highest destruction rate with 13411 kW. This is followed by the anerobic digestion unit, boiler 1 and boiler 2 with destruction rates of 2999 kW, 2071 kW, and 2225 kW, in this order.

According to the thermodynamic simulation, the energy and exergy efficiency of the gasifier is calculated to be 74% and 72%, respectively. For the anerobic digestion facility, the energy and exergy efficiencies are found to be 67% and 66.5%, respectively. This integrated system is observed the highest energy and exergy efficiency compared to all case studies investigated with 58.7% and 56.8%, respectively.

A parametric study is also completed to examine the change in overall energy and exergy efficiencies of case study 2 by changing the operating temperature of the gasification unit. The operating temperature varied from 700 °C to 1227 °C and the results are demonstrated in Figure 5.17. As expected, the overall energy and exergy efficiency increases when the operating temperature of the gasification unit increases. The highest energy and exergy efficiency are seen to be 58.7% and 56.8%, respectively at the chosen operation temperature of 1227 °C.

Another parametric study looked at the impact of feedstock moisture content at the gasifier on the overall case study's energy and exergy efficiencies. Accordingly, the moisture content is varied from 0% to 20%. As expected, both energy and exergy efficiencies showed a dramatic decrease as the moisture content in the feedstock increased. The highest energy and exergy efficiencies are observed to be 59.72% and 57.71%, respectively when the feedstock is fully dried. Furthermore, the least energy and exergy efficiencies are seen to be 36.32% and 36.15% when the moisture content is at 20%. This shows the importance of having low moisture content for feedstock for the gasifier.

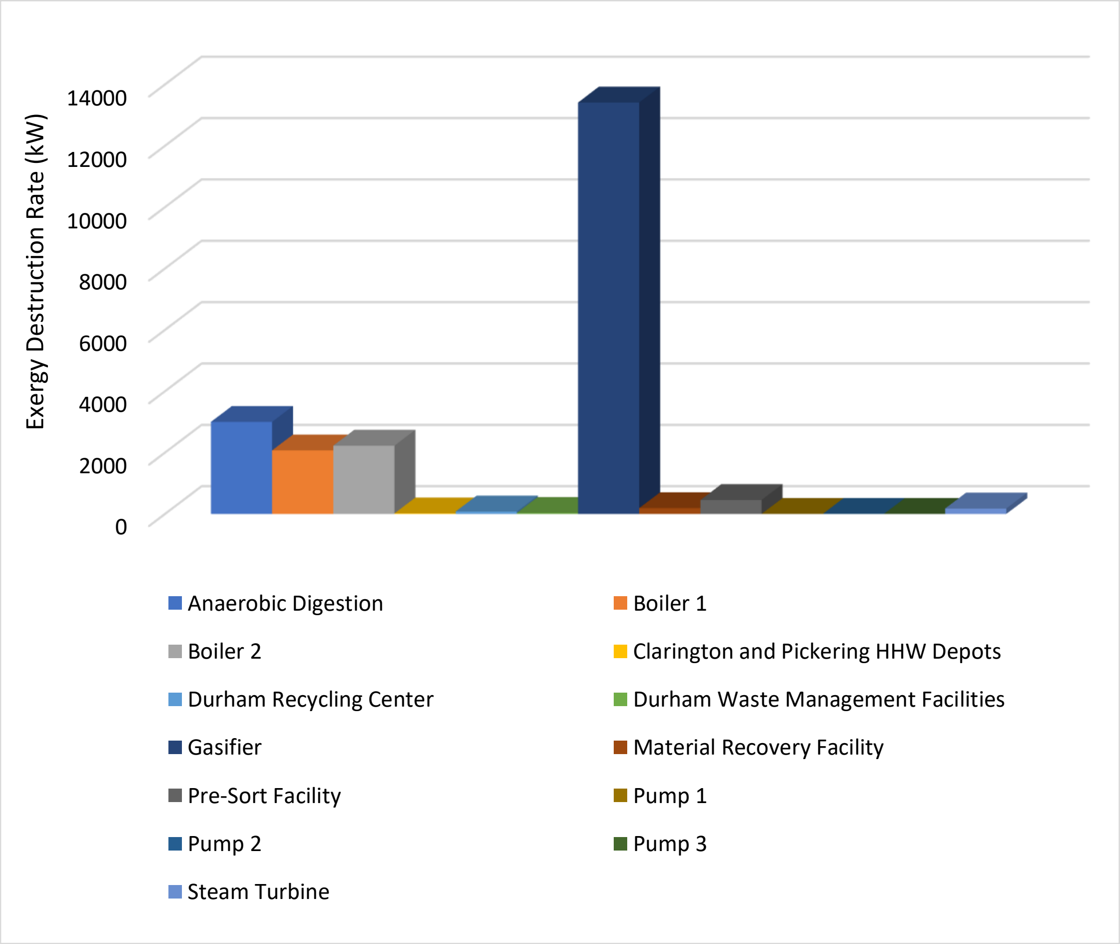

Figure 5.11: Exergy Destruction Analysis of Waste Management Facilities for Case Study 2

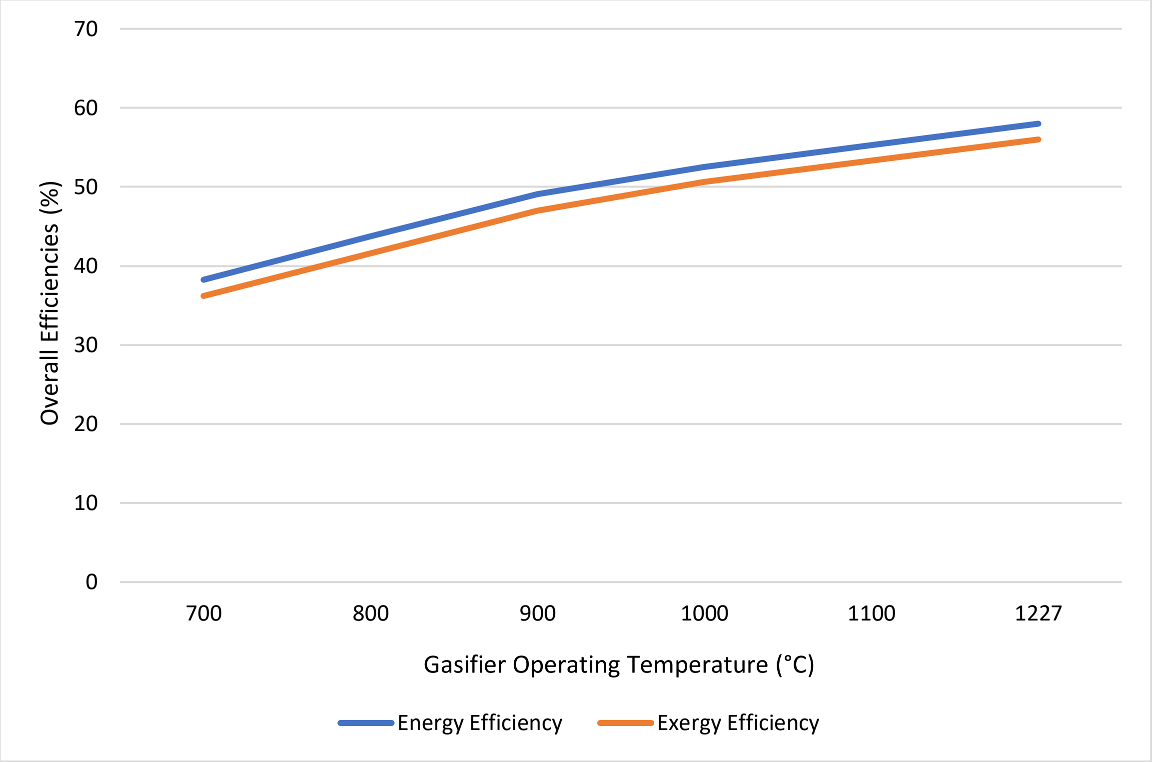

Figure 5.12: Impact of Varying Operating Temperature of Gasifier on Overall Efficiencies

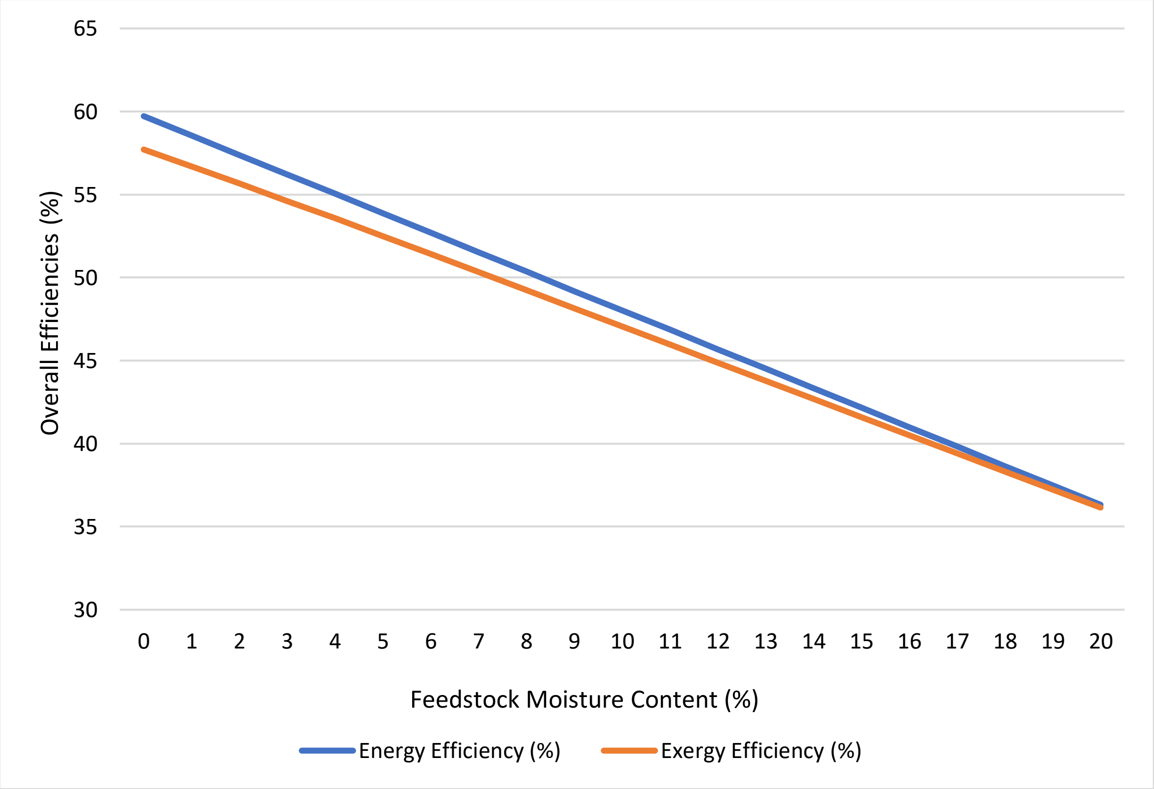

Figure 5.13: Impact of Varying Moisture Content in Feedstock at Gasifier on Overall Efficiencies

Another parametric study is conducted to determine the monthly energy and exergy efficiencies of the 2nd proposed case study according to the change in the air temperature. The ambient temperature varied based on monthly average air temperature in Durham Region. As illustrated in Figure 5.14 the highest energy and exergy efficiencies are seen to be 57.1% and 55.2% in July. Moreover, lower energy and exergy efficiencies are observed in the winter months with the lowest in the month of January with 50.5% and 48.53%, respectively.

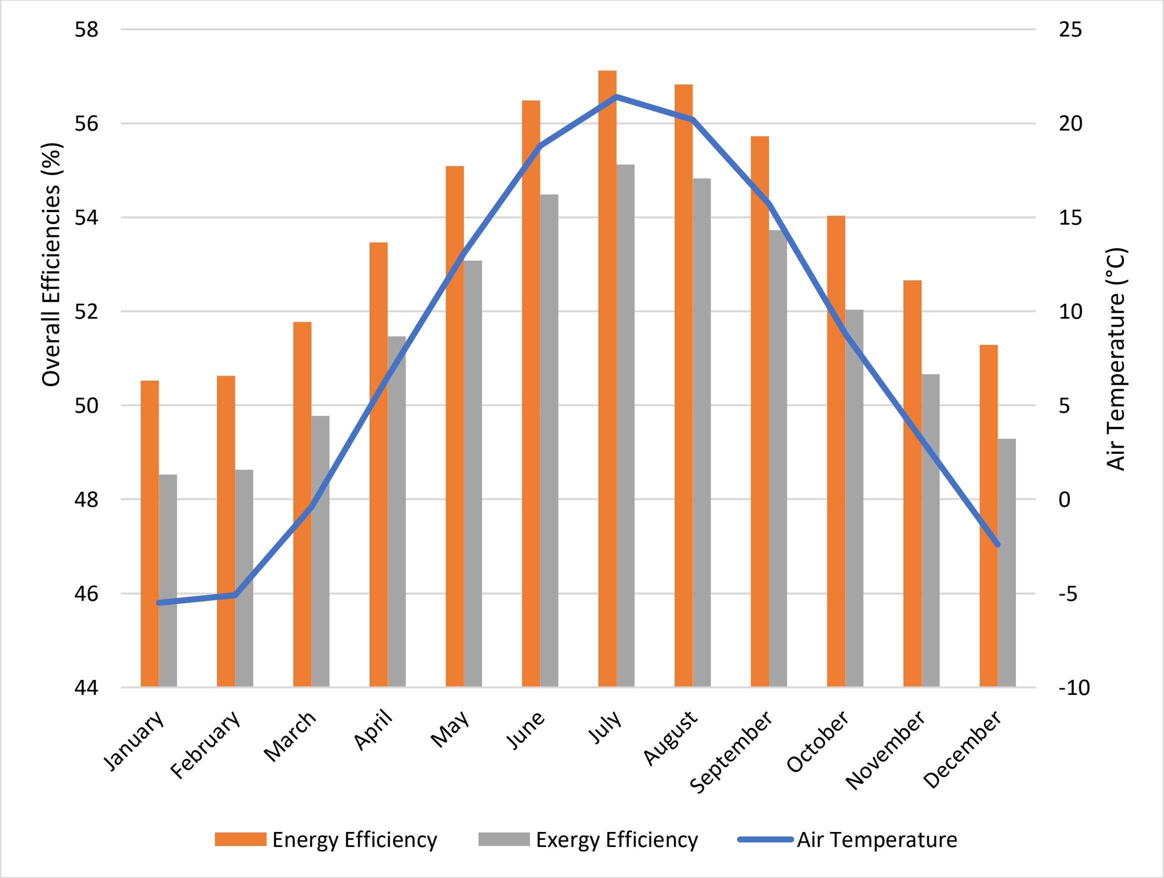

Figure 5.14: Impact of Varying Air Temperature on Overall Efficiencies for Case Study 2

5.1.4 Thermodynamic Analysis of Case Study 3

In case study 3, a pyrolysis unit is implemented into the existing waste management system for gasoline range pyrolysis oil production through the utilization of waste. This unit is also combined with a pre-sort and anerobic digestion unit for the mechanical treatment and organic treatment in this case study. The gasoline production rate is calculated to be 0.85 kg/s. Various coproduct streams are generated in this process including the fuel gas and off gas production. The total energy recovery rate through the utilization of these co-products is 6673.2 kW, while the biogas production is found to be 0.99 kg/s by the organic matter stabilization. Exergy destruction rates for this system's components are calculated and illustrated in Figure 5.15. As seen, the pyrolysis and anaerobic digestion units have the highest energy destruction rate with 54120 kW and 2999 kW, respectively.

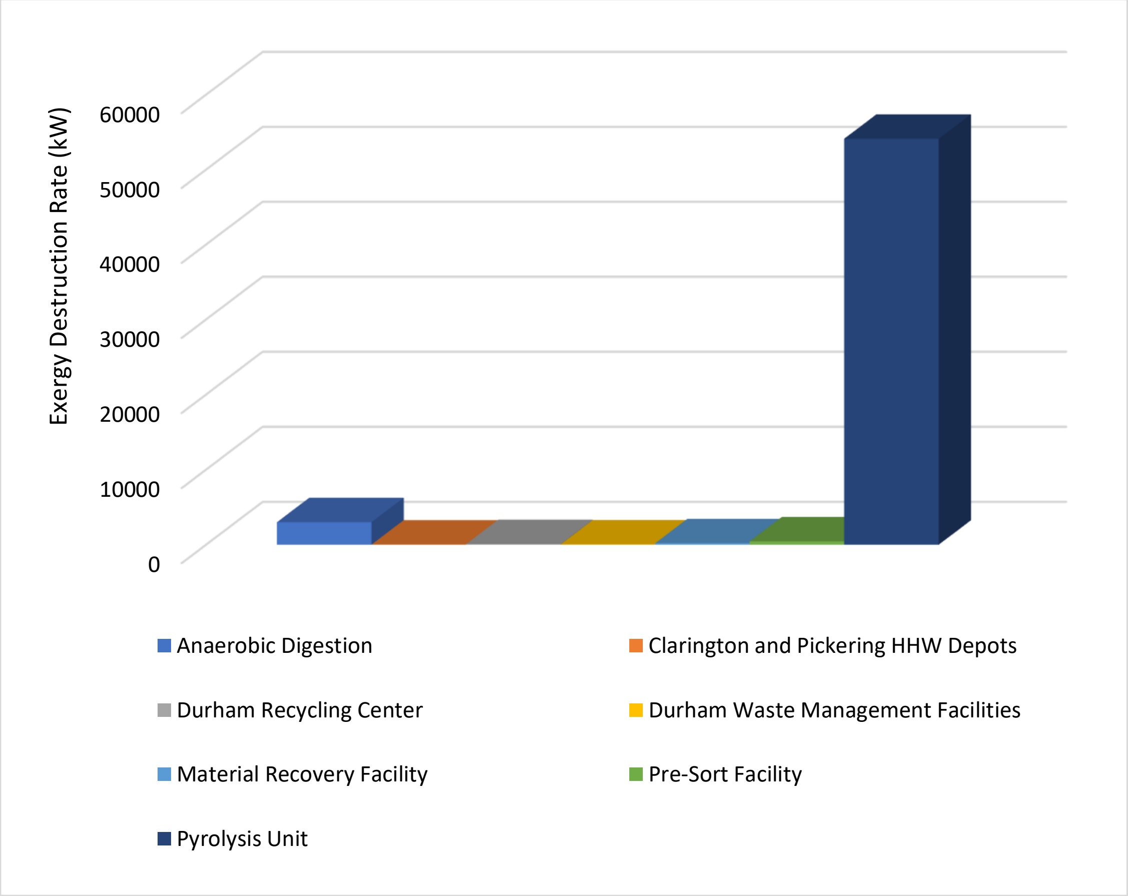

Figure 5.15: Exergy Destruction Analysis of Waste Management Facilities for Case Study 3

Energy and exergy efficiencies of this pyrolysis unit are calculated to be 32.8% and 32.7%, in this order, while the exergy and energy efficiency of the anerobic digestion facility, the energy and exergy efficiencies are found to be 67% and 66.5%, respectively. This system is found to have the second highest energy and exergy efficiencies with 40% and 39%, respectively.

A parametric study is completed to investigate seasonal energy and exergy efficiencies of case study 3 by changing ambient temperature. The ambient temperature varied based on monthly average air temperature in Durham Region. As seen in Figure 5.16, higher energy and exergy efficiencies are seen in the summer months with the highest efficiencies observed to be 39.1% and 38.2% in July. Moreover, lower energy and exergy efficiencies are seen in the winter months with the least energy and exergy efficiencies observed to be 32.53% and 31.5% in January.

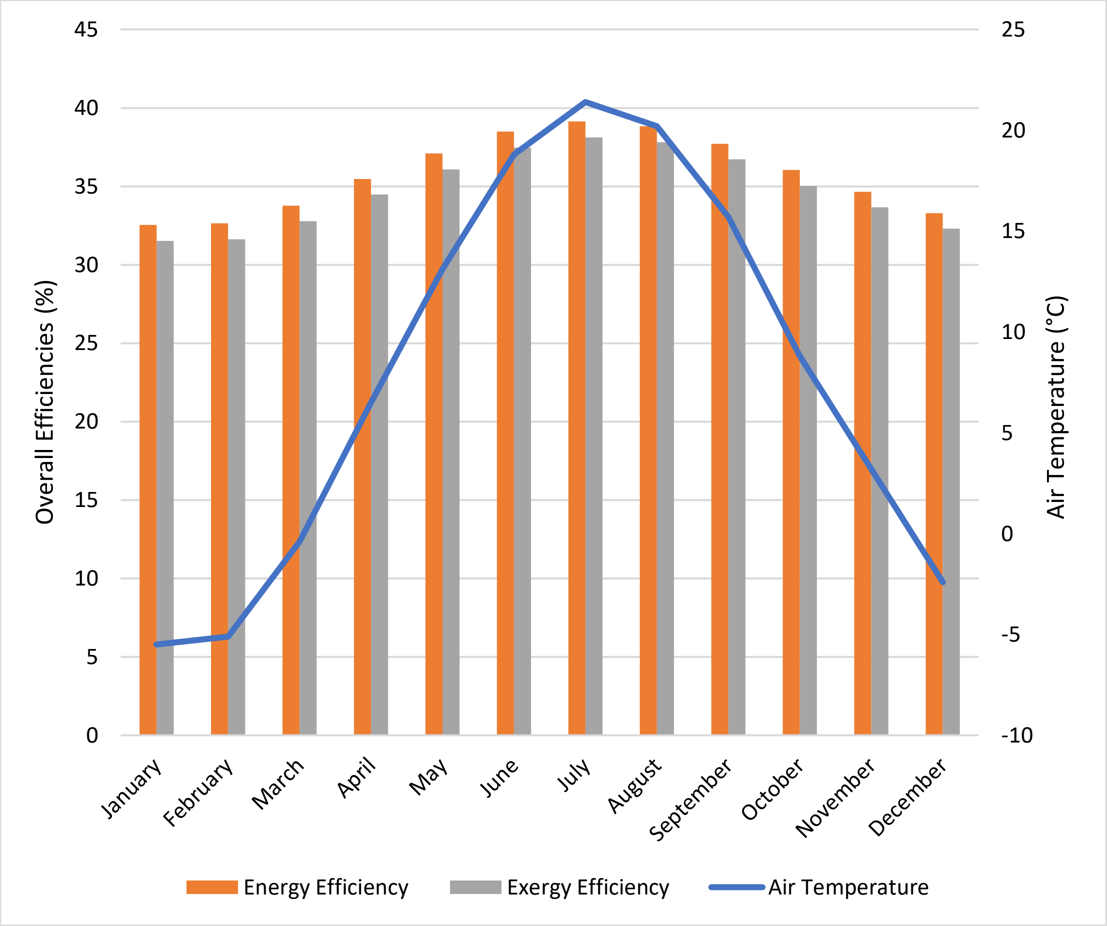

Figure 5.16: Impact of Varying Air Temperature on Overall Efficiencies for Case Study 3

5.2 LCA Impact Categories

Site-specific data is obtained from Durham Region to complete LCA modeling for this study. Furthermore, Ecoinvent database is used for the possible improvement case studies considered within this study. The functional unit of this study is selected to be 1kg municipal solid waste and the following impact categories are chosen to further investigate the environmental impact of each case study: abiotic depletion potential, acidification potential, global warming potential, ozone layer depletion potential, and human toxicity potential. Furthermore, Figure 5.17 illustrates the overall GHG emissions caused by the management of 1kg municipal solid waste for each waste management case study and given in the unit of kg CO_2 eq.

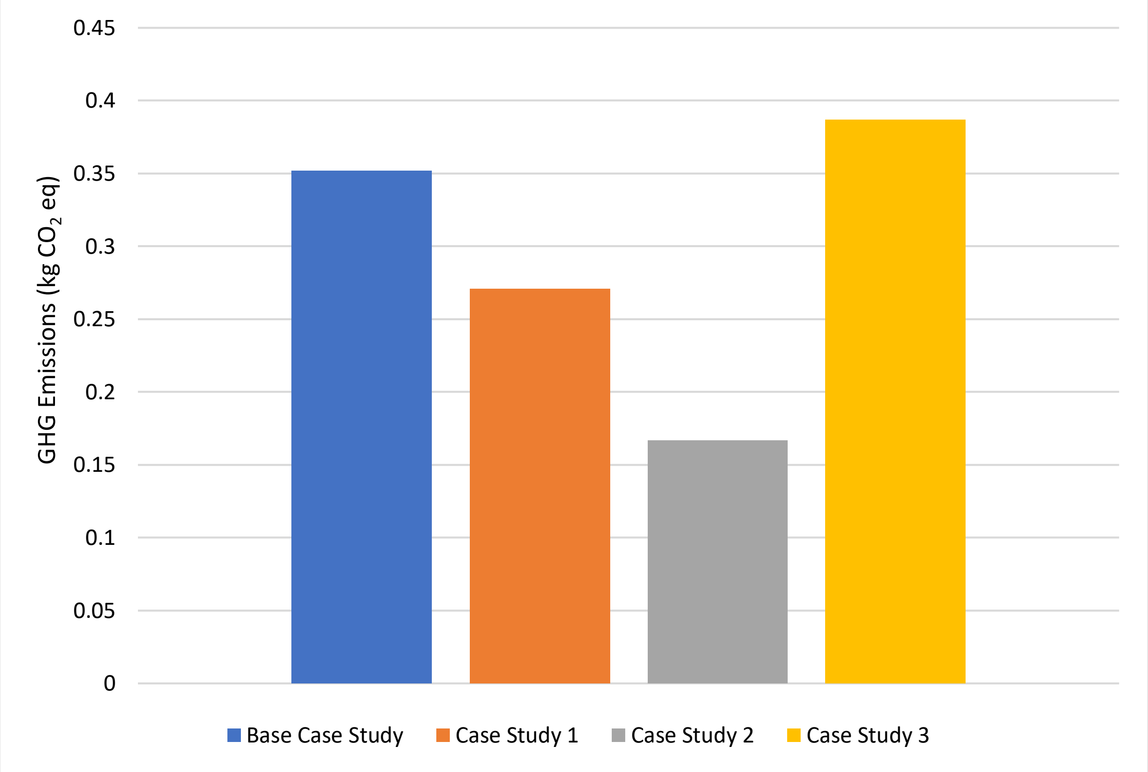

Figure 5.17: Comparison of Waste Management Case Studies According to GHG Emissions

5.3 Considered Improvement Case Studies for Waste Management Systems in Durham Region Results

In this section, the environmental impacts of the existing waste management system in Durham Region and possible improvements case studies are investigated. For the LCA modeling, 1kg municipal solid waste is chosen to be this study's functional unit and results are obtained for 1kg municipal solid waste. When reporting the contribution of each process and sub-process, a cut-off approach is used to reveal more significant contributors. The recyclable materials in the municipal solid waste are assumed to be burden-free within this study. Table 5.1 illustrates the LCA results according to the chosen environmental impact categories for the waste management systems.

Table 5.1: LCA results of waste management systems according to impact categories.

Impact Category	**Base case study**	**Case study 1**	**Case study 2**	**Case study 3**
ADP (kg SB eq)	5.95E-07	4.84E-07	2.48E-06	2.13E-07
AP (kg SO_2 eq)	0.000232	0.000223	0.000503	0.00171
GWP (kg CO_2 eq)	0.352	0.271	0.167	0.387
ODP (kg CFC-11 eq)	3.65E-09	3.87E-09	1.15E-08	2.80E-09
HTP (kg 1,4 DB eq)	2.7	1.62	0.0874	0.149

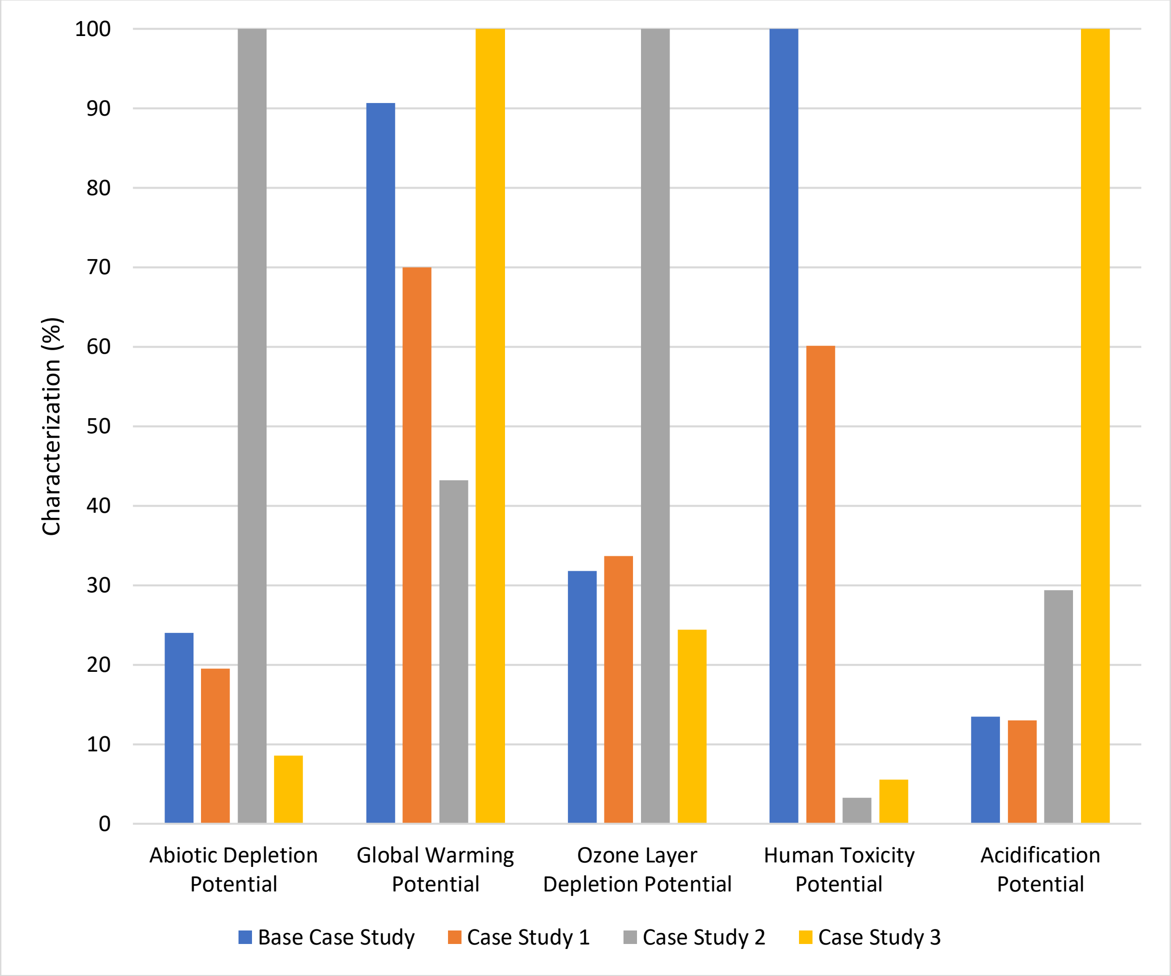

Figure 5.18: Comparison of LCA results for the waste management systems

Figure 5.18 also shows the general comparison of the waste management systems according to the five impact categories in percentage. As seen in the figure, case study 3, where a pyrolysis unit is implemented to produce gasoline as a useful output, has the highest environmental impact in GWP and AP categories while case study 2, where a gasification unit is used as a final disposal method for unfavorable recyclables and non-recyclables, shows the least impact in most categories. The results obtained are discussed in detail in the following sections specifically for each environmental impact category.

5.3.1 Abiotic Depletion Potential (ADP)

ADP environmental impact category looks at any possible effects on human welfare, human health, and ecosystem health. It is directly related to the extraction of minerals and fossil fuels because of the inputs within the boundary layer in the systems (SimaPro, 2014). ADP is calculated for each waste management case study based on kg SB eq/ kg MSW.

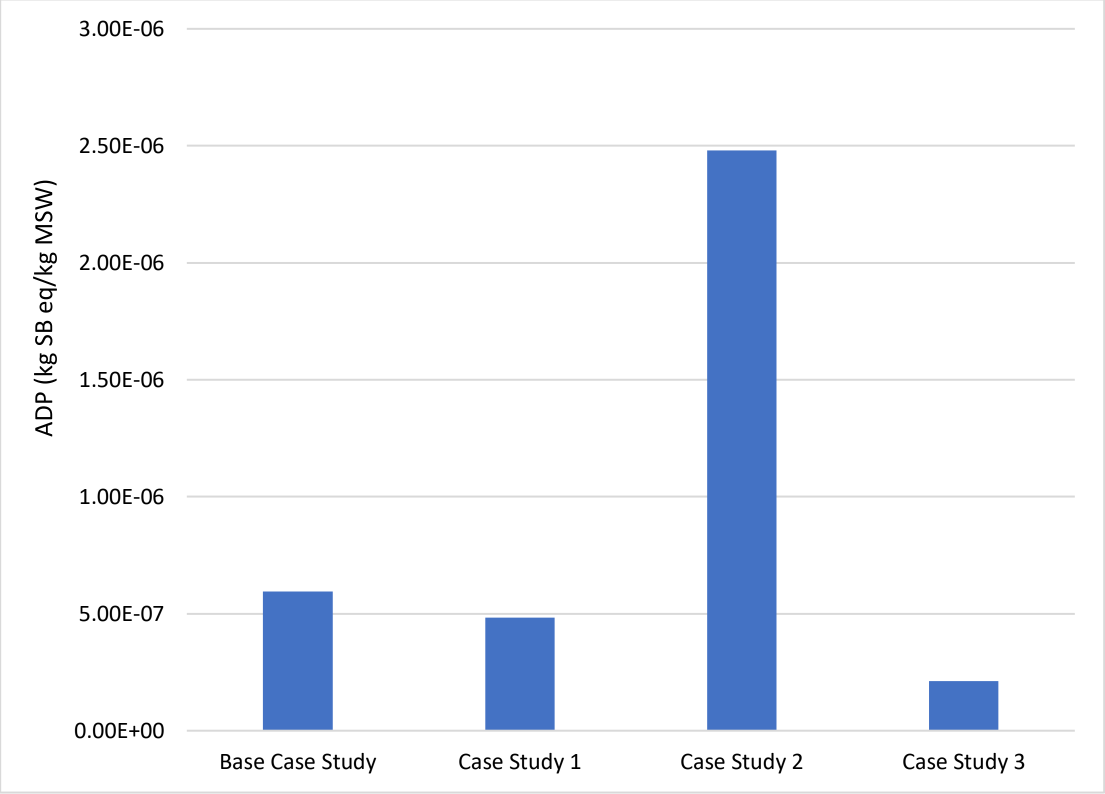

Figure 5.19: Abiotic Depletion Potential of waste management case studies

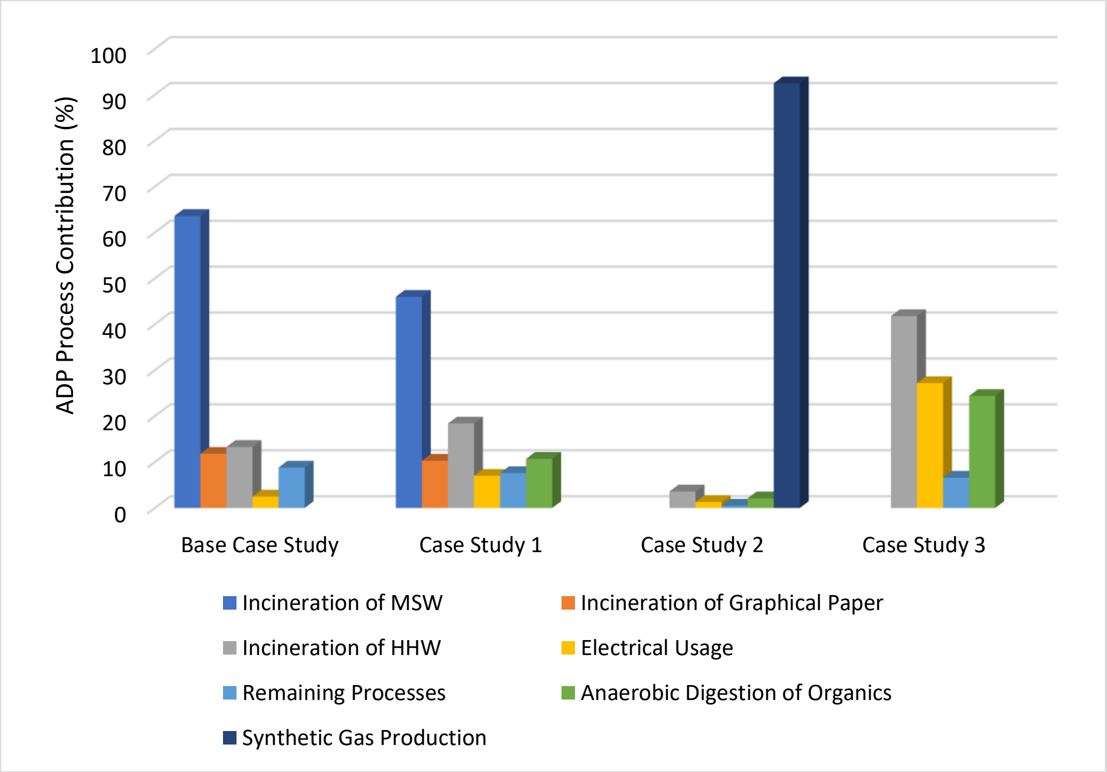

Figure 5.20: Overall ADP Process Contributions of Waste Management Case Studies

As demonstrated in Figure 5.19, case study 3 has the least contribution and is calculated to be 2.13E-07 kg SB eq while case study 2, is observed to have the highest contribution, 2.48E-06 kg SB eq. This was followed by case study 1, 4.84E-07 kg SB eq, and the base case study, 5.95E-07 kg SB eq, for this impact category.

Significant contributors are also broken down for each waste management case study for ADP and the cut-off is selected to be 2%. Figure 5.20 shows the overall break down for the highest process contributors of ADP for each case study.

In the base case study, as expected, the incineration process for MSW and waste graphical paper is found to be responsible for over half of the ADP contribution with 63.6% and 11.8%, respectively. This value is followed by the incineration of HHW, electricity usage, and the remaining processes with 13.3%, 2.5%, and 8.8%, in this order. Similar results are seen for case study 1, where a pre-sort and anaerobic digestion facility is implemented for the mechanical treatment of black bag garbage and as a main disposal case study for organics.

The incineration processes of MSW, HHW, and graphical paper are also observed to have the highest contribution to ADP with 46%, 18.4%, and 10.3%, in this order. Furthermore, bio-waste, which is generated in the treatment of organics in the digesters, is calculated to be responsible for 10.7%, electricity usage is responsible for 7% and the remaining process contributes to 7.6% of the total ADP contribution.

In case study 2, the synthetic gas production process is seen to be the major contributor to ADP with approximately 92.5%. For this case study, the management of HHW is only responsible for 3.6% of ADP and this is followed by the organic’s treatment, electricity usage, and the remaining processes with 2.1%, 1.3%, and 0.5%, in this order. For case study 3, the incineration of HHW has the highest ADP with 41.8%. The other major contributors for case study 3 are observed to be electricity usage, bio-waste treatment processes, and remaining processes with 27.2%, 24.4%, and 6.6% in this order.

Network diagrams for each case study, which demonstrate the ADP contribution of each process and sub-process according to the case studies, are observed from SimaPro software and illustrated in Figure 5.21, Figure 5.22, Figure 5.23, and Figure 5.24.

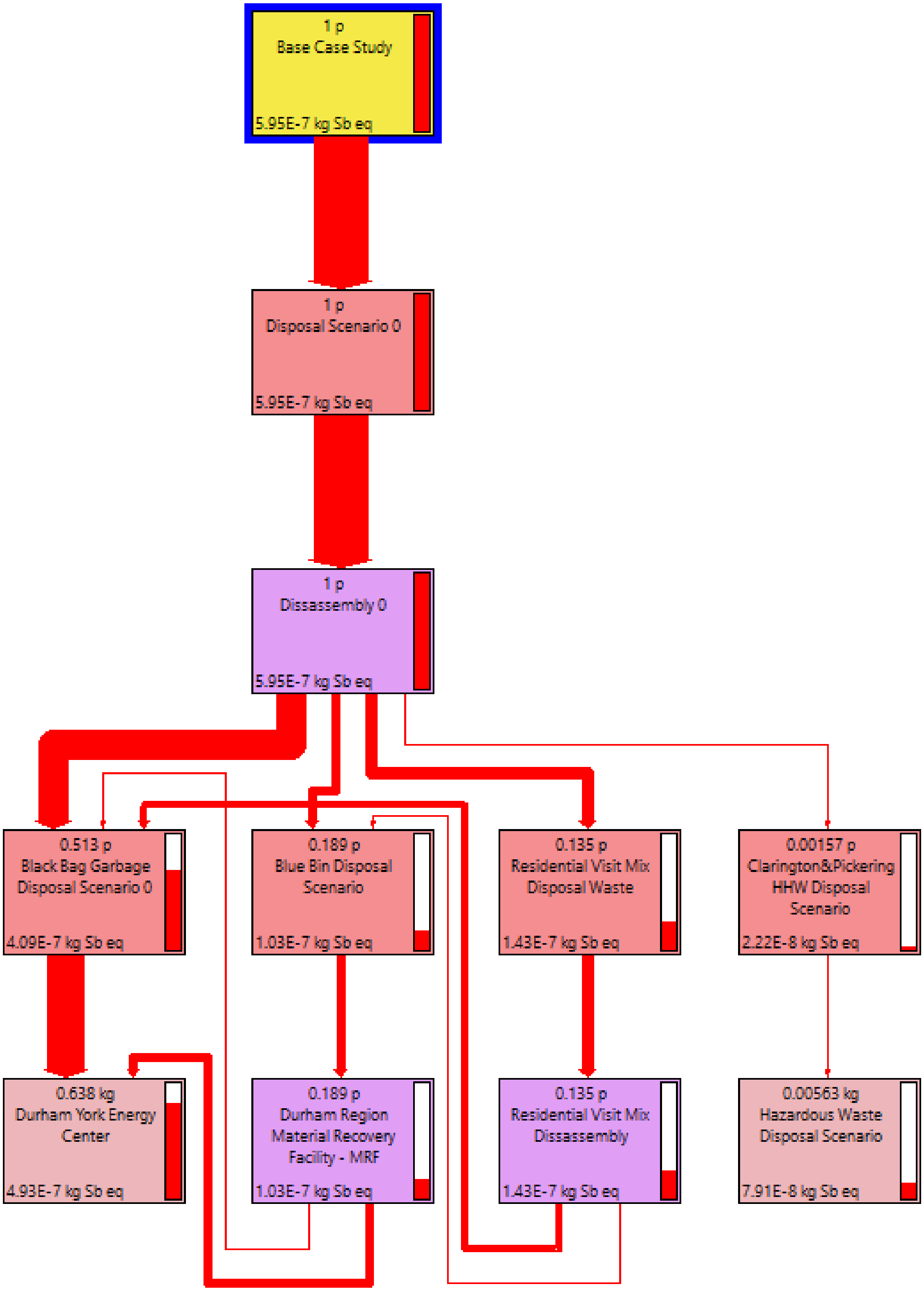

Figure 5.21: LCA Network Diagram for Abiotic Depletion Potential of Base Case Study (cut-off 10%)

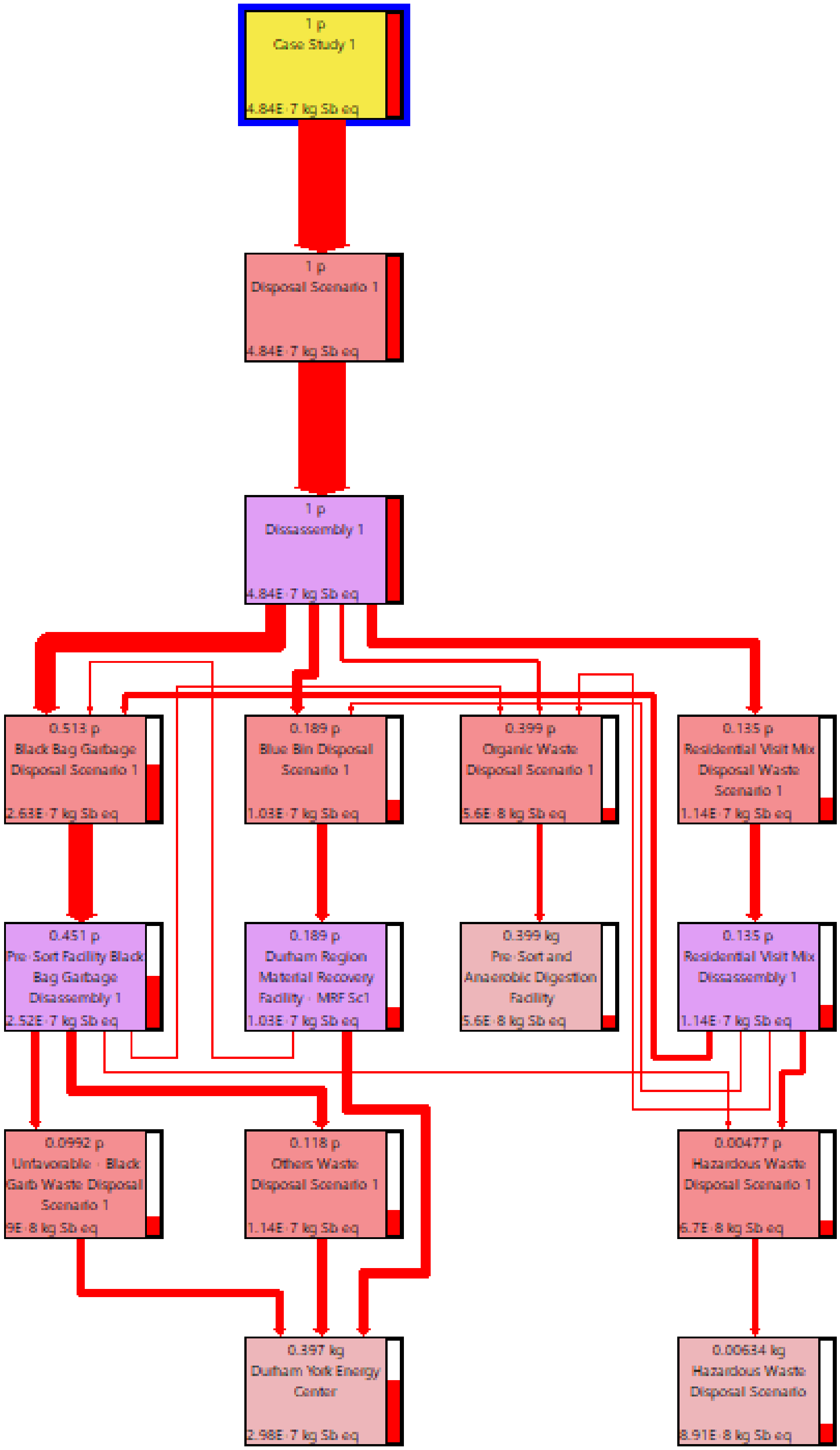

Figure 5.22: LCA Network Diagram for Abiotic Depletion Potential of Case Study 1 (cut-off 10%)

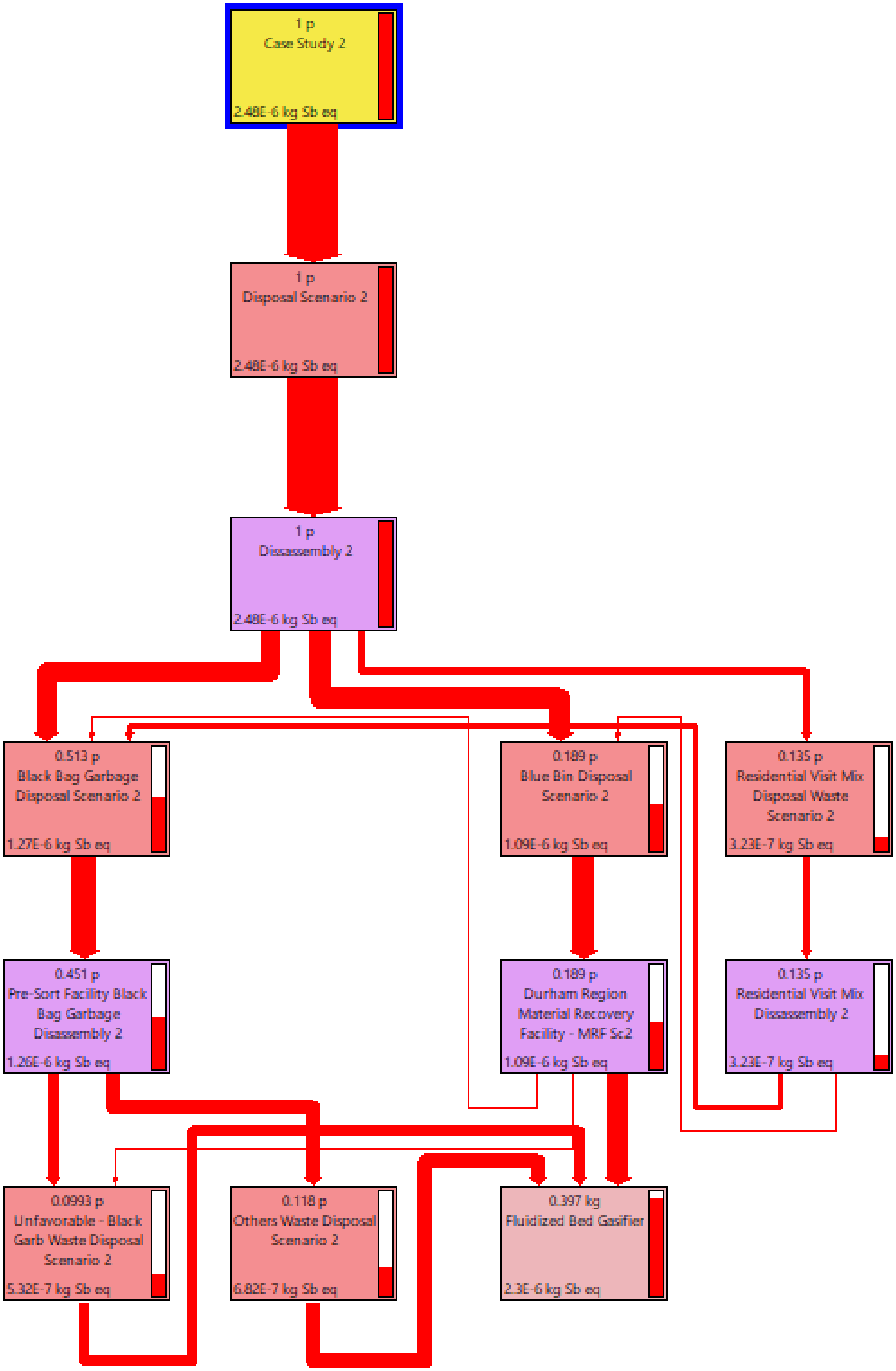

Figure 5.23: LCA Network Diagram for Abiotic Depletion Potential of Case Study 2 (cut-off 10%)

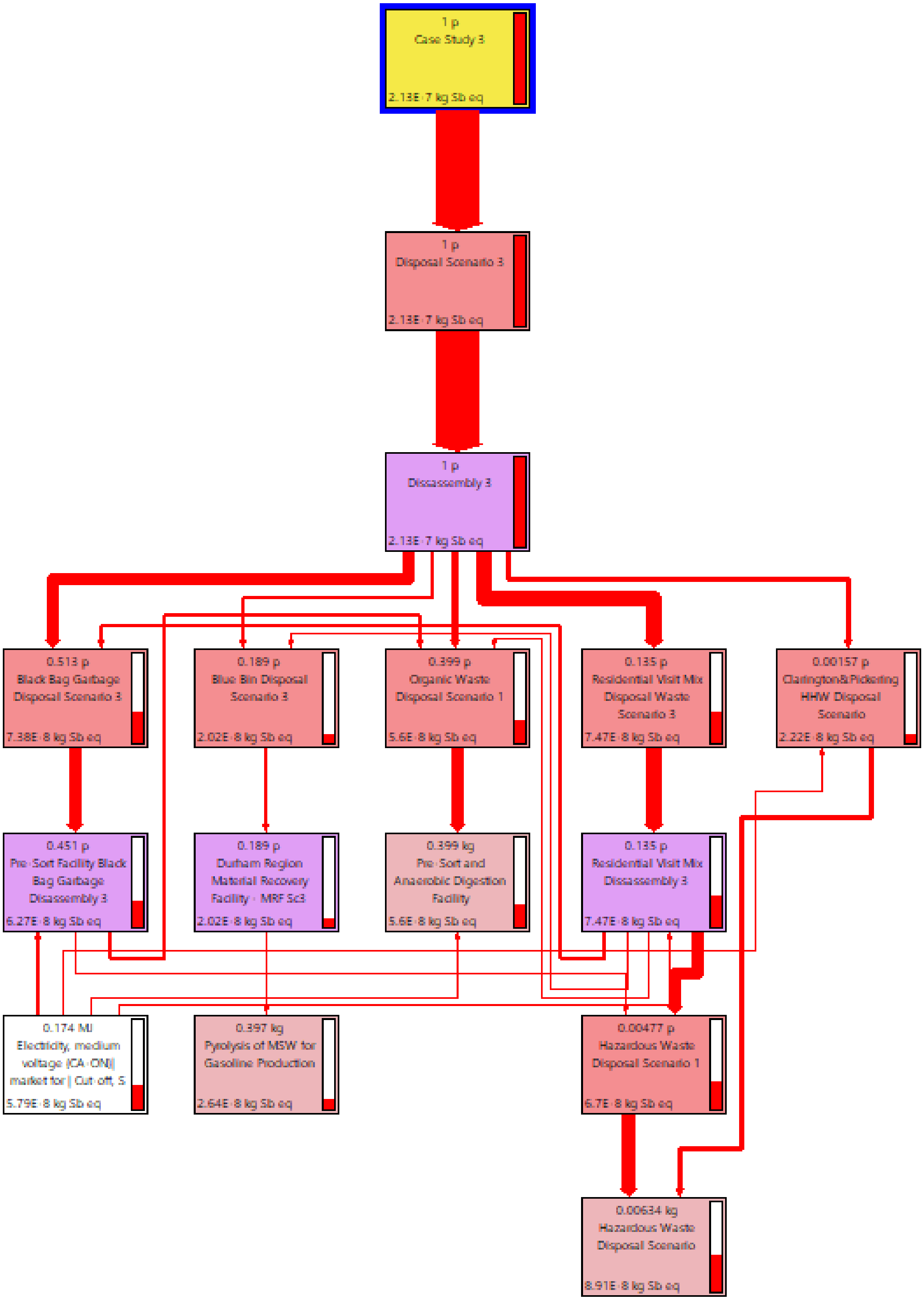

Figure 5.24: LCA Network Diagram for Abiotic Depletion Potential of Case Study 3 (cut-off 10%)

5.3.2 Acidification Potential (AP)

Acidification potential environmental impact category demonstrates impacts on soil, groundwater, surface water, organisms, ecosystems, and materials and is calculated according to the fate and deposition of acidifying substances in systems (SimaPro, 2014). In this section, AP is calculated for each waste management case study and given in the unit of kg SO_2 eq/kg MSW. Figure 5.25 shows the comparison between the waste management case studies according to the AP environmental impact category. As seen, case study 3 has the highest contribution to AP with 0.00171 kg SO_2 eq while case study 1 is observed to have the lowest AP with 0.000223 kg SO_2 eq. Similar results to case study 1, which is 0.000232 kg SO_2 eq, are obtained for the base case study, which is then followed by case study 2 with 0.000503 kg SO_2 eq.

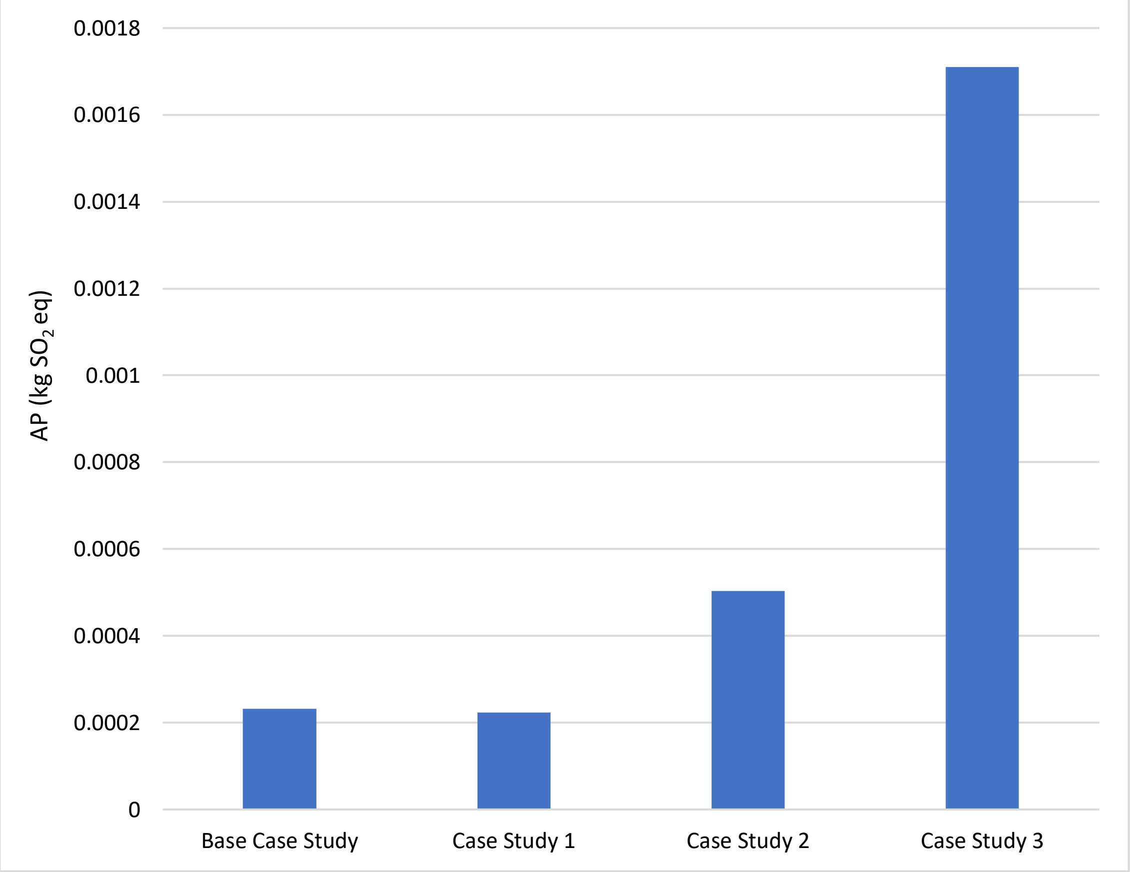

Figure 5.25: Acidification Potential of Waste Management Case Studies

Significant contributors to AP are investigated for each waste management case study and the cut-off is selected to be 1% for the results. Figure 5.26 shows the overall break down for the highest process contributors of AP for each case study.

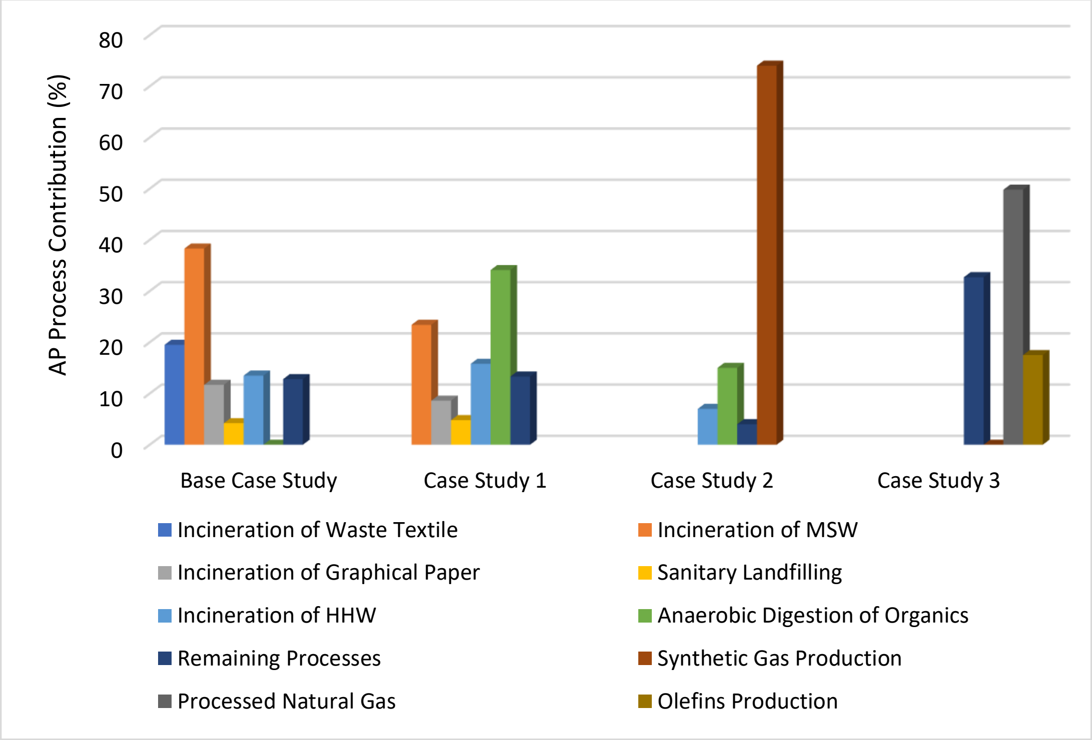

Figure 5.26: Overall AP Process Contributions of Waste Management Case Studies

The highest contributors for the base case study are observed to be the incineration of MSW and waste textile with approximately 38.3% and 19.5%, respectively. Moreover, the incineration process of HHW and waste graphical paper is found to have 13.5% and 11.7%, respectively, of the total AP within this case study. Finally, the sanitary landfilling and remaining process are found to have 4.2% and 12.8% of AP contribution, in this order.

As mentioned above, case study 1 had the lowest AP within the considered case study. The organics treatment process and the incineration of MSW have the highest AP with 34.1% and 23.4%, in this order. The incineration process of HHW and waste graphical paper and landfilling processes are found to be responsible for 15.8%, 8.6%, and 4.8% of AP contribution, in that order. The remaining processes are calculated to be responsible for 13.3% of the total AP. In case study 2, synthetic gas production in the gasification process is observed to have the most AP within the process and sub-process with 74%. Furthermore, the second highest contributor is seen to be the biowaste treatment process in the digesters with 15%. The other AP contributors are observed to be the incineration of HHW and remaining processes with 7% and 4%, respectively. Case study 3, which has the highest AP within the case studies, natural gas processed at the pyrolysis plant has the most contribution to AP with approximately 49.8%. This is followed by natural gas used for olefins production, transportation of fuel, and the remaining processed with 17.5%, 7.2%, and 25.5%, in this order. Network diagrams for each case study, which demonstrates the AP contribution of each process and sub-process according to the case studies, are observed from SimaPro software and illustrated in Figure 5.27, Figure 5.28, Figure 5.29 and Figure 5.30.

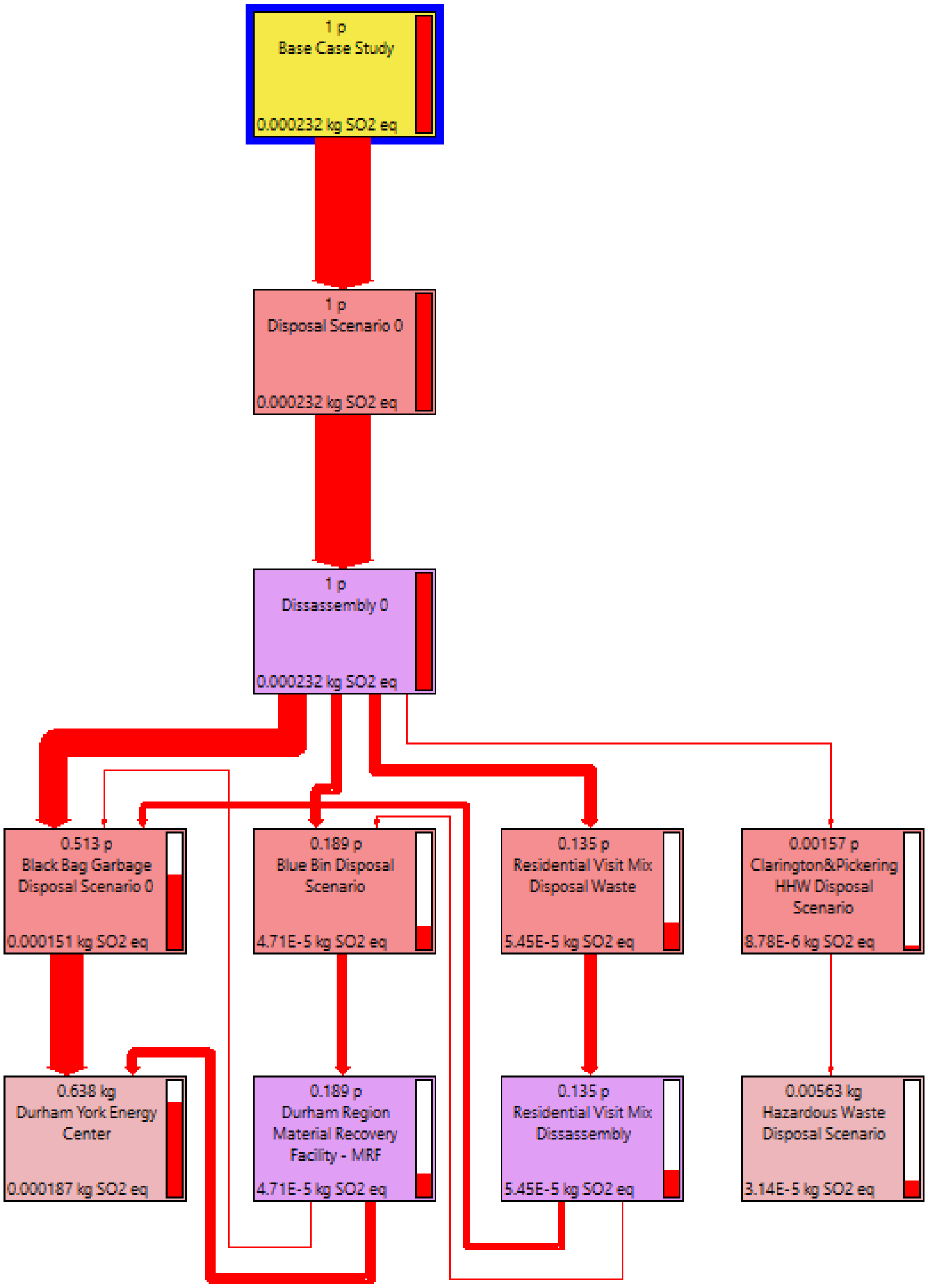

Figure 5.27: LCA Network Diagram for Acidification Potential of Base Case Study (cut-off 10%)

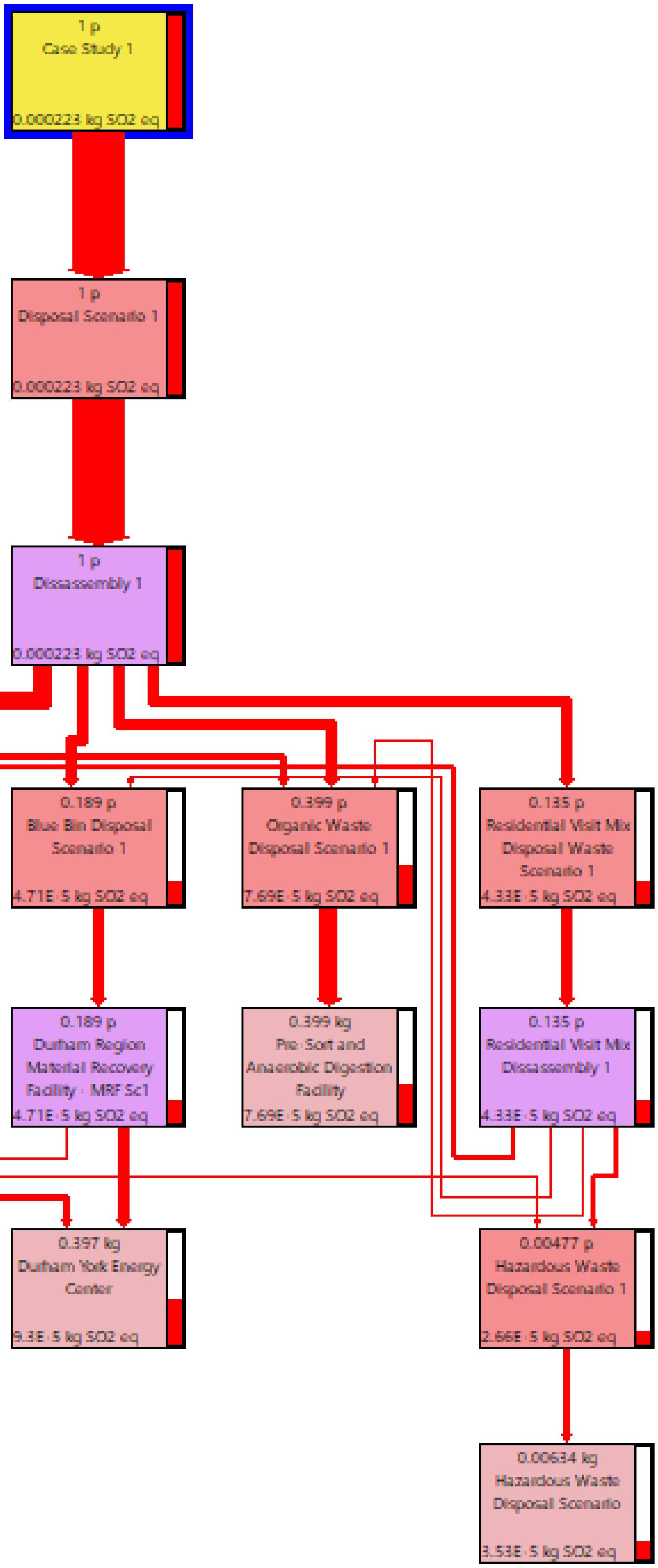

Figure 5.28: LCA Network Diagram for Acidification Potential of Case Study 1 (cut-off 10%)

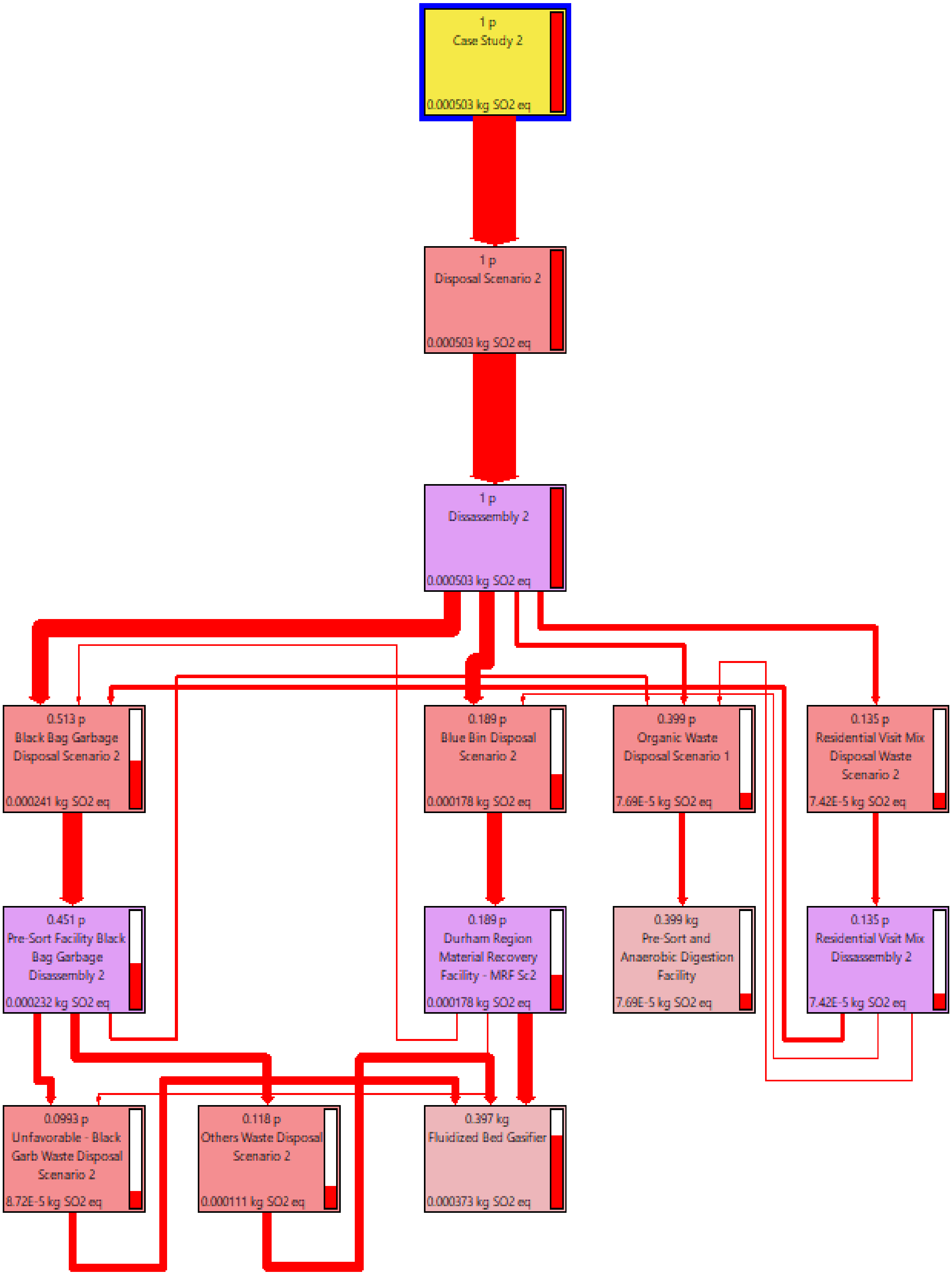

Figure 5.29: LCA Network Diagram for Acidification Potential of Case Study 2 (cut-off 10%)

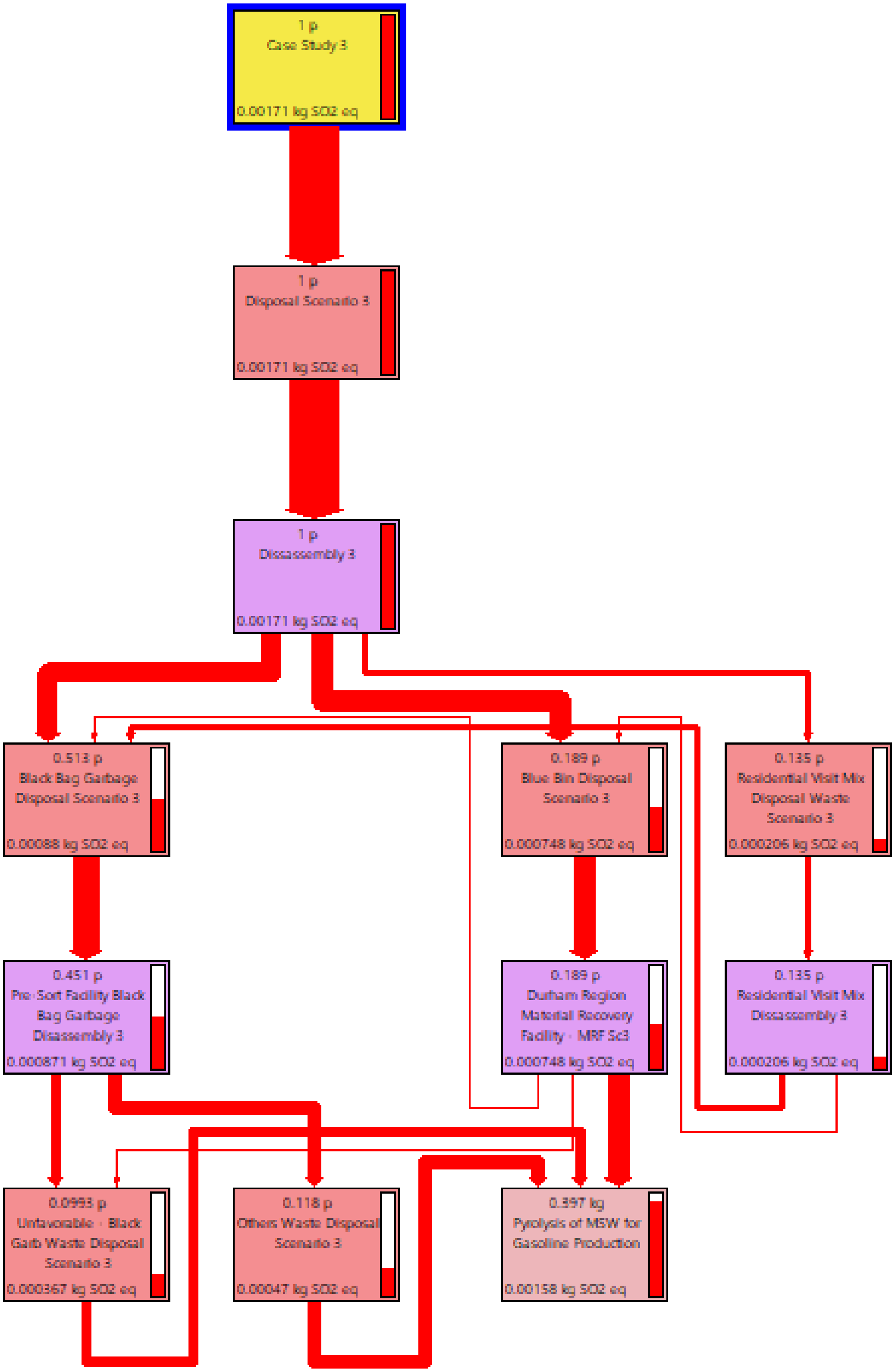

Figure 5.30: LCA Network Diagram for Acidification Potential of Case Study 3 (cut-off 10%)

5.3.3 Global Warming Potential (GWP)

Global Warming Potential (GWP) looks at environmental issues, such as climate change, caused by greenhouse gas emissions which can result in negative effects on ecosystem health, human health, and human welfare. In this section, the existing waste management case study and improvement case studies are investigated according to the GWP environmental impact category for a time horizon of 100 years (GWP100) and is expressed as kg carbon dioxide/kg MSW (SimaPro, 2014). As demonstrated in Figure 5.31, case study 3 has the highest GWP when compared to the other case studies. GWP of case study 3 is calculated to be 0.387 kg CO_2/kg MSW, while case study 2 is observed to be the least contributor to GWP with 0.167 kg CO_2/kg MSW. For the base case study, which is the second highest between case studies, the GWP is 0.352 kg CO_2/kg MSW followed by case study 1 with 0.271 kg CO_2/kg MSW.

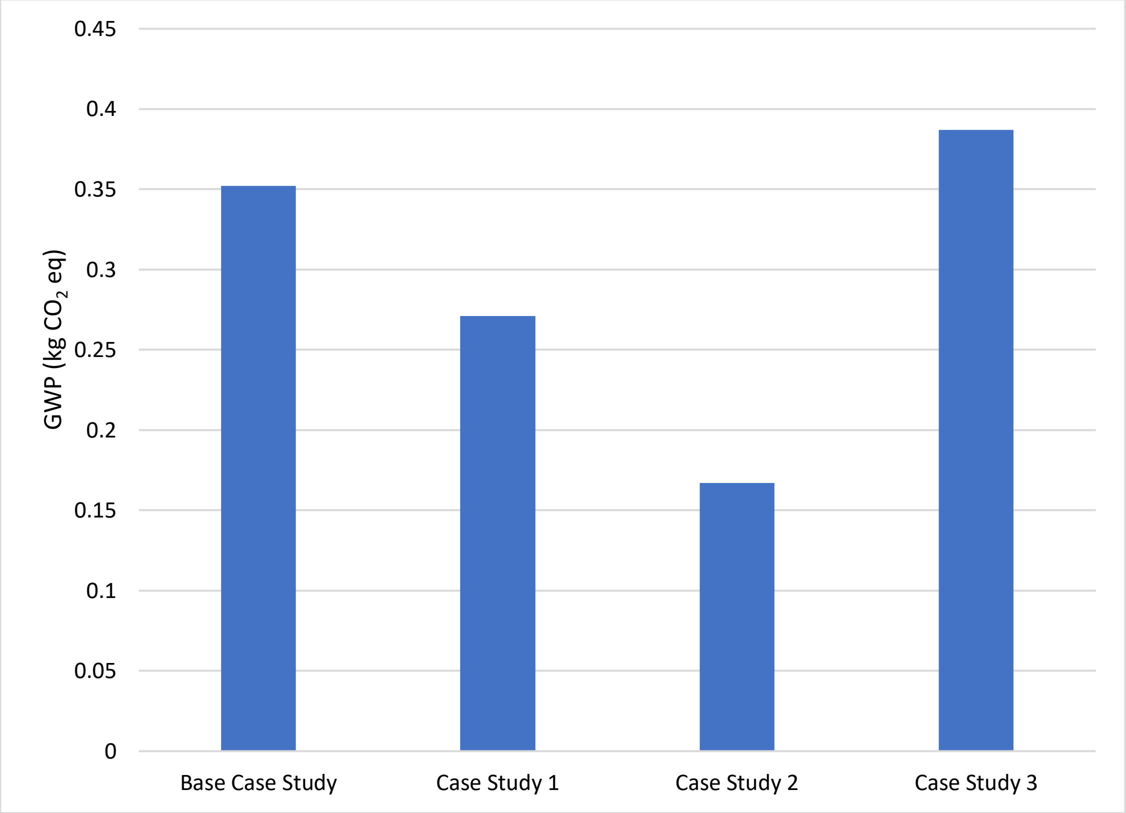

Figure 5.31: Global Warming Potential of Waste Management Case Studies

Major contributors to GWP are explored for each waste management case study and cut-off is selected to be 2% for the results. Figure 5.32 shows the overall break-down for the highest process contributors of GWP for each case study.

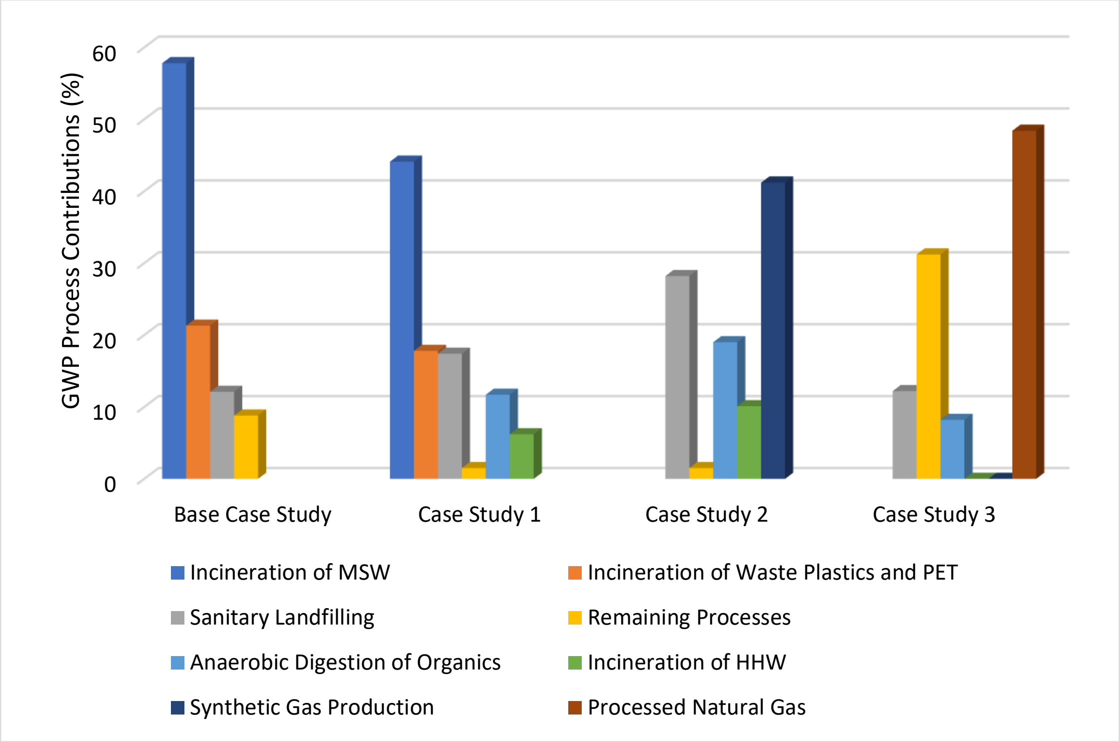

Figure 5.32: Overall GWP Process Contributions of Waste Management Case Studies

For the base case study, which the existing waste management system in Durham Region, the highest contributors are found to be the incineration process and sanitary landfilling process for MSW with 57.8% and 12.1% respectively. This is followed by the treatment of waste plastic in municipal incineration, Polyethylene terephthalate (PET) incineration, and remaining processes which were observed as 10.1%, 11.2%, and 8.8%, in this order. For case study 1, where pre-sort anaerobic digestion is implemented, the major contributors for GWP are seen to be the same as the base case study. The contribution of these two major processes MSW incineration, and sanitary landfilling, are observed to contribute to GWP with 44.1% and 17.4%, in this order. This is followed by the treatment of organics in the anaerobic digestion facility, incineration of HHW, waste plastic and PET incineration and the remaining processes with 11.7%, 6.2%, 17.8%, and 2.8%, in this order.

In case study 2, which has the least contribution to GWP among all waste management systems, the most GWP contributors are seen to be the synthetic gas production and the sanitary landfilling process with 41.2% and 28.2% respectively. This is followed by organics treatment in AD, incineration process of HHW, and remaining processes with 19%, 10.1%, and 1.5% in this order. In case study 3, which has the highest contribution for GWP, the extraction, transportation, and combustion of natural gas in industrial boilers for the pyrolysis process has the most significant impact on GWP with 48.4%. This is followed by the sanitary landfilling process, organics treatment in AD, and remaining processes with 12.2%, 8.2%, and 31.2% in this order. Network diagrams for each case study, which demonstrates the GWP contribution of each process and sub-process according to the case studies, are observed from SimaPro software and illustrated in Figure 5.33, Figure 5.34, Figure 5.35 and Figure 5.36.

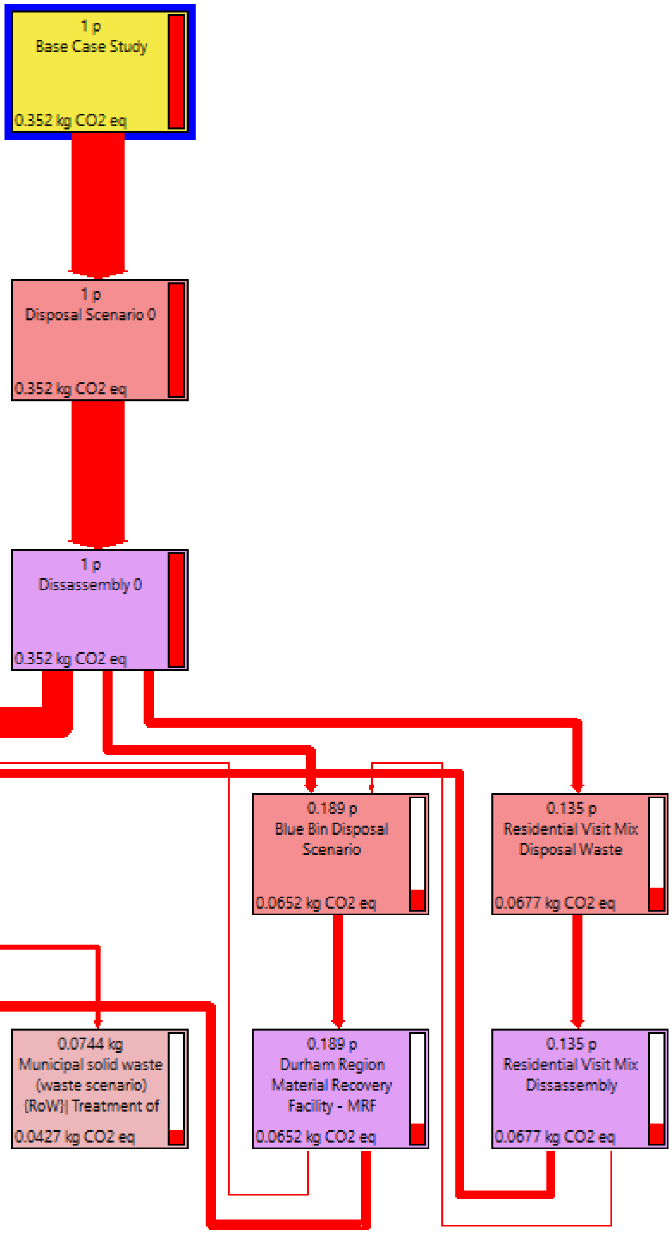

Figure 5.33: Global Warming Potential of Base Case Study (cut-off 10%)

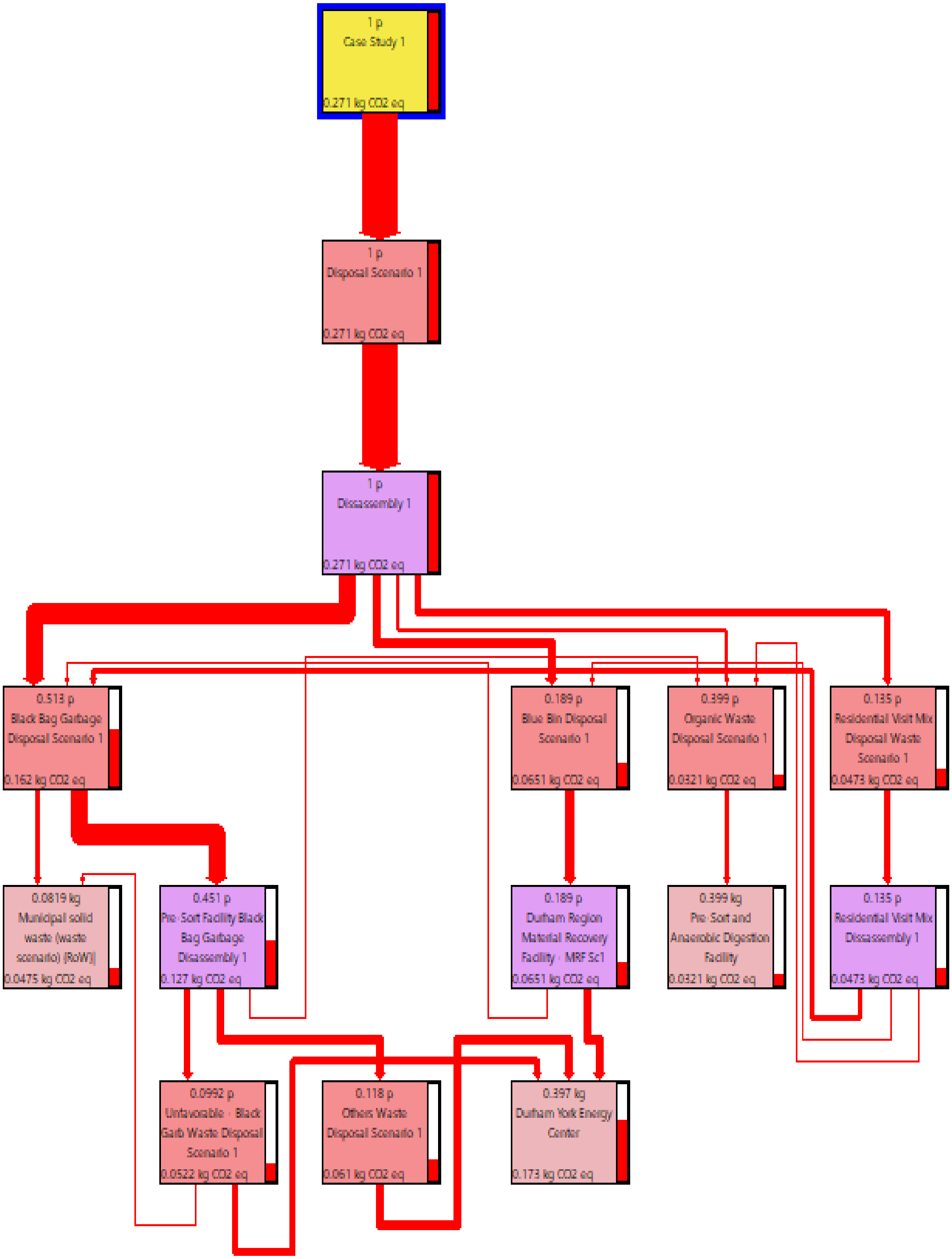

Figure 5.34: Global Warming Potential of Case Study 1 (cut-off 10%)

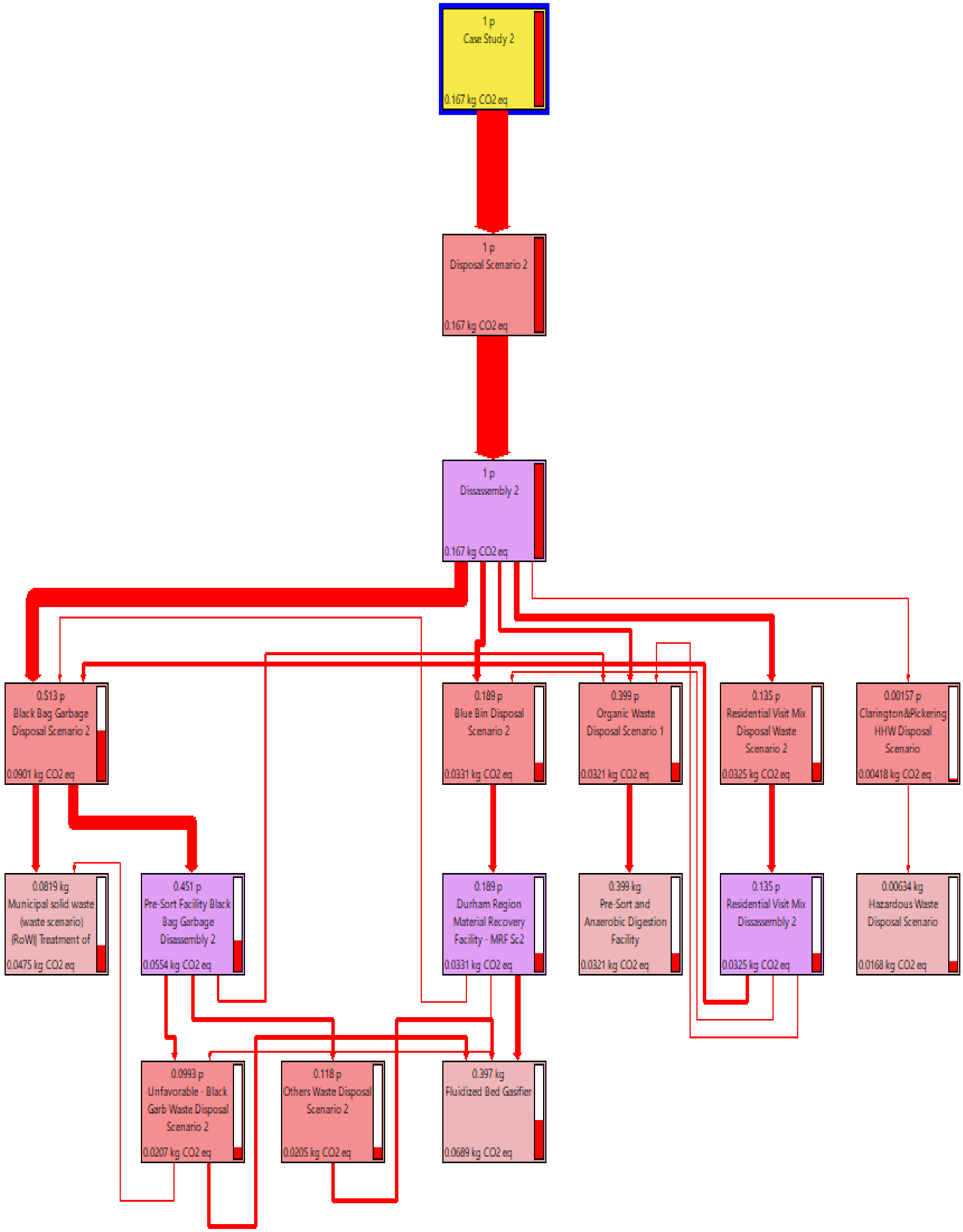

Figure 5.35: Global Warming Potential of Case Study 2 (cut-off 10%)

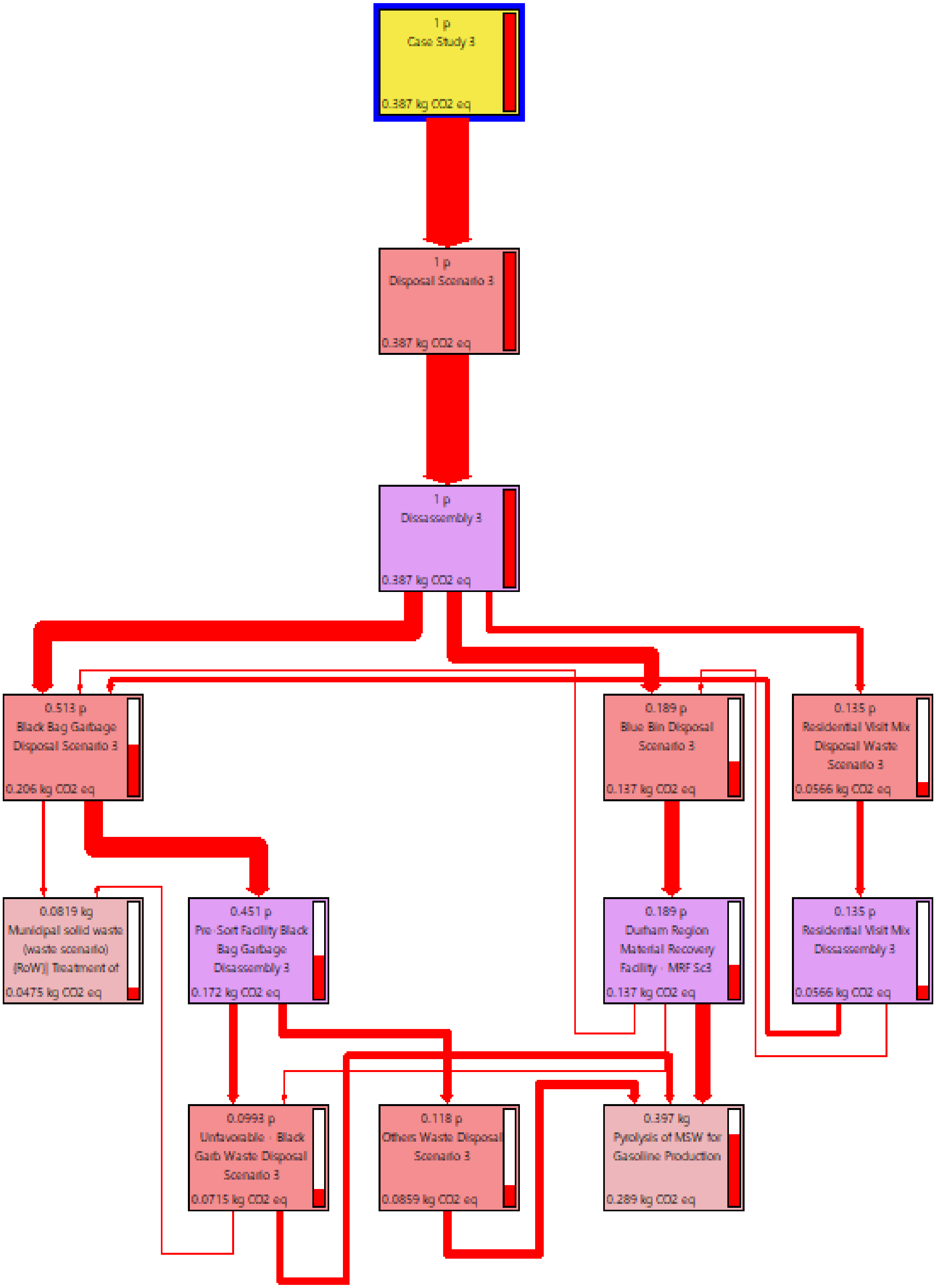

Figure 5.36: Global Warming Potential of Case Study 3 (cut-off 10%)

5.3.4 Ozone Layer Depletion Potential (ODP)

Ozone layer depletion potential looks at stratospheric ozone depletion which results in a large amount of UV-B radiation penetrates the earth’s surface. ODP examines the negative effects on human health, animal health, terrestrial and aquatic ecosystems, and biochemical cycles from this ozone depletion. All of the waste management case studies are examined according to their ODPs and the results are defined as kg CFC-11 equivalent/kg MSW (SimaPro, 2014). Figure 5.37 illustrates the comparison of waste management case studies by means of their ozone layer depletion potential. As seen, case study 3 has the least environmental impact in the ODP category with 2.8E-09 kg CFC-11 equivalent while case study 2, where AD is integrated for biogas production, is observed to have the highest contribution to ODP with 1.15E-08 kg CFC-11. Base case study and case study 1 are seen to have similar results by means of their ODP contribution with 3.65E-09 and 3.87E-09 kg CFC-11, in this order.

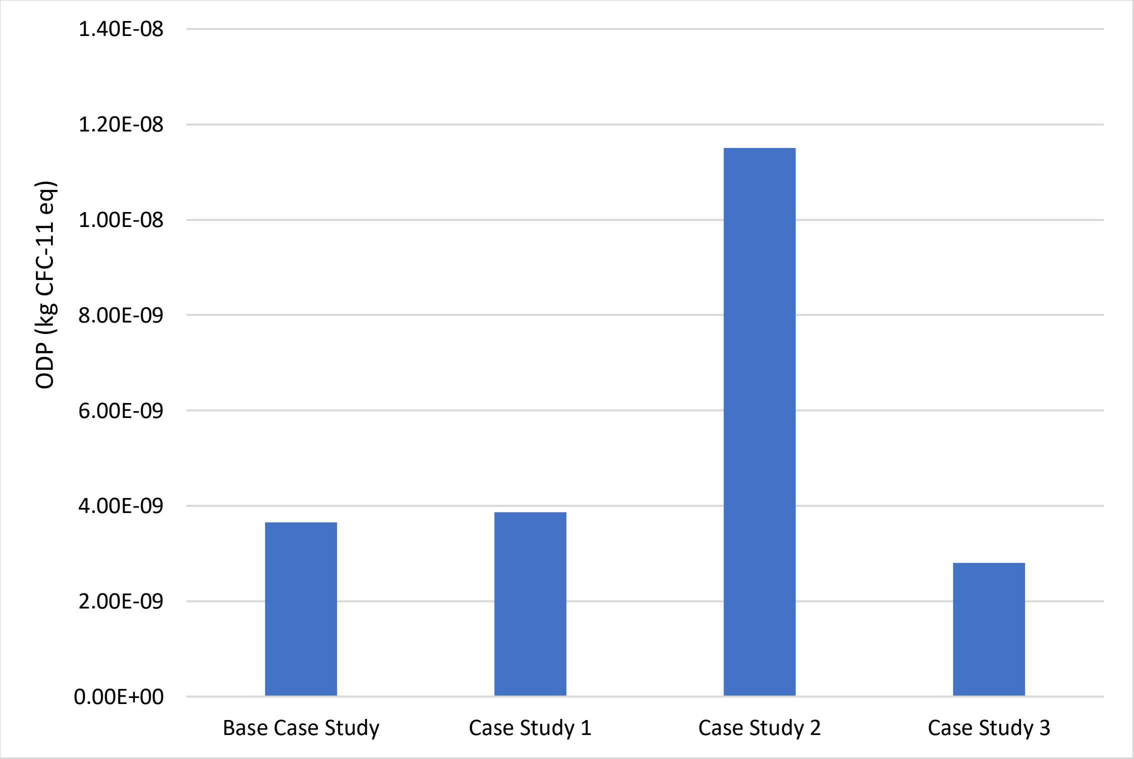

Figure 5.37: Ozone Layer Depletion Potential of Waste Management Case Studies

Major contributors to ODP are investigated for each waste management case study and cut-off is selected to be 2% for the results. Figure 5.38 shows the overall break-down for the highest process contributors of ODP for each case study.

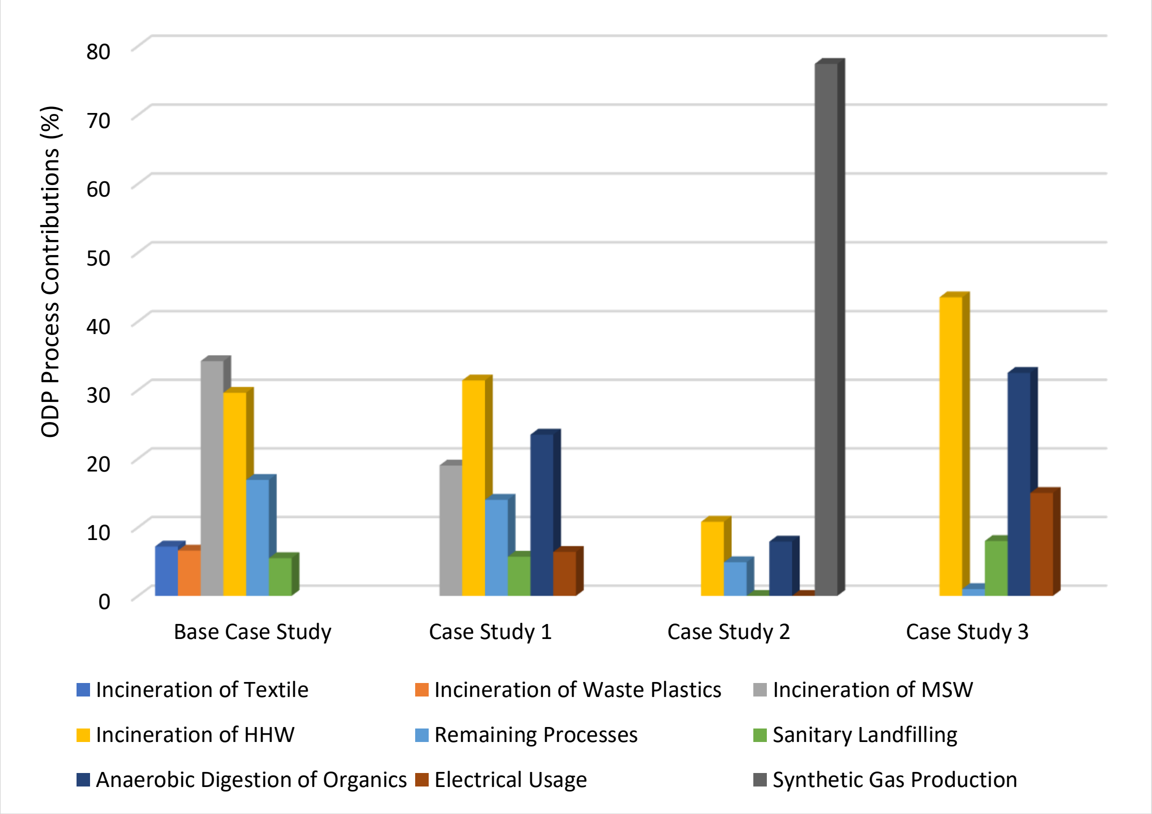

Figure 5.38: Overall ODP Process Contributions of Waste Management Case Studies

Base case study, which is the existing waste management system in Durham Region, the incineration of MSW and HHW are observed to have the highest ODP with 34.2% and 29.6% respectively. Also, municipal incineration of waste plastic and textile are responsible for 6.6% and 7.2% of ODP contribution, in that order. This is followed by the sanitary landfilling process, and the remaining process with 5.5% and 16.9% respectively. In case study 1, the incineration of HHW and MSW have more than half of the ODP contribution with values of 31.4% and 19%, respectively. Organics treatment in AD, electricity usage in MWS, sanitary landfilling process, and remaining processes, make up the rest of ODP contribution with 23.5%, 6.4%, and 5.7%, 14% in this order. Case study 2, which integrates a gasification unit into the existing waste management systems, is seen to have the highest ODP contribution. It is seen that the synthetic gas production process and the incineration of HHW make up the largest portion of ODP contribution with 77.4% and 10.6% respectively. Another major contributor for ODP is observed to be the organics treatment process in AD with 7.9%. The remaining processes are responsible for 4.1% of all ODP contributions. Case study 3, which integrates a pyrolysis unit into the existing waste management system for gasoline production, has the lowest ODP among all case studies. Similar to all the case studies, the incineration of HHW is one of the major contributors to ODP with 43.5%. The following contributors are responsible for the remaining ODP in this case study, organics treatment with 32.5%, general electricity usage with 15%, sanitary landfilling process with 8%, and the remaining processes with 1%. Network diagrams for each case study, which demonstrates the ODP contribution of each process and sub-process according to the case studies, are observed from SimaPro software and illustrated in Figure 5.39, Figure 5.40, Figure 5.41, and Figure 5.42, respectively.

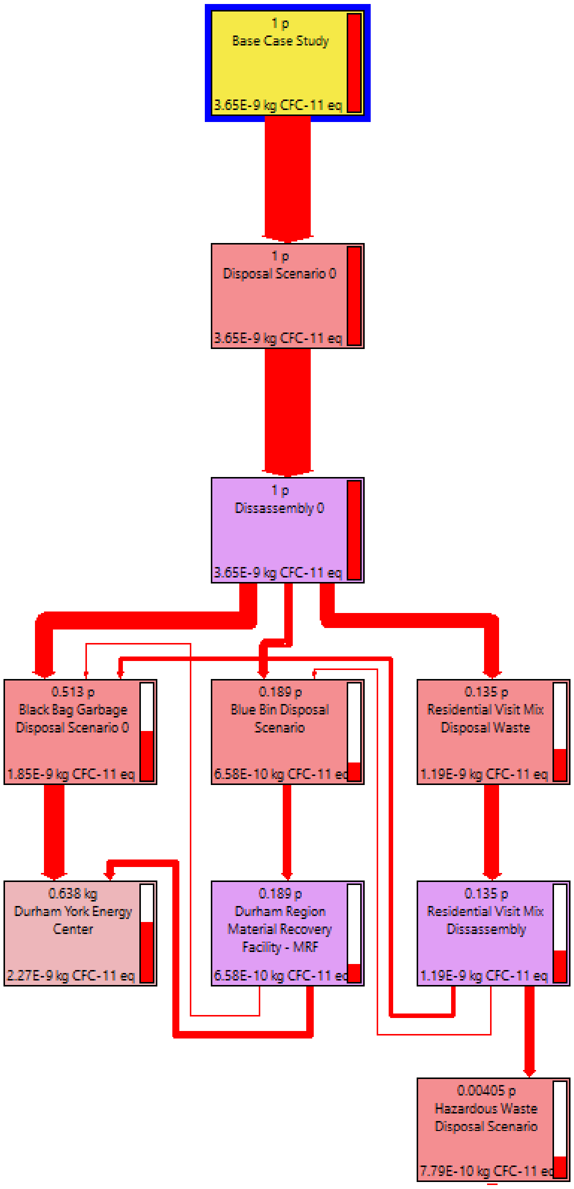

Figure 5.39: Ozone Depletion Potential of Base Case Study (cut-off 10%)

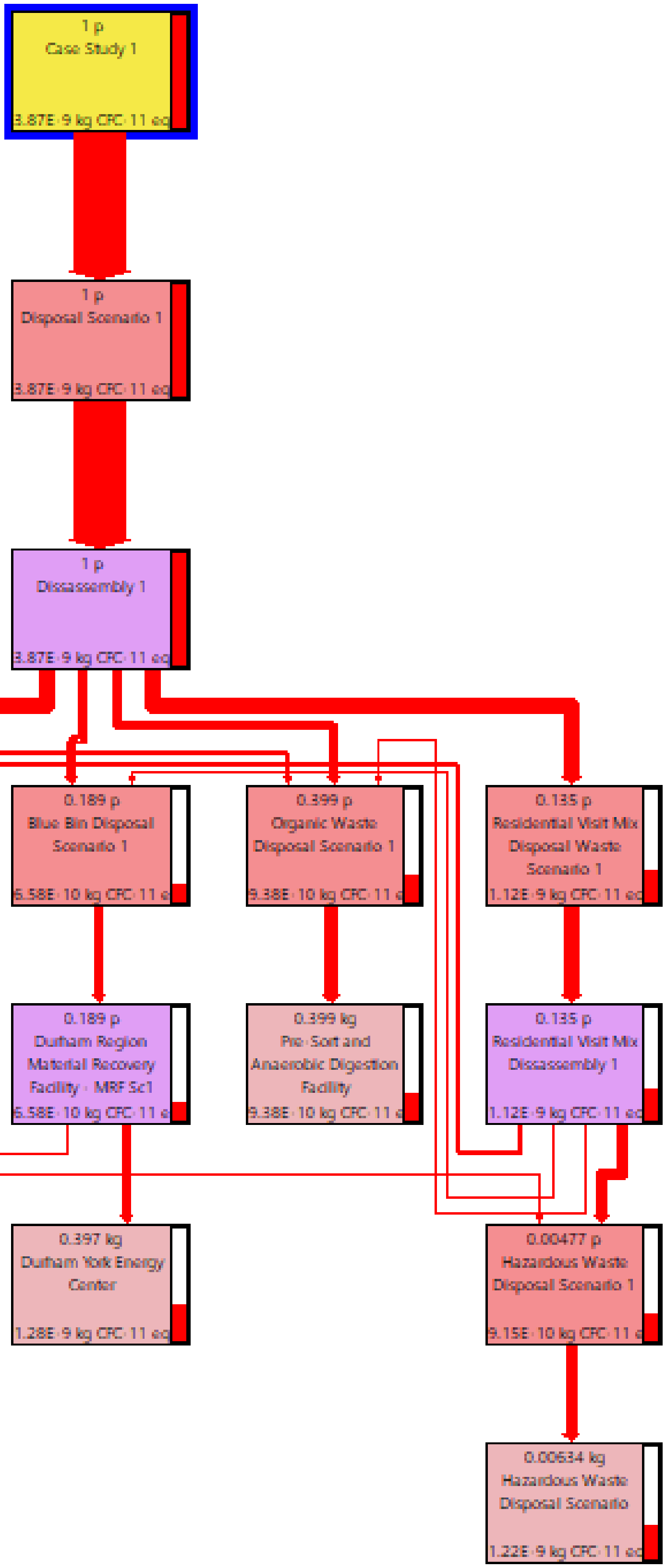

Figure 5.40: Ozone Depletion Potential of Case Study 1 (cut-off 10%)

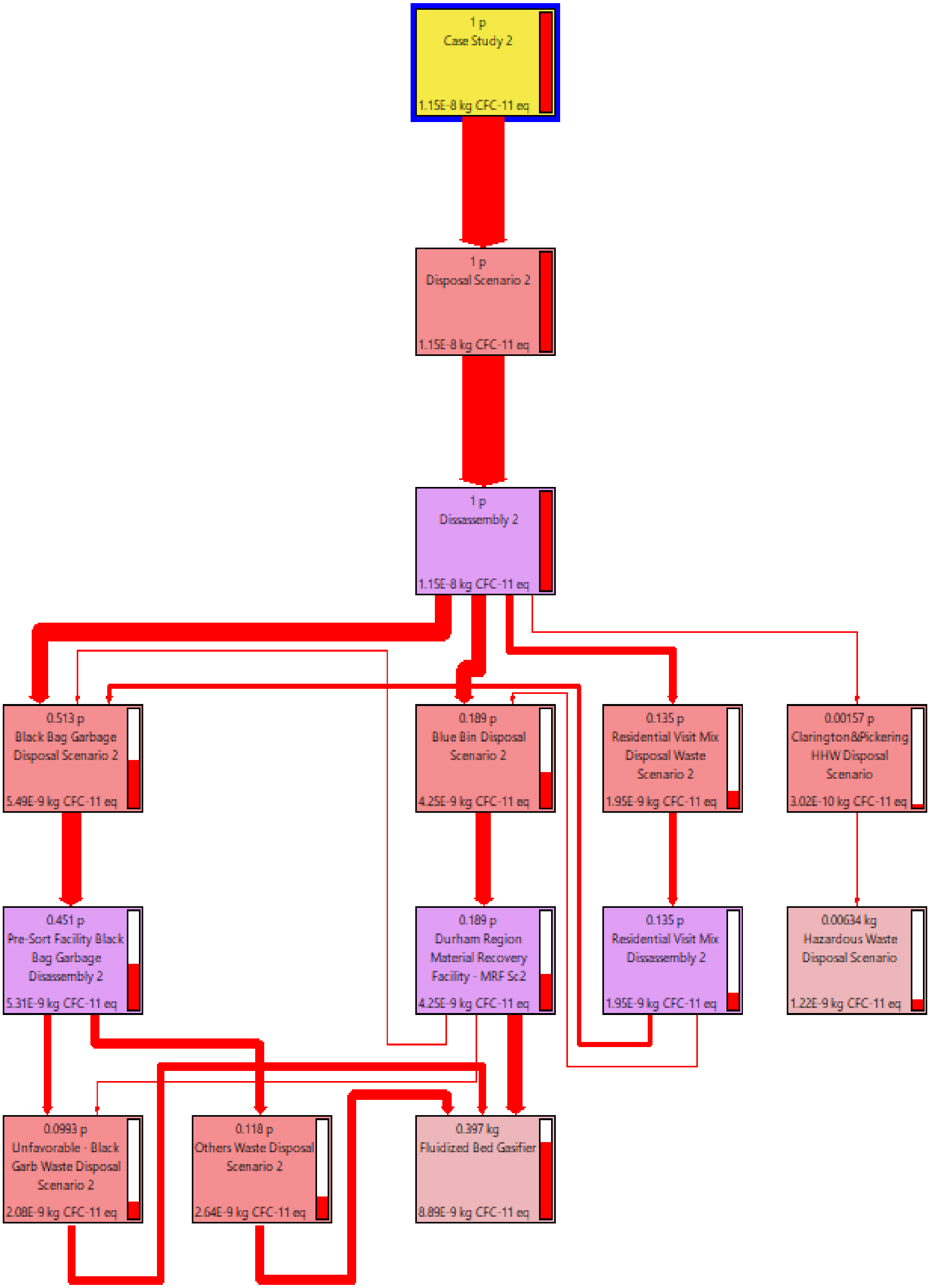

Figure 5.41: Ozone Depletion Potential of Case Study 2 (cut-off 10%)

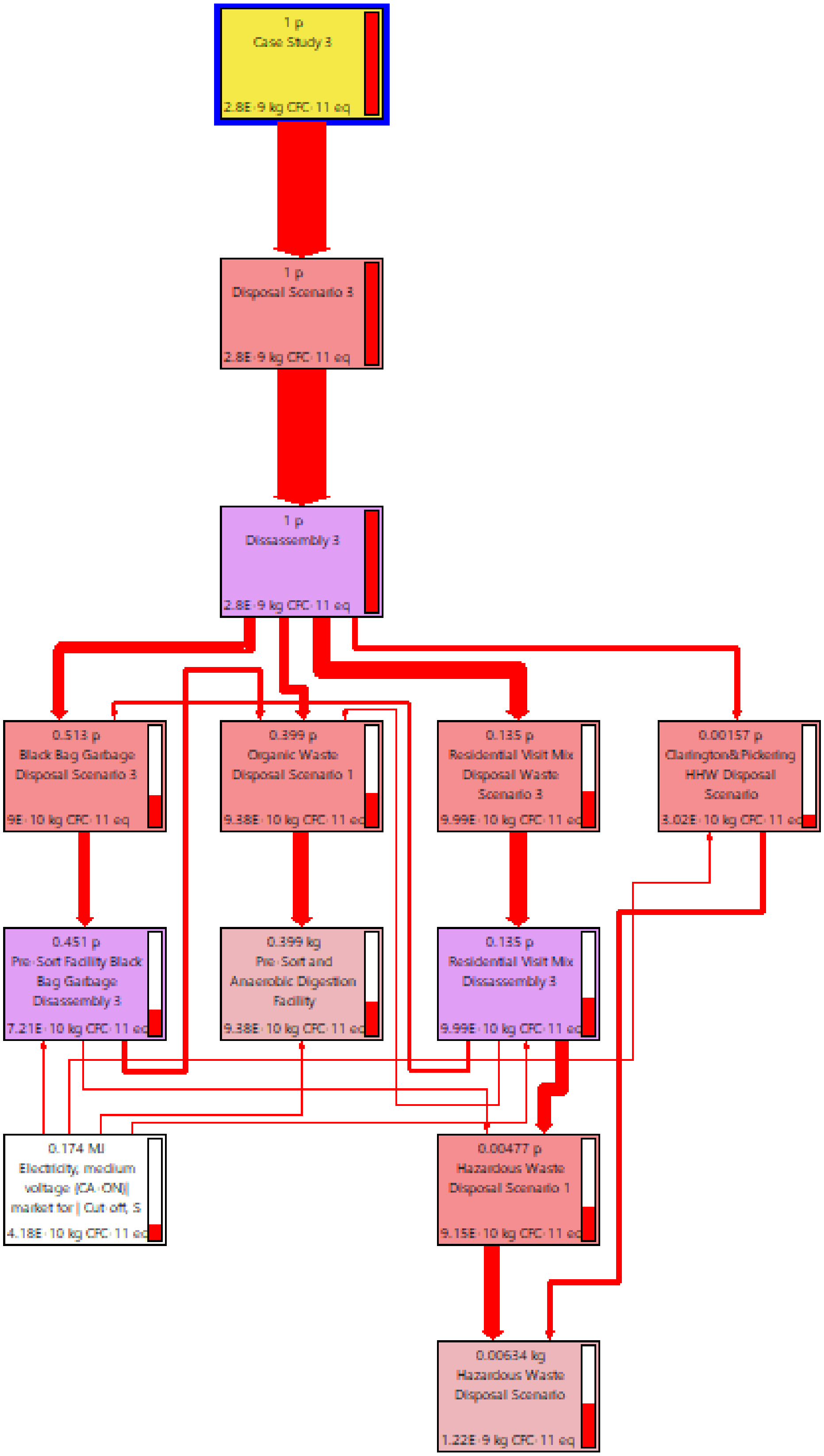

Figure 5.42: Ozone Depletion Potential of Case Study 3 (cut-off 10%)

5.3.5 Human Toxicity Potential (HTP)

Human Toxicity Potential examines the effects of toxic substances on the human environment. This impact category uses USES-LCA, describing fate, exposure, and effects of toxic substances for an infinite time span. HTP is expressed as 1,4-dichlorobenzene equivalents/kg MSW (SimaPro, 2014). Figure 5.43 demonstrates LCA results of waste management case studies for Human Toxicity Potential impact category. Among all waste management case studies, case study 2 is observed to be most environmentally friendly by means of its HTP contribution with 0.0874 kg 1,4 DB eq. However, the base case study is seen to have the highest HTP with a contribution of 2.7 kg 1,4 DB eq. Case studies 1 and 3 are the next highest contributors to HTP with a value of 1.62 and 0.149 kg 1,4 DB eq, respectively.

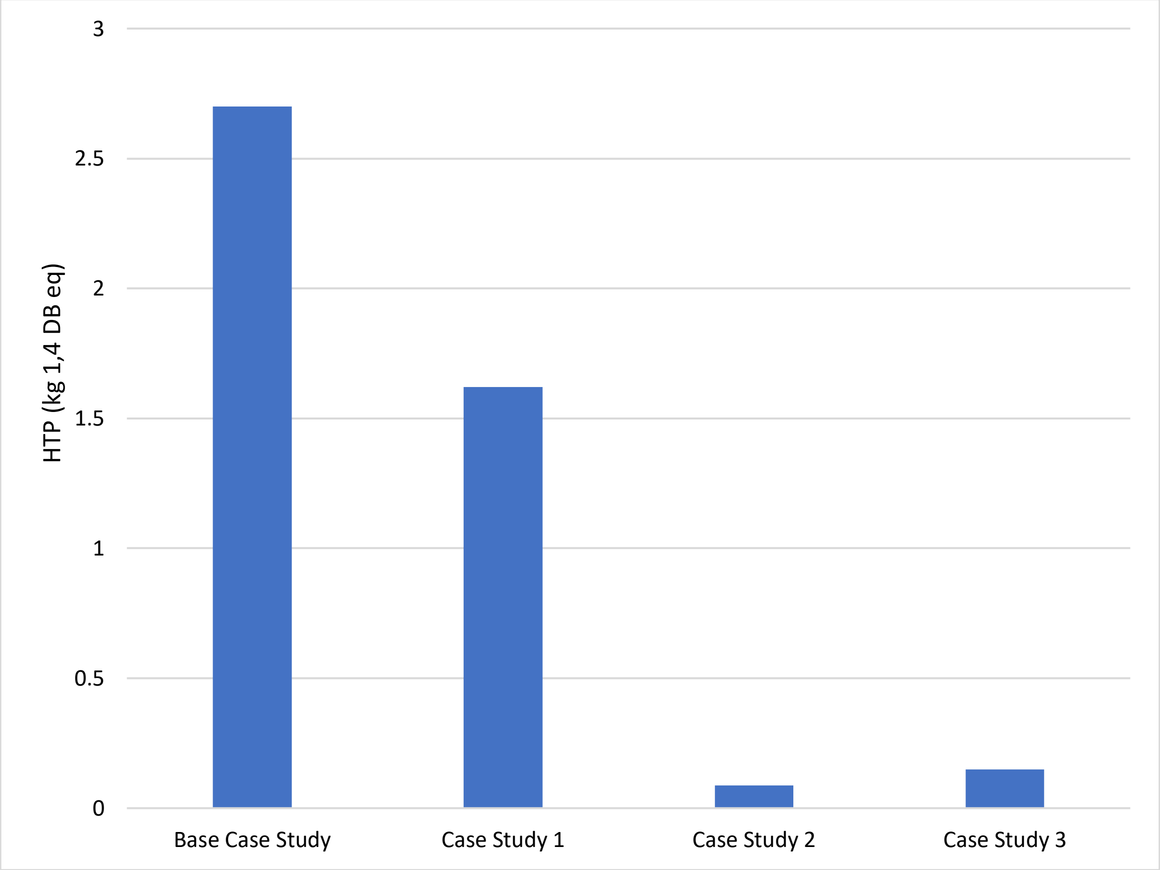

Figure 5.43: Human Toxicity Potential of Waste Management Case Studies

Major contributors to HTP are explored for each waste management case study and cut-off is selected to be 1% for the results. Figure 5.44 shows the overall break-down for the highest process contributors of HTP for each case study.

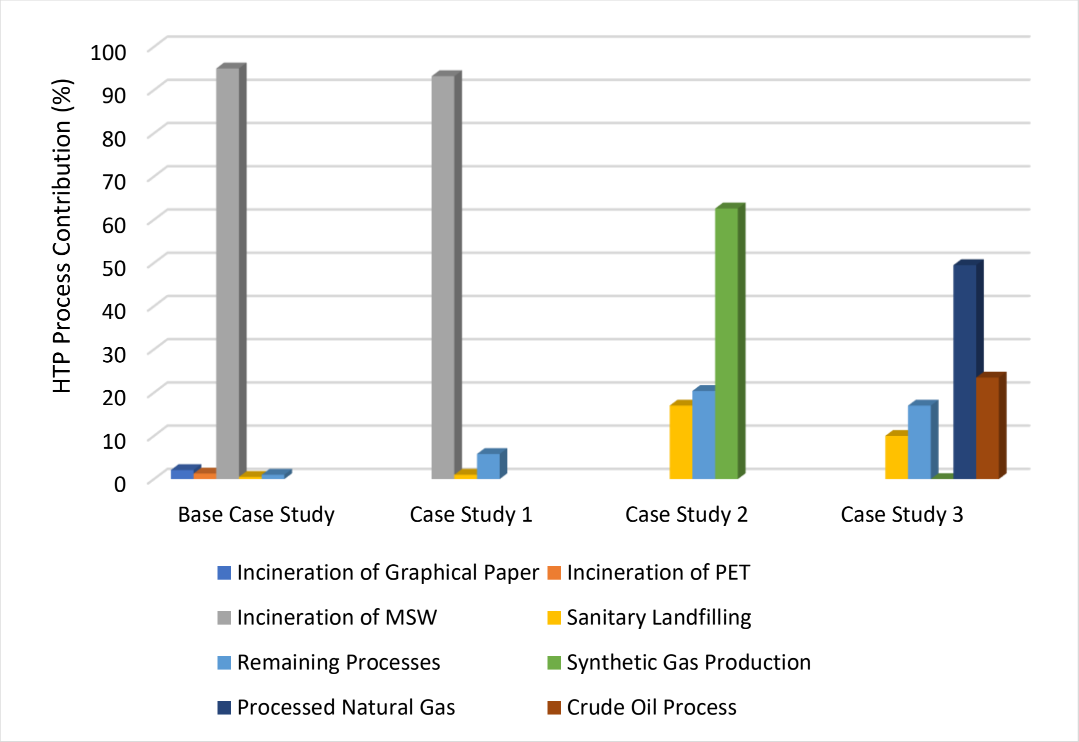

Figure 5.44: Overall HTP Process Contributions of Waste Management Case Studies

For the base case study, 95.1% of the HTP contribution comes from the incineration of MSW. This is followed by municipal incineration of waste graphical paper and PET, landfilling process, and remaining processes with 2.1%, 1.3%, 0.5%, and 1%, in this order. In case study 1, which has the second highest HTP, has similar results to the base case study with the majority of HTP contribution coming from the incineration process of MSW with 93.2%. Landfilling process and remaining processes contribute to HTP with 1% and 5.8%, respectively. In case study 2, which has the lowest HTP, synthetic gas production has expectedly the highest contribution to HTP with 62.6%. This is followed by the sanitary landfilling process and remaining processes with 17% and 20.4% respectively.

In case study 3, which has the second lowest HTP contribution, natural gas processes such as site usage, extraction, and burning have the majority of HTP contribution for the pyrolysis process with 49.5%. Crude oil extraction and production processes related to pyrolysis unit, landfilling process, and the remaining processes make up the rest of the HTP contribution with 23.5%, 10%, and 17%, in that order. Network diagrams for each case study, which demonstrates the HTP contribution of each process and sub-process according to the case studies, are observed from SimaPro software and illustrated in Figure 5.45, Figure 5.46, Figure 5.47 and Figure 5.48, respectively.

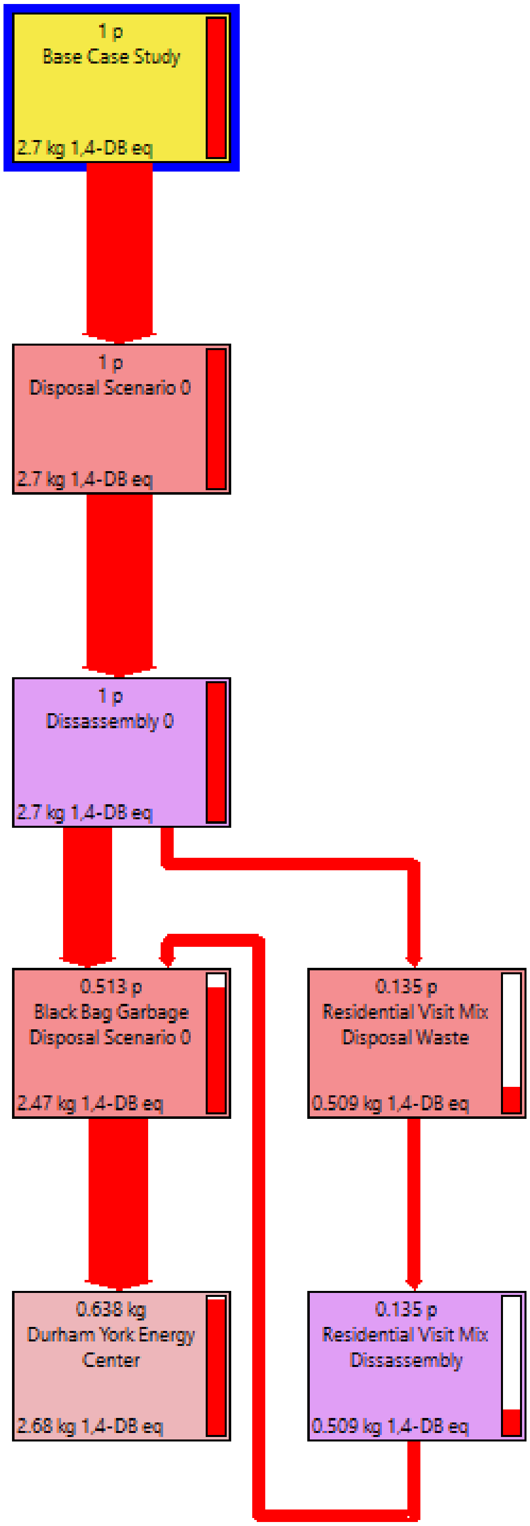

Figure 5.45: Human Toxicity Potential (HTP) of Base Case Study (cut-off 10%)

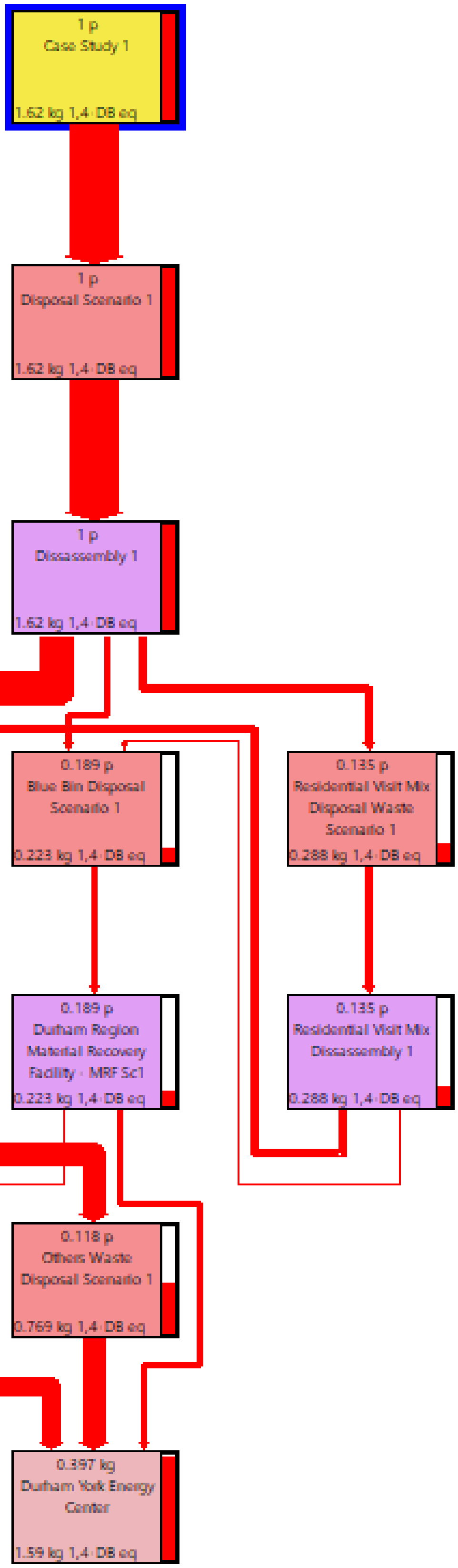

Figure 5.46: Human Toxicity Potential (HTP) of Case Study 1 (cut-off 10%)

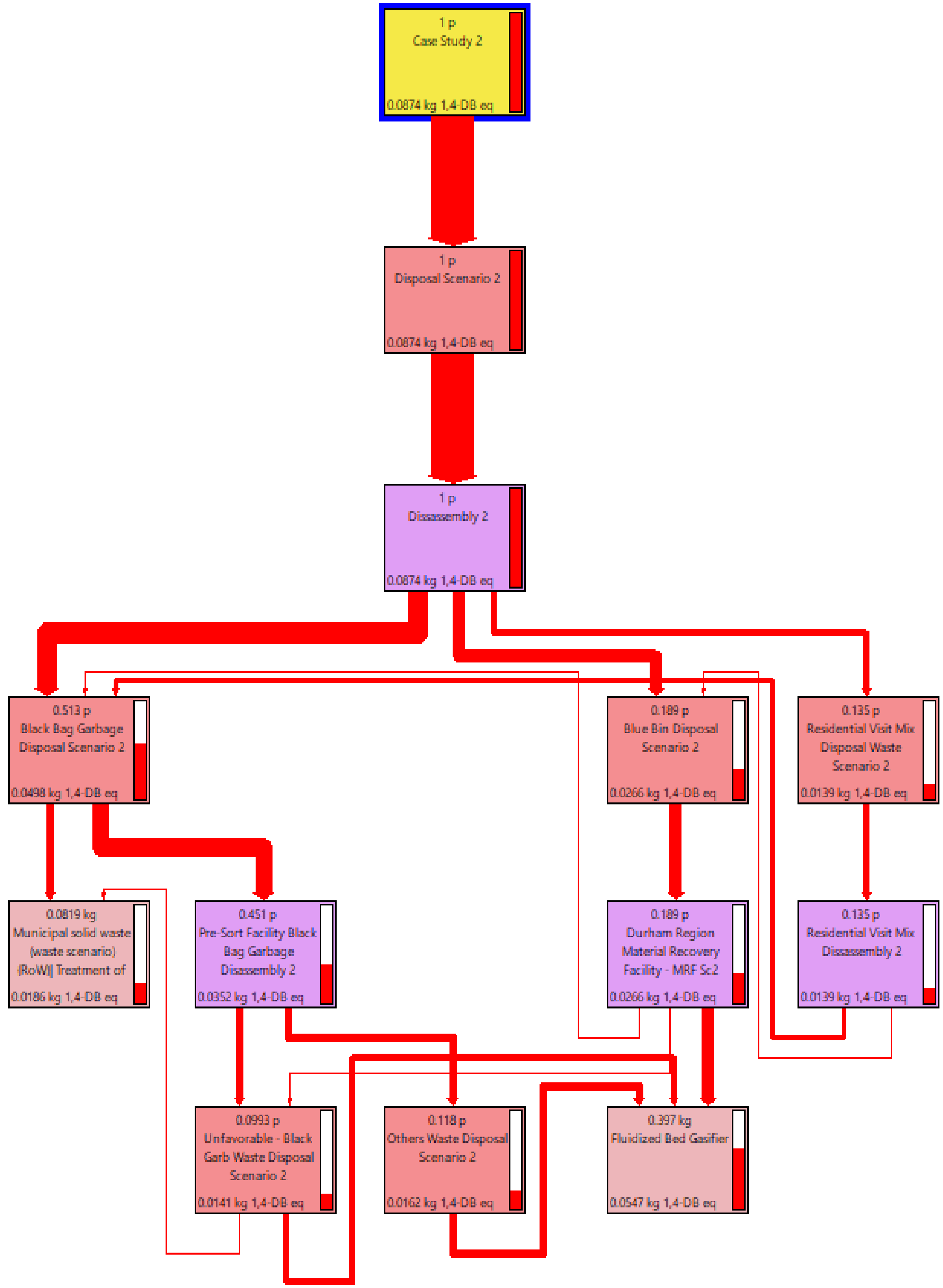

Figure 5.47: Human Toxicity Potential (HTP) of Case Study 2 (cut-off 10%)

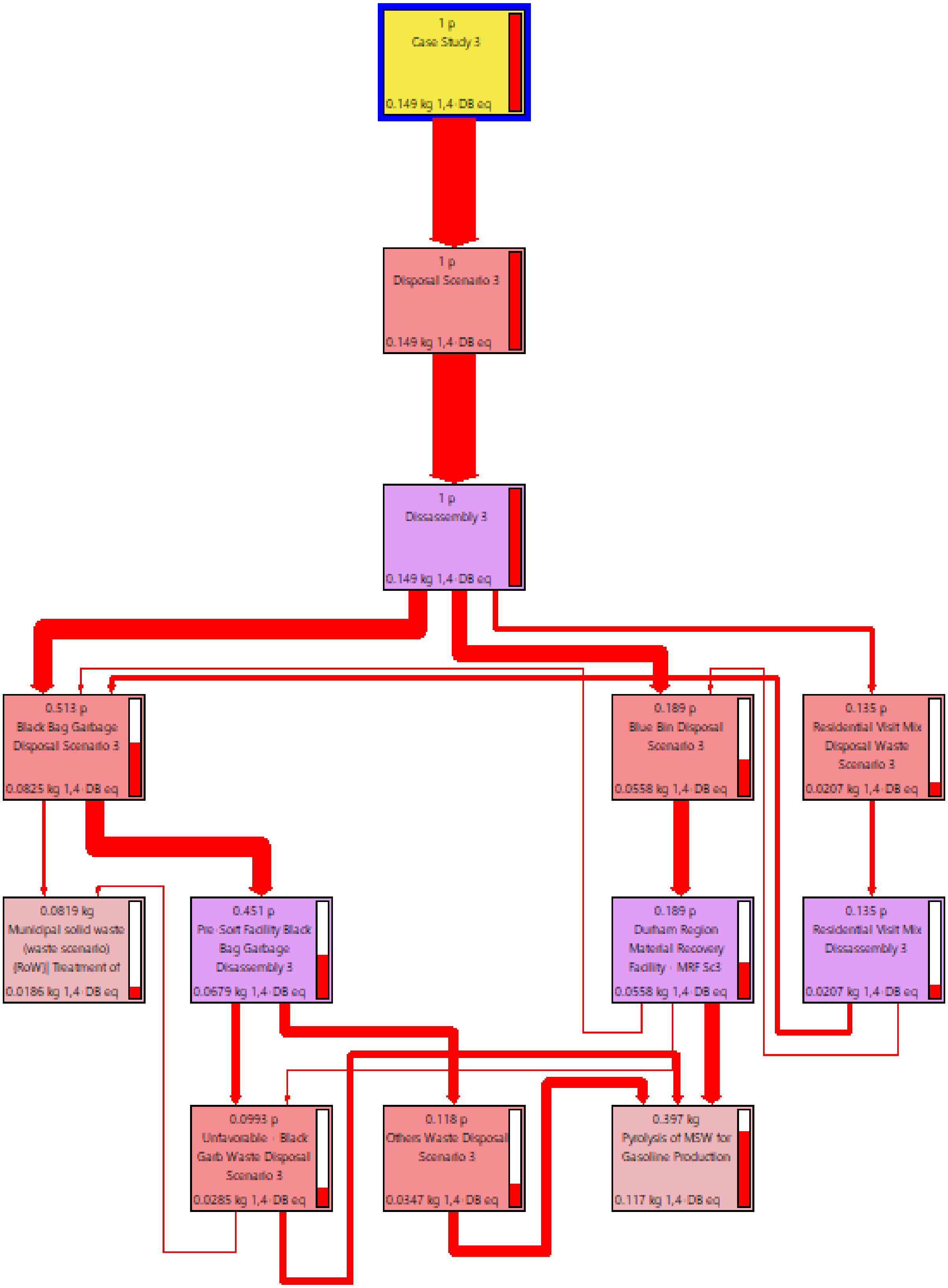

Figure 5.48: Human Toxicity Potential (HTP) of Case Study 3 (cut-off 10%)

5.4 Considered Improvement Case studies for Waste Collection and Transportation in Durham Region Results

In this section, the environmental impacts of the diesel-fueled trucks which are currently used for waste collection and transportation in Durham Region are investigated. Different case studies are considered to determine the possible GHG reduction caused by waste collection and transportation.

Accordingly, electrical trucks, CNG trucks, and hydrogen trucks are taken into consideration by means of their Life Cycle Impact Assessment. For the LCA modeling, EURO 6 trucks are selected for the infrastructure of the vehicles and environmental impact assessment is completed according to 1kg km. This means the transportation of 1kg municipal solid waste per kilometer. Table 5.2 illustrates the LCA results according to the chosen environmental impact categories for the waste collection and transportation trucks.

Table 5.2: LCA results of diesel and alternative fueled trucks according to impact categories.

Impact Category	**Diesel Fueled Truck**	**Electric Garbage Truck**	**Natural Gas Fueled Truck**	**Hydrogen Fueled Truck**
ADP (kg SB eq)	4.54E-09	4.71E-09	4.59E-09	4.86E-09
AP (kg SO_2 eq)	4.40E-07	2.19E-07	2.40E-07	3.10E-07
GWP (kg CO_2 eq)	0.000169	3.92E-05	0.000115	4.59E-05
ODP (kg CFC-11 eq)	3.36E-11	5.57E-12	1.53E-11	1.18E-11
HTP (kg 1,4 DB eq)	7.53E-05	0.00011	7.45E-05	9.44E-05

Figure 5.54 illustrates the general comparison of the waste collection and transportation trucks according to the five impact categories in percentage. As seen in the below figure, the diesel fueled trucks have the highest contribution among all comparison trucks in GWP, ODP, and AP environmental impact categories, while electric trucks have the lowest environmental impact in the above categories mentioned. However, it is observed that electric trucks have the highest contribution in HTP. Hydrogen trucks show generally low contribution in all impact categories except ADP. Finally, natural gas fueled trucks shows the lowest impact in HTP. The results obtained are discussed in detail in the following sections specifically for each environmental impact categories.

5.4.1 Abiotic Depletion Potential (ADP)

ADP investigates the possible effects on human welfare, human health, and ecosystem health, related to the extraction of minerals and fossil fuels (SimaPro, 2014). ADP is calculated for each waste collection and transportation truck based on kg SB eq/ kg km. Figure 5.49, demonstrates the comparison of the trucks considered within this study in terms of their ADP. As seen in the figure, hydrogen-fueled truck has the highest ADP contribution with 4.86E-09 kg SB eq while diesel-fueled trucks show the least contribution to ADP category with 4.54E-09 kg SB eq. This is followed by electric and compressed natural gas fueled trucks with 4.71E-09 and 4.59E-09 kg SB eq.

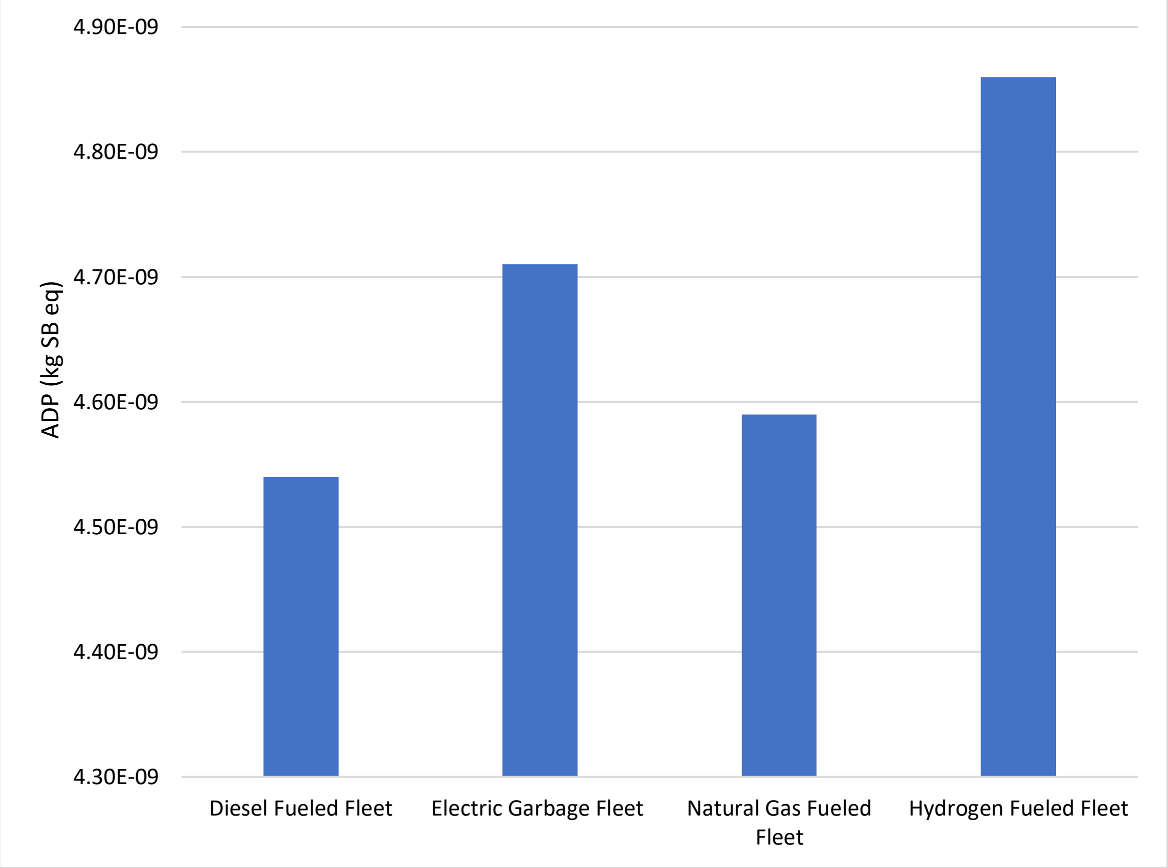

Figure 5.49: Abiotic Depletion Potential of Diesel and Alternative Fueled Trucks

5.4.2 Acidification Potential (AP)

Acidification Potential looks at the environmental impacts on soil, groundwater, surface water, organisms, ecosystems, and materials according to the fate and deposition of acidifying substances in systems (SimaPro, 2014). In this section AP is calculated for each waste collection and transportation trucks and given in the unit of kg SO_2 eq/kg km. Figure 5.50 illustrates the comparison between waste collection and transportation trucks according to their AP environmental impact. The highest AP contributor among all case studies belongs to diesel fueled trucks with 4.40E-07 kg SO_2 eq compared to electric trucks which had the lowest AP with 2.19E-07 kg SO_2 eq. The second highest is observed to be hydrogen fueled trucks followed by natural gas fueled trucks with 3.10E-07 and 2.40E-07 kg SO_2 eq, respectively.

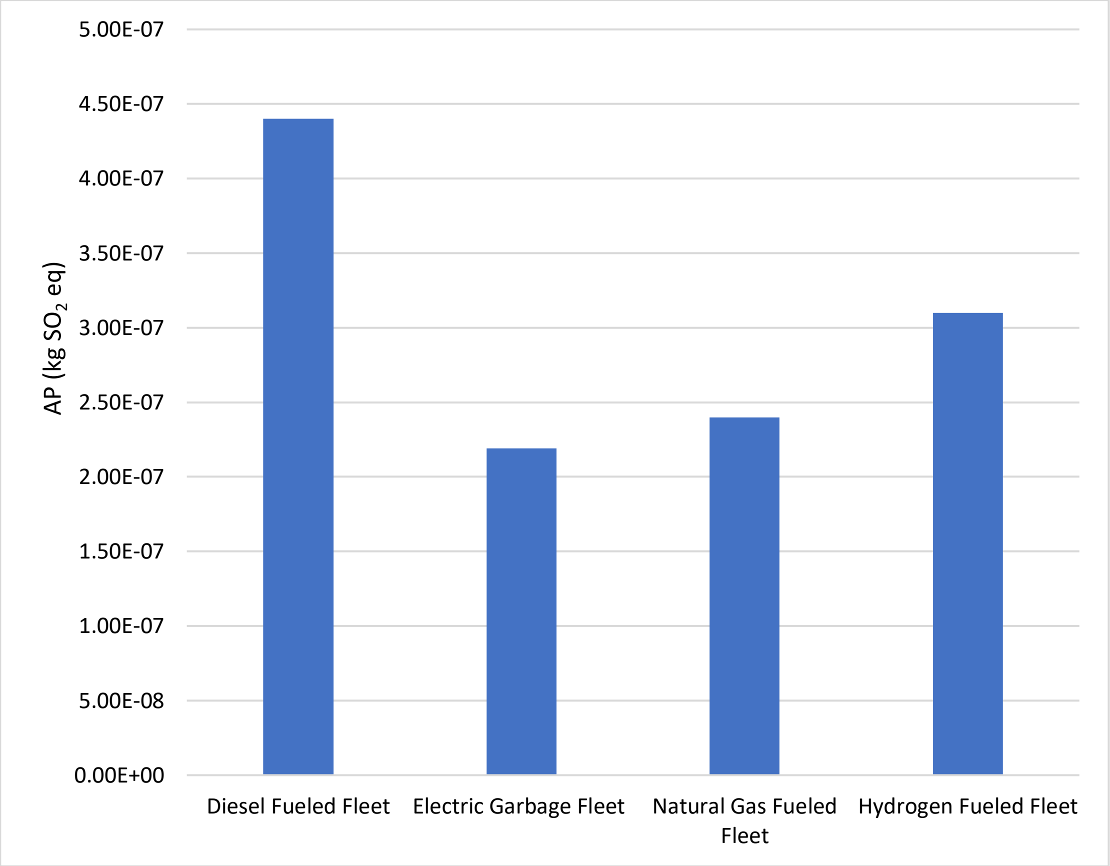

Figure 5.50: Acidification Potential of Diesel and Alternative Fueled Trucks

5.4.3 Global Warming Potential (GWP)

Global Warming Potential investigates greenhouse gas emissions and their contribution to environmental issues such as climate change, and the negative effects on ecosystem health, human health, and human welfare (SimaPro, 2014). The waste collection and transportation case studies are examined according to GWP environmental impact category for time horizon of 100 years and is expressed as kg carbon dioxide/kg km. Figure 5.51 shows the comparison of diesel and alternative fueled trucks by means of their GWP. The two alternative-fueled trucks which show the least environmental impact in the GWP category are seen to be electric and hydrogen trucks with values of 3.92E-05 and 4.59E-05 kg CO_2 eq in that order. Comparatively, the other alternative flued truck, natural gas, shows the second highest contribution to GWP with 0.000115 kg CO_2 eq. Expectedly, the existing diesel fueled truck contributes the most environmental impact in the GWP category with a value of 0.000169 kg CO_2 eq.

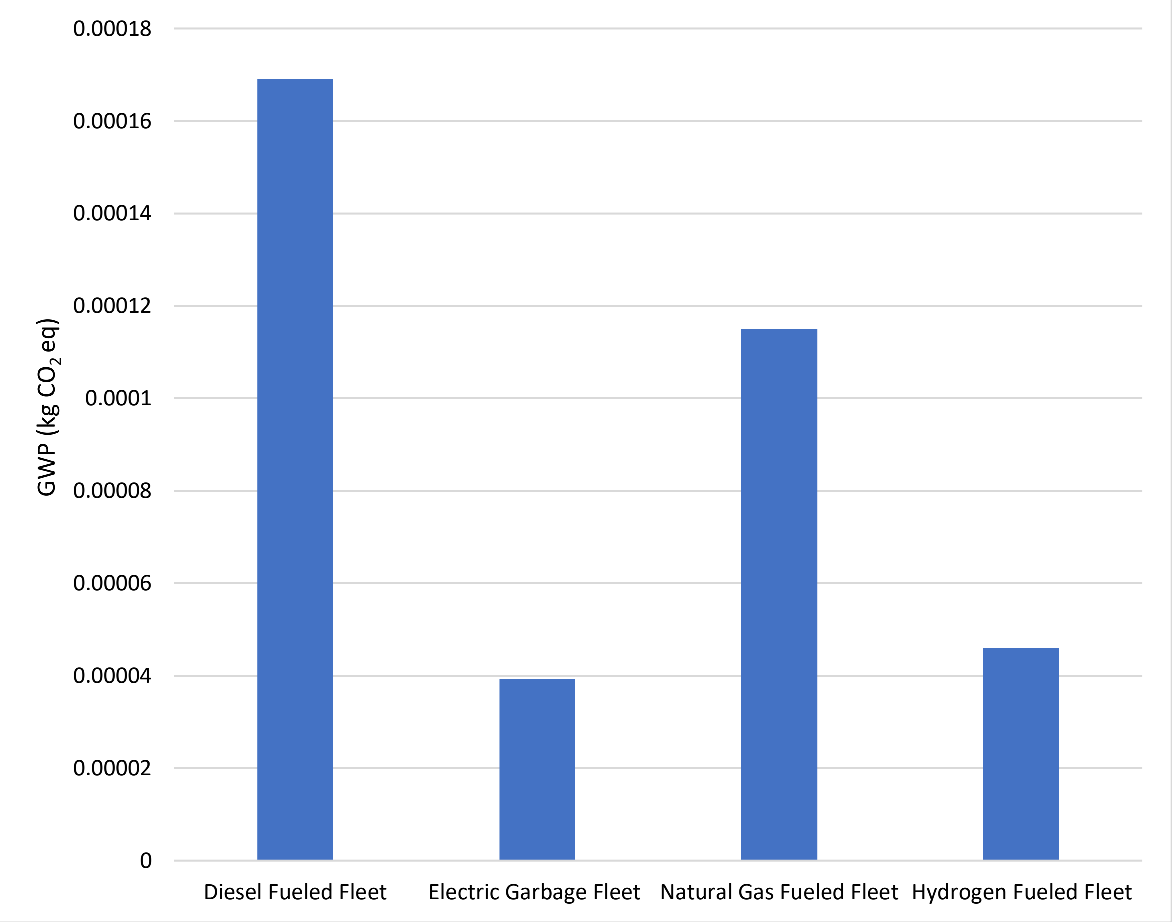

Figure 5.51: Global Warming Potential of Diesel and Alternative Fueled Trucks

5.4.4 Ozone Layer Depletion Potential (ODP)

Ozone layer depletion potential investigates the negative effects on human health, animal health, terrestrial and aquatic ecosystems, and biochemical cycles from this ozone depletion (SimaPro, 2014). All the waste collection and transportation case studies are examined according their ODPs, and the results are defined as kg CFC-11 equivalent/kg km. Figure 5.52 demonstrates the LCA results of diesel and alternative fueled trucks in terms of their ODP contribution. Compared to the alternative fueled trucks, the existing diesel fueled trucks show a much greater environmental impact in the ODP category with 3.36E-11 kg CFC-11 eq. All three alternative fueled trucks show a much lower ODP contribution with natural gas and hydrogen flued trucks second and third highest and expectedly electric fueled trucks being the lowest ODP contributor. The ODP contribution for natural gas, hydrogen, and electric fueled trucks are observed to be 1.53E-11, 1.18E-11, and 5.57E-12 kg CFC-11 eq in that order.

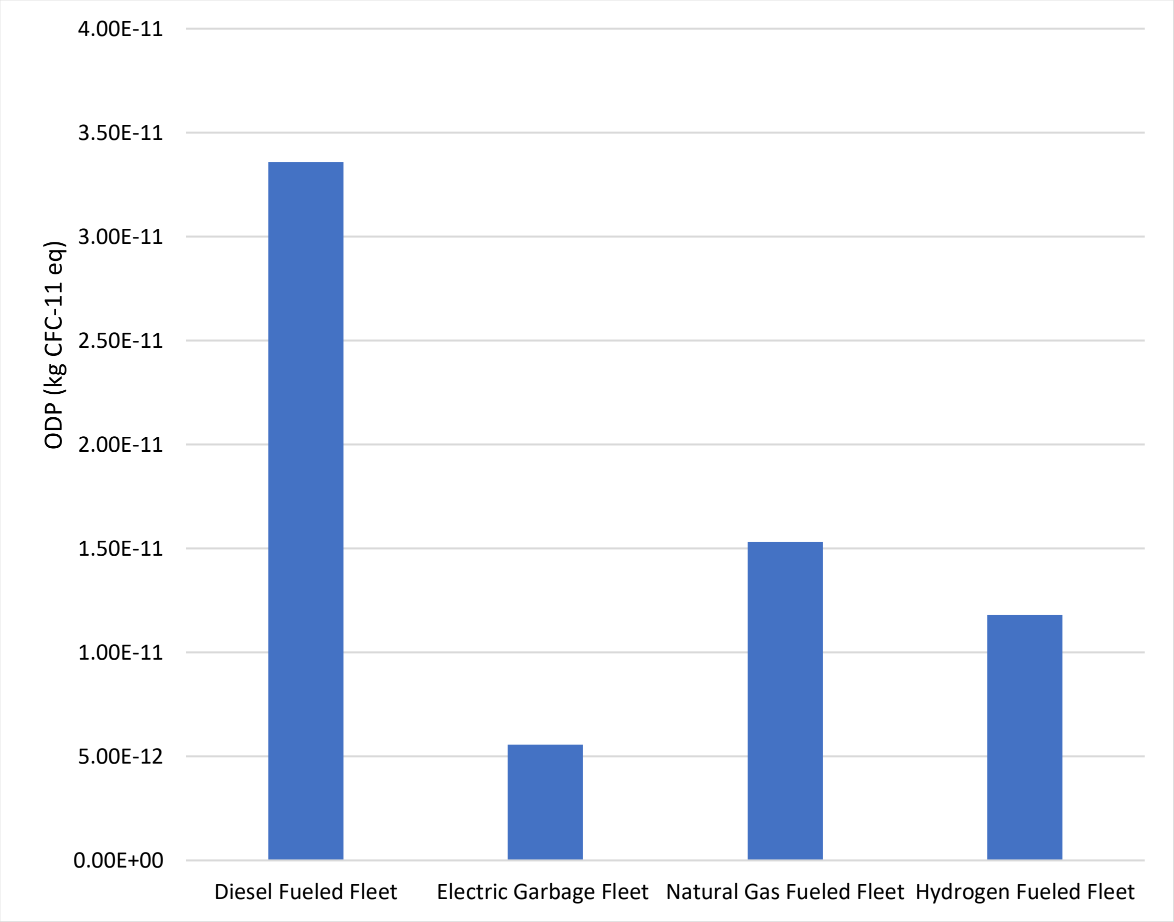

Figure 5.52: Ozone Layer Depletion Potential of Diesel and Alternative Fueled Trucks

5.4.5 Human Toxicity Potential (HTP)

Human Toxicity Potential looks at the fate, exposure, and effects of toxic substances for an infinite time span and the negative effects of these toxic substances on the human environment (SimaPro, 2014). The environmental impact category of HTP is expressed as 1,4-dichlorobenzene equivalents/kg km. Figure 5.53 illustrates the comparison between waste collection and transportation trucks according to their HTP environmental impact. The case study which had the highest HTP contribution is observed to be electric fueled trucks with 0.00011 1,4-DB eq while the case study which has the lowest HTP contribution is seen to be natural gas fueled trucks with 7.45E-05 1,4-DB eq. The second and third highest case studies for the HTP category were as following hydrogen fueled trucks with 9.44E-05 1,4-DB eq and diesel fueled trucks with 7.53E-05 1,4-DB eq.

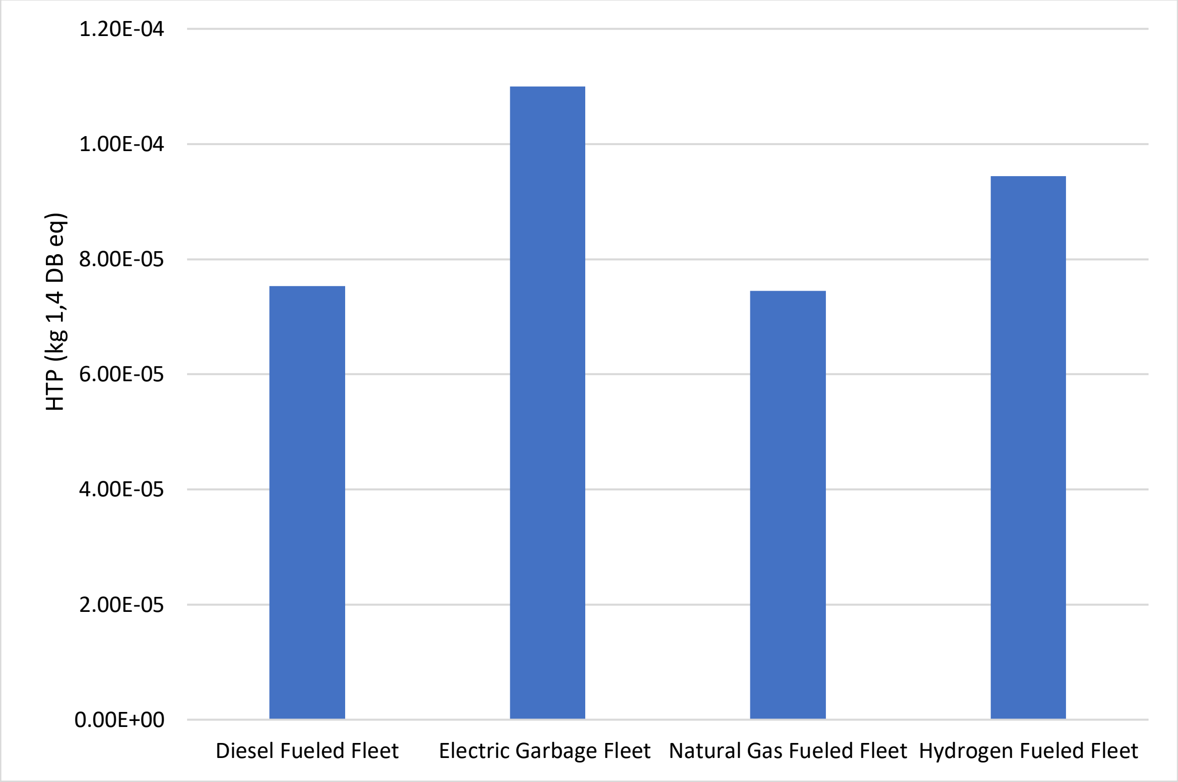

Figure 5.53: Human Toxicity Potential of Diesel and Alternative Fueled Trucks

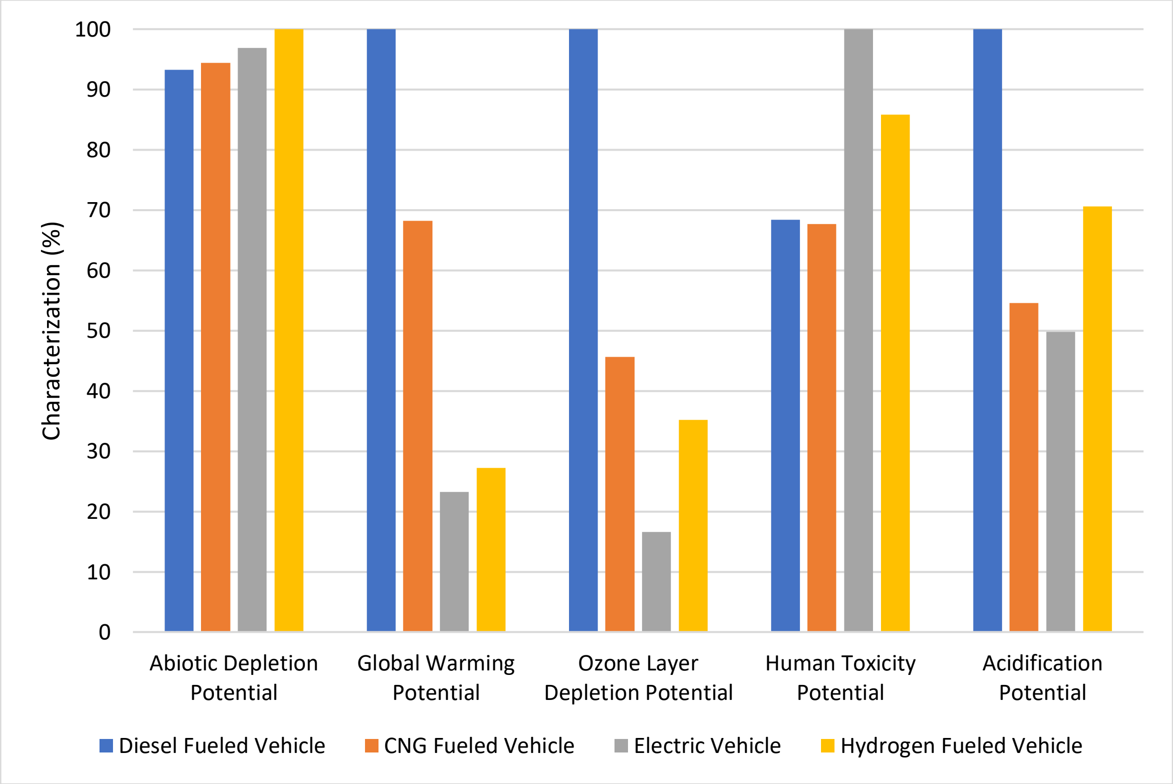

Figure 5.54: Comparison of LCA Results for the Waste Collection and Transportation Trucks

Chapter 6: Conclusions and Recommendations

This chapter summarizes the main conclusions and results of this thesis as well as recommendations for future research studies in the waste management and waste collection and transportation research area.

6.1 Conclusions

In this study, site-specific data is used to complete a comprehensive life cycle assessment to reduce GHG emissions at waste management facilities in Durham Region. Multiple case studies are investigated for waste management systems to see improvements in terms of their environmental impacts. Accordingly, five impact categories are selected for this LCA study which are abiotic depletion potential, acidification potential, global warming potential, ozone depletion potential, and human toxicity potential.

The base case study which heavily relies on the incineration of municipal solid waste is used as the baseline case for LCA comparison. There are three improvement case studies considered and investigated for waste management systems for Durham Region. Case study 1 includes a pre-sort and anaerobic digestion facility for the mechanical treatment of black bag garbage and the main treatment of organics generated in the region. In case study 2, a gasification unit is implemented into the existing waste management system as the main disposal method for unfavourable and non-recyclable plastics to generate hydrogen enriched synthetic gas. Moreover, anaerobic digestion is utilized in case study 2 as the main disposal of organics for biogas production. Case study 3 integrates a pyrolysis unit for the main disposal method of unfavourable recycles and non-recyclables for gasoline production. Anaerobic digestion is also used within this case study instead of composting processes.

A comprehensive thermodynamic analysis is also completed to investigate the feasibility in terms of energy and exergy efficiencies of the above waste management case studies. Accordingly, the systems are compared to determine the which case study has the highest energy and exergy efficiency in addition to their life cycle assessment.

According to the results obtained for waste management systems short-, medium- and long-term sustainable development goals should be defined and implemented. As a short-term goal, Durham Region should consider implementing a mixed pre-sort and anaerobic digestion facility as the main treatment method for municipal organics as stated in case study 1 as Durham Region has started investing in the infrastructure needed. For medium-term and long-term, Durham Region should start investigating the possible economical benefits of integrated gasification combined cycle as case study 2 showed lower impact by means of global warming potential and higher energy and exergy efficiency. Furthermore, United Nations have defined 17 sustainable development goals that they aim to achieve by 2030. Durham Region aims to implement case study 1 by 2024, and this system will be in line with four of the UN goals which are Affordable and Clean Energy, Sustainable Cities and Communities, Climate Action, and Life on Land (Sustainable Development Goals, 2021).

For the reduction in GHG emissions caused by waste collection and transportation services, various alternative fuels are used for the trucks and compared with the existing diesel-fueled trucks in Durham Region. A comprehensive LCA is completed, and the results are interpreted according to the five environmental impact categories mentioned above. The alternative fueled trucks examined in this study consisted of electric, natural gas, and hydrogen fueled trucks.

For waste collection and transportation services short-, medium- and long-term sustainable development goals should be implemented in Durham Region. For a short-term goal, Durham Region should consider implementing CNG trucks, where the fuel can be derived from the AD facility which is currently being built. For a medium-term goal, electric and hydrogen trucks should be used as they have a lower overall environmental impact compared to diesel fueled trucks. For a long-term goal, hydrogen trucks should replace the existing trucks as they are more environmentally friendly and have more economical benefits. As mentioned above Durham Region's goal is to replace diesel fueled garbage collection vehicles with CNG and electric vehicles by 2030. These will be inline with three of the UN goals which are Affordable and Clean Energy, Sustainable Cities and Communities, and Climate Action (Sustainable Development Goals, 2021).

The following points are a summary of the LCA results for the waste management and waste collection and transportation case studies:

- Base case study, where incineration is mainly used for the energy recovery and treatment of MSW is observed to have the highest environmental impact in HTP due to the municipal solid waste incineration process.
- Base case study has the second highest impact in GWP and ADP due to municipal solid waste incineration and landfilling processes used as a main disposal method of MSW.
- Case study 1, where pre-sort and anaerobic digestion is implemented, is seen the have the lowest impact in AP with an environmental impact reduction of approximately 4% compared to the base case study.
- Case study 1 has the second highest impact in HTP and ODP categories due to the municipal solid waste incineration, hazardous waste, and organics treatment processes.
- Case study 1 is observed to have the lowest levelized cost of electricity production among all case studies with a value of 0.16$/kWh.
- Case study 2, where a gasification unit is integrated with pre-sort and AD, has the lowest impact in HTP and GWP with a reduction of about 96.7% and 52.4% compared to the base case study.
- Case study 2 has the highest environmental impact in ODP and ADP due to the synthetic gas production process in the gasifier.
- Case study 2 shows much higher sustainability as this case study has the highest energy efficiency with the least global warming potential and a competitive levelized cost of electricity.
- Case study 3, where a pyrolysis unit is utilized, has the lowest impact in ODP and ADP with a reduction of approximately 23.3% and 64.2% compared to the base case study.
- Case study 3 has the highest impact in GWP and AP due to the combustion, extraction, and transportation of natural gas for the pyrolysis process.
- Diesel-fueled trucks are observed to have the lowest impact in ADP, however, have the highest impact in AP, ODP, and GWP.

- Electric fueled trucks have the least environmental impact in GWP, ODP, and AP categories with a reduction of 76.8%, 83.4%, and 50.2% compared to diesel fueled trucks.
- Electric fueled trucks have the highest impact in HTP with a 31.6% increase compared to diesel fueled garbage trucks.
- Hydrogen-fueled trucks are observed to have low impacts in ODP and GWP categories with an environmental impact reduction of 64.8% and 72.8%, respectively compared to the diesel fueled garbage trucks.
- Hydrogen-fueled trucks have the highest environmental impact in ADP with an increase of 6.7% compared to diesel fueled trucks.
- Compressed natural gas fueled garbage trucks has the least impact in HTP and generally lower environmental impact in ADP and AP categories.
- Case study 2 is found to have the highest energy and exergy efficiency with 58.7% and 56.8%, respectively due to the integration of a combined gasification unit.
- Implementing pre-sort and anerobic digestion unit, in case study 1, increases the regional waste management energy and exergy efficiencies from 23% and 22% to 32.7% and 31.8%, respectively.
- Integrated pyrolysis unit and pre-sort and AD, case study 3, is observed to have the second highest energy and exergy efficiencies with 40% and 39%
- Base case study, the existing waste management system, has the lowest energy and exergy efficiencies with 23% and 22%, respectively.
- Incineration in case study 1 is observed to have the highest exergy destruction rate with 62135 kW, and this is followed by Pyrolysis unit and incineration in the base case study with 54120 kW and 50124 kW, in this order.
- The biogas production rate in the digestors is found to be 8253.66 m^3/h and the net heating value of this biogas is observed to be 16855.1 kJ/kg.
- The syngas production rate is calculated to be 5.49 kg/s and the net heating value of this syngas is observed to be 17574 kJ/kg.
- The gasoline production rate is calculated to be 0.85 kg/s and the energy recovery rate from the utilization of fuel gas and off gas is found to be 6673.2 kW.

6.2 Recommendations

A comprehensive life cycle assessment of the existing waste management system is investigated, and improvement case studies are considered to reduce regional GHG emissions. Waste-to-energy systems have become more favorable as the population and energy demand continuously increase in the world. Furthermore, as the population increases waste management will become more challenging and problematic therefore waste should be seen as a possible resource for useful output productions.

Life cycle assessment studies are based on the cradle-to-grave approach, and it enables researchers to see the major GHG contributors within an activity, a process, or a system. In this study, according to the results obtained, a more circular economy approach is adapted for the existing waste management system by implementing improvement case studies for waste management and waste collection and transportation systems. More accurate LCA studies with more realistic assumptions and site-specific data should be utilized for the considered improvement case studies for the region.

Future studies should focus on completing a comprehensive life cycle assessment with site specific data for different waste management systems and improvement case studies to help reduce regional GHG emissions. Furthermore, studies should include dynamic thermodynamic analysis of different improvement waste management systems and prototyping waste management case studies in a small scale to see the feasibility of the investigated waste management systems. Some specific recommendations for future studies include:

- Environmental impacts of waste-to-energy systems are completed with five environmental impact categories selected. Future studies can include different impact categories to determine these waste-to-energy systems' environmental effects on the other categories.
- Different integrated systems can be combined with the existing waste management system in Durham Region and a thermodynamic analysis and LCA can be completed to investigate possible improvements.

- Future LCA and thermodynamic studies should consider the current waste management's GHG emission compared to the previous years' GHG emission due to domestic solid waste treatment processes.
- Future LCA and thermodynamic studies should include seasonal average municipal solid waste composition to investigate the case studies' seasonal environmental impact and energy and exergy efficiencies for bias uncertainty.
- Wastewater treatment process can be implemented into the improvement case studies to utilize wastewater sludge, which can be derived from primary and secondary sedimentation tanks in a biological wastewater treatment facility, as an alternative resource in AD for biogas production.
- Optimization studies can be completed for the proposed waste-to-energy systems to examine possible improvements in energy and exergy efficiency and environmental impacts on the selected impact categories.
- Prototyping of these proposed systems can be completed to explore the feasibility of waste management systems in a real-time study.
- Different alternative fuels, such as ammonia, can be used in future LCA studies for waste collection and transportation for possible environmental impact reduction.

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