Life Cycle Assessment of Municipal Solid Waste Management in the Region of Waterloo, Canada

by

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Author's declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Waste generation is an unavoidable consequence of human activities. Recent studies have highlighted Canada as the second-largest waste generator per capita, with the Region of Waterloo, Ontario, exemplifying a dynamic urban region characterized by rapid economic and population growth. This project performs a consequential LCA of three different municipal solid waste management (MSWM) scenarios in the Region of Waterloo. Scenario 1 models a business-as-usual MSWM system where: organic waste is composted, recyclables are recycled, and residuals are disposed off in a landfill where electricity is generated because of landfill gas production and collection. Scenario 2 considers an incinerator for residual waste treatment, and an anaerobic digestion for organic waste, while the recycling process remains the same as in Scenario 1. Scenario 3 models the province's Extended Producer Responsibility (EPR) recovery targets for recyclables, maintaining the same treatment pathways for organic waste and residuals as in Scenario 1. The functional unit (FU) is set to the management of 1 ton of residential MSW in the Region of Waterloo in 2021. Data is collected from the Region's database, LCA software and databases such as EASETECH and Ecoinvent 3.9.1, publicly available reports on waste composition in 2021, and literature. The waste-specific LCA software EASETECH is used; IPCC 2021 is selected for the Global Warming Potential (GWP100), and Traci 2.1 is selected for the following environmental impact categories: particulate matter formation (PM2.5), photochemical ozone formation, and eutrophication. Sensitivity analysis is conducted to further explore the influence of changes in assumptions made to assess the scenarios. Results indicate that Scenario 2 contributes to the least favorable results considering the GWP100, PM2.5, and eutrophication. Scenario 3 achieves the most significant offsets in GWP and photochemical ozone formation impact categories, with savings of 134% and 95%, respectively, in comparison to Scenario 1. When the GWP20 is selected instead of the GWP100, Scenario 1 becomes the least favorable scenario for MSWM, whereby the result increases from -35 kg CO_2 eq per FU with a GWP100 to 119 kg CO_2 eq per FU with a GWP20. Policymakers can prioritize the GWP20 results due to the immediate impacts of gases with shorter lifetimes, such as methane. The need for more rigorous research with better data quality is highlighted for further understanding of sustainability implications of MSWM in a Canadian context.

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List of abbreviations

AD: Anaerobic Digestion

APC: Air Pollution Control

CHP: Combined Heat and Power

CIF: Continuous Improvement Fund

COD: Chemical Oxygen Demand

DTU: Technical University of Denmark

ECCC: Environment and Climate Change Canada

EPA: Environmental Protection Agency

EPR: Extended Producer Responsibility

ELCD: European reference Life Cycle Database

EU: European Union

GHG: Greenhouse gases

GWP: Global Warming Potential

HDPE: High density polyethylene

IPCC: Intergovernmental Panel on Climate Change

LDPE: Low density polyethylene

PET: Polyethylene Terephthalate

PP: Polypropylene

PS: Polystyrene

LCA: Life cycle assessment

LCI: Life cycle inventory

LHV: Lower Heating Value

MSW: Municipal Solid Waste

MSWM: Municipal Solid Waste Management

MRF: Material recovery facility

PM2:5: Particulate Matter 2.5 micrometers

RDF: Refuse Derived Fuel

RPRA: Resource Productivity and Recovery Authority

RER: Rest of Europe

SUPR: Single Use Plastic Regulation

US: United States

WARM: Waste Reduction Model

WtE: Waste-to-energy

Chapter 1: Introduction

Municipal Solid Waste

Waste is an inevitable byproduct of human activity, reflecting our consumption patterns and impacting our environment in profound ways. Solid waste encompasses any garbage or refuse, sludge from wastewater treatment plants, water supply treatment plants, or air pollution control facilities, as well as other discarded materials resulting from industrial, commercial, mining, agricultural operations, and community activities. Importantly, the term "solid waste" is not only restricted to solid materials; it can also include liquid, semi-solid, and contained gaseous materials (US EPA, 2016). Municipal solid waste (MSW), a specific subset of solid waste, consists of everyday items discarded by households and, at times, commercial and institutional sources. This includes common refuse such as packaging, food scraps, yard clippings, and household items (Chen et al., 2020). Effective management of MSW is essential for minimizing environmental impact, conserving resources, and maintaining public health and safety.

A rapid population and economic growth has led to an increase in MSW generation. As of 2023, the world produced around 2.1 billion tons of MSW, and by 2050 the global MSW is expected to rise by 70%, reaching around 3.4 billion tons per year (Alam et al., 2022; Filipenco, 2023; The World Bank, 2018). The increase in a country's affluence typically increases MSW generation. According to Irwan et al., (2012), there has been a 40% rise in the GDP of Organization for Economic Cooperation and Development (OECD) countries since 1980, which has corresponded with a similar 40 % increase in the amount of MSW produced. More specifically, urbanization centralizes inhabitants in towns, cities, and metropolitan regions, which exerts profound challenges for the management of MSW (J. Cheng et al., 2020).

Furthermore, the composition of MSW can be affected by the GDP per capita. As average local income rises, both the composition and volume of MSW change, with higher GDP per capita leading to more pre-manufactured goods and, consequently, an increase in packaging waste (Y.-C. Chen, 2018). As a result, the lower heating value (LHV) of the MSW stream is relatively high in developed countries (i.e. 2600-3000 kcal/kg in South Korea) (Nanda & Berruti, 2021). In contrast, MSW in developing countries tends to have more organic (food) waste, increasing the moisture content, which in turn lowers the LHV. For instance, in India, the LHV of the MSW is between 800 to 1100 kcal/kg (Nanda & Berruti, 2021). A difference in composition necessitates a difference in management approaches, leading to diverse environmental impacts amongst regions.

Municipal Solid Waste Management (MSWM)

MSWM represents the final stage of the life cycle of a product and/or service, where the product or resource discarded by the consumers and producers is managed. Each type of waste (i.e. recyclables, organics, and residuals) could be treated and/or re-purposed in a separate way, and the treatment option depends on the geography, economy, policies, and many more factors. A typical linear economic concept based on take-make-dispose model is unsustainable as it requires large quantities of raw materials to be readily available for manufacturing, which aggravates pollution due to the degradation of natural systems. Circular economy presents a shift in perspective whereas resources' use is maximized over time to minimize waste disposal and reach a "wasteless" economic structure (Kirchherr et al., 2017). This model encourages the efficient use of resources, which generates economic value by maintaining the added value in products.

Recycling activities follow the circular economy model whereby recycled material can replace primary materials by a specific factor, reducing activities needed to extract raw materials. The main categories of materials that could be recycled and recovered into secondary products are the following: plastics, glass, metals, and paper. The global recycling rates can greatly differ among the different waste categories. While the global recycling rate of plastic only reached 9% in 2023, the recycling rates of metals, paper, and glass were 80%, 60%, and 50%, respectively (OECD, 2022; Maitlo et al., 2022). The reason for this difference is attributed to different factors such as the material composition, the technology sorting efficiency, and the secondary market of the recycled product. To increase recycling efficiencies, growing academic and industrial focus has been placed on the implementation of chemical recycling technologies that are able to manage hard-to-recycle plastic waste.

When segregated, organic waste has two common pathways: composting and anaerobic digestion (AD). Composting is an aerobic process that breaks down organic waste into a nutrient-rich material that can be used as a soil amendment in agricultural activities. The production of compost for agriculture has been gaining increased interest due to its improved effect on biological, physical, and chemical soil properties. AD of MSW is a process that breaks down the organics in the absence of oxygen, reduces the volume of the waste and kills pathogens available in the MSW. AD has two main outputs: biogas and digestate. Biogas primarily consists of methane (50-75%), offering a renewable energy source, and digestate is nutrient-rich that holds potential as a soil enhancer (Li et al., 2019). The adoption of AD and composting not only mitigates environmental risks associated with poor management of organic waste but also enhances food, energy, and water security.

As for the management of the residual waste, which is the waste remaining after organics and recyclables have been diverted, landfilling is a widespread disposal technology used to deal with that kind

of waste. Sanitary landfills are well maintained sites that have technologies (i.e. leachate collection and daily/intermediate/final cover) directed towards maintaining a level of environmental compliance. They are usually mounted with a gas collection system that collects the gas and generates electricity out of it. Incineration is another widely used technology in some parts of the world (especially in Europe where land availability is limited) due to its capability to accept a wide range of material input, which reduces the reliance on landfills, and generates energy as a byproduct to be used as electricity and/or heating (Turconi et al., 2011).

Municipal Solid Waste Management – Global North vs Global South

Understanding the complexities of MSWM is essential for developing sustainable solutions that address environmental concerns while safeguarding public well-being. MSWM is a major societal and governance challenge that involves a multitude of stakeholders. The management approaches differ between the Global North and the Global South, typically because of a difference in consumption patterns, waste composition, economic growth, and the policies that are in place. Landfilling is a traditional and common practice used for the disposal of the non-recyclable portion of MSW generated around some parts of the world.

In the Global South, most developing countries practice open dumping, with some countries reaching a 90% share of open dumps among all available MSWM facilities (Sabour et al., 2020). The environmental impacts associated with open dumps are more significant when the organic waste ratio is higher in the MSW stream. The degradation of biodegradable waste generates gas with almost 50% to 55% of methane content, which has a global warming potential 28 times higher than carbon dioxide over a 100-year time horizon (Sabour et al., 2020).

In the Global North, sanitary landfills represent the most common disposal method for the MSW. The involvement of the community in the waste disposal activity decreases collection costs and enhances the efficiencies of waste-specific diversion technologies (i.e. recycling, composting, anaerobic digestion) (Abubakar et al., 2022). However, even within the Global North, there are differences in both the MSWM technologies used and the share of each technology. For instance, by the end of 2016, there were approximately 17,500 AD plants in the European Union (EU). Countries like Germany, Denmark, and the United Kingdom have implemented effective public policies and financial incentives and measures, such as landfill taxes, bans, and dedicated to organic waste collection systems, to support biogas production. On the contrary, in the United States of America (USA), there are fewer than 350 AD plants, and most of them are small-scale operations on farms, that process collected organic wastes or agricultural residuals (Miller, 2022). Additionally, less than 10 % of the wastewater treatment plants equipped with AD technology harness biogas for energy production (Linville et al., 2015). In Canada, composting to produce a soil

amendment is the most popular treatment for organic waste management (Adhikari et al., 2010). In terms of WtE technologies such as incineration, Germany has been the leading country in the incineration of the MSW whereby the waste incinerated per capita has more than doubled in the last ten years (Blockwaste, 2020). In the context of other developed countries such as Canada, the availability of land facilitated the development of landfilling facilities around the country, which made this waste management option the most widespread and the cheapest way to deal with the garbage waste (Dastjerdi et al., 2021).

The Region of Waterloo

Recent studies done in 2024 show that Canada is the second largest waste generator per capita with 2.33 kg of waste generated per capita per day, following the US with 2.58 kg per capita per day (Filipenco, 2023). It is valuable to study the environmental impacts of diverse MSWM pathways in the context of a developed nation with such MSW generation results; Canada is thus selected as the study area.

Due to Canada's vast land area, landfilling of MSW has been a prominent waste management option. In 2015, the ratio of landfills per capita in the prairie provinces of Canada was more than 15 times higher than that in the USA (Mensah et al., 2023). Nevertheless, some municipalities are currently investigating WtE alternatives due to the limited lifetime of landfills that are currently available (Region of Waterloo, 2019). Moreover, a significant focus is being drawn towards diversion initiatives. In 2021, the Government of Canada published the Single-use Plastics Prohibition Regulations as part of the Government of Canada's comprehensive plan to meet its target of zero plastic waste by 2030. Municipalities around Ontario have also started transitioning into an extended producer responsibility (EPR) framework whereby producers are responsible for the management of the recyclables from collection all the way to recycling (RPRA, 2024). The mentioned EPR regulation incentivizes producers to innovate their products and optimize their supply chains to facilitate recycling schemes.

The Region of Waterloo, situated in the province of Ontario, is a vibrant urban region characterized by its dynamic economy, academic institutions, and a diverse population. The Region forecasts a population growth of 60% between 2020 (population of 624,000) and 2050 (population of 1 million) (Brown, 2024; Region of Waterloo, 2024b). As urbanization continues to increase, so do the challenges associated with MSWM. In the Region of Waterloo, an integrated MSWM pathway is currently being followed. all the residuals of MSW post recycling are sent to an engineered landfill with gas recovery. The biogas is sent to a third party, Toromont Energy, which generates electricity enough to power around 4,000 to 6,000 households of the Region (Region of Waterloo, 2021). Organic waste is composted, while the recyclables are sorted and then sent to different destinations for recovery. Understanding the environmental implications

of MSWM strategies in Waterloo is essential not only for local policy decisions but also as a case study with broader relevance to urban regions across Canada and globally.

1.1. Research objectives

To the best of the author's knowledge, there has been only one MSWM LCA study conducted for the Region of Waterloo that considered GHG emissions of different MSWM strategies (Lai et al., 2014). Other LCA studies on MSWM in Canada were largely focused on major metropolitan cities of Canada (i.e. Toronto, Montreal, Vancouver). Each of the studies focused on a specific MSW category instead of studying an integrated waste management approach.

The purpose of this study is to quantitatively assess the environmental impacts of three different management alternatives for MSW in the Region of Waterloo, Ontario. The first scenario is the business-as-usual (BAU) case (Scenario 1). This scenario represents the current state of MSWM in the Region of Waterloo. The second hypothetical case (Scenario 2) consists of two WtE technologies: an incinerator is used to process the residual waste and recover energy out of the combustion process; and, an AD is used to process organic waste and produce biogas. The third alternative (Scenario 3) considers the EPR recovery targets set by the province with all treatment pathways kept similar to the BAU model.

By using LCA, a comparative assessment of the characterized results of different environmental impact categories of the three scenarios will be presented. The boundaries of the study start at waste collection at the facility until the waste treatment, energy generation, and waste residues disposal.

The study addresses the following two research questions:

- How does waste-to-energy system impact the environmental profile of MSWM in the Region of Waterloo?
- How do the new EPR recycling recovery targets set by the province of Ontario affect the results of the LCA study?

The main target audience of this research are the following:

- First, the Region of Waterloo Waste Management facility will be better informed about the environmental benefits and burdens of the current landfilling scenario, potential WtE scenario, and the shift to the EPR targets as of 2024.
- Second, stakeholders working on the new diversion initiatives, such as EPR, would find the results of the study relevant to their work.

This chapter introduced the topic of MSW, MSWM, the difference in management across the globe, and the case of MSWM in the Region of Waterloo. It sets the tone and introduces the key themes that are later touched upon in the upcoming chapters. Chapter 2 presents the systematic literature review of MSW, MSWM, and LCA of MSWM. Chapter 3 is dedicated to an explanation of the case study of the Region of Waterloo. Chapter 4 describes the methods section of the LCA study detailing all the steps needed to achieve the objectives, and Chapter 5 presents the LCA results of the three scenarios alongside the sensitivity analysis. Chapter 6 of this thesis discusses the overall contribution of research and its limitations providing directions for future research. Chapter 7 presents the conclusion, which reflects upon the entire thesis.

Chapter 2: Literature Review

The purpose of the literature review is to present available knowledge around the following research areas: MSW and its diversity, available methodological tools to quantify environmental impacts of a system, LCA tools to study MSWM, and LCA in the context of MSWM in Canada. `

2.1. Municipal Solid Waste

MSW originates as the solid waste of a municipality collected from households, offices, small-scale institutions, and commercial enterprises. However, MSW varies considerably in its composition and its classification, although it comprises of both biodegradable and non-biodegradable fractions from organic and inorganic materials, respectively. Carbon content in solid waste is a crucial aspect. Carbon can be classified as fossil fuel-derived, with the fossil carbon fraction varying based on waste type, and biogenic carbon which is stored in biological materials. This distinction has implications for calculating GHG emissions during estimates of environmental impacts of MSWM options (Kim et al., 2016).

The waste classification also differs worldwide. As an example of a country in the Global South, China classifies its MSW into the following categories: recyclables (paper, glass, metal, plastics, textile), kitchen waste (leftover food waste, yard waste), hazardous waste (i.e. battery, electronics, drugs), and residual waste. The construction waste, industrial waste and agricultural waste are not classified as part of the MSW in China (Ding et al., 2021). In the USA, which is part of the Global North, MSW is defined as the garbage from homes, schools, hospitals, and businesses, but excludes industrial, hazardous, and construction wastes (US EPA, 2016). However, in Canada, MSW is divided into six sub-components: residential, industrial, commercial, and institutional, and construction & demolition (Canada, 2017). Nevertheless, the classification differs from region to region, with some countries extending their classification of MSW to include industrial and construction waste, while others only considering residential and institutional waste as part of MSW. This difference can heavily impact the waste composition reported as well as the MSWM scheme undertaken.

Typically, MSW includes both biodegradable and non-biodegradable fractions from organic and inorganic materials. The three main groups of a MSW are the recyclables, the organics, and the residuals. Among all the components of MSW, the garbage is the most heterogeneous, which includes textiles, fabrics, biomedical wastes, personal hygiene products, health care items, cosmetics, pharmaceuticals, pet litter, leather, rubber and polymeric residues (Nanda & Berruti, 2021). Waste composition can vary greatly between regions. Industrialized areas tend to generate larger quantities of waste, which includes a higher

proportion of recyclable materials and electronics. In contrast, industrializing regions usually generate less MSW, with a larger fraction being biodegradable (Vergara & Tchobanoglous, 2012).

2.2. Municipal Solid Waste Management

The common focus of MSWM is on the three following categories of waste: recyclables, organics, and residual waste. Table 1 summarizes the following parameters for the diverse MSWM pathways: technology type, operating temperature, composition of feedstock, outputs, advantages, and disadvantages. Even though landfilling is considered as the least preferred management pathway worldwide, it is the most common disposal method performed on a global scale. The recyclable portion of MSW (i.e. metal, glass, paper, plastics) has a high potential for recovery, whereby multiple methods of recycling can lead to various products. The most common method for recovering secondary materials is through mechanical recycling, whereby each type of waste is recovered in a separate facility (i.e. paper in paper mills and steel in steel mills), and new products are marketed as secondary materials. Incineration is another alternative to landfilling and/or recycling. In addition to incineration, other thermochemical techniques such as gasification and pyrolysis can be used to recover syngas and liquid fuel from the waste stream. Nevertheless, gasification and pyrolysis are not widely implemented due to several limitations, which include the need to pre-treat the waste and transform it into a refuse derived fuel (RDF), the complexity of the technologies, the capital-intensive requirements, and their high capital costs. Moreover, gasification requires very strict safety standards, which limits its ability to operate for a full calendar year (Porshnov, 2022). As for organic waste management, composting is more prominent than AD, which can be attributed to the low product yield, the commercial limitation, and the need for preprocessing and long treating times of AD (Lin et al., 2018). Nevertheless, organic waste constitutes a significant portion of the landfilled waste, and their degradation heavily contributes to the GHG emissions happening on site.

Table 1:Difference in key parameters between the following MSWM pathways: Recycling, landfilling, incineration, composting and anaerobic digestion

	Chemical recycling: Pyrolysis	**Chemical recycling: Gasification**	**Mechanical recycling**	**Incineration**	**Landfill**	**Composting**	**Anerobic digestion**
Technology type	Thermochemical decomposition (*Vijayakumar & Sebastian, 2018*	Thermochemical conversion *(Mahinpey & Gomez, 2016)*	Sorting, washing, drying, grinding, re-granulating and compounding.	Combustion	Disposal	Aerobic decomposition	Anaerobic decomposition
Temperature of operation	~500 ºC (*Vijayakumar & Sebastian, 2018*	~700 ºC *(Mahinpey & Gomez, 2016)*	~200 ºC *(WWW, 2023)*	At least 85 ºC *(The World Bank, 1999)*	Optimal temperature for methane generation of 57 ºC	At least 55 ºC *(Ontario, 2024)*	Thermophilic (55 ºC) or mesophilic (35 ºC) (*Ontario, 2022)*
Composition of feedstock (MSW)	All components of MSW. (*Vijayakumar & Sebastian, 2018*	All components of MSW. *(Mahinpey & Gomez, 2016)*	Different technologies for different materials (i.e. paper, plastics, metals) and sub-materials (i.e. HDPE and mixed plastics).	Mixed MSW	All components of MSW.	Organic waste	Organic waste
Output/s	Liquid oil, bio-char, syngas (*Vijayakumar & Sebastian, 2018*	Syngas, tar *(Mahinpey & Gomez, 2016)*	Secondary material	Fly ash, bottom ash, flue gas, energy in the form of steam.	Landfill gas and leachate.	Compost	Digestate and biogas (*Ontario, 2022)*
Advantages	-Feedstock flexibility: unsorted plastics can be used an input. -No need for pre-treatment of product; liquid oil produced (after refining) is of high quality *(Maitlo et al., 2022)*	-Syngas decreases the solid waste produced as well as the environmental emissions. *(Maitlo et al., 2022)*	-Fast process (Heating shredding and remolding). -Less energy intensive than chemical recycling. *(Maitlo et al., 2022)*	-Reduction in plastic waste size. -No need for pre-sorting. -Energy recovered. *(The World Bank, 1999)*	-Low tipping fee. -Possibility of land reuse after landfill closure. -Hazardous landfills accept hazardous waste. *(Maitlo et al., 2022)*	-Fast degradation. -Compost as soil amendment. -Less costly than AD. *(Lin et al., 2018)*	-Low processing temperatures and high selectivity of products produced. *(Maitlo et al., 2022)* -Small area -Reduced odor *(Lin et al., 2018)*
Disadvantages	- Pre-sorting of waste is required. -Lack of product control. - Low energy efficiency. *(Maitlo et al., 2022)*	- Pre-sorting of waste is required. -The use of air as a gasifying agent reduces the calorific value of syngas. - Tar is a by-product that needs further re-processing. *(Maitlo et al., 2022)*	- Needs presorting. - Decrease in performance of secondary material. - Number of reprocessing cycles is limited. -Sorting at household level *(Maitlo et al., 2022)*	Environmental emissions (i.e. particulate matter, dioxins, CO, furan). *(The World Bank, 1999)*	-Plastic waste needs a great amount of landfill space. -Methane emissions from organic degradation. -Soil and water pollution through leaching. *(Maitlo et al., 2022)*	-Need for large area. -Odor pollution. -GHG emissions, notably NOx. -Leachate production. (*Lin et al., 2018)*	- Low product yield - Commercially limited. -Need for a preprocessing phases and long treating time (*Maitlo et al., 2022)*

2.2.1 Municipal Solid Waste Management of residuals

- **Landfilling**

The landfilling of waste represents a prevalent approach for residual waste left after residents and businesses have sorted recyclables and organic waste. Landfills have the potential to generate revenue by utilizing landfill gas and leachate for energy generation (Nanda & Berruti, 2021). Various types of landfills exist, with different air pollution control technologies as well as different gas recovery models, which leads to a variety of emissions profiles. Roughly 33 % of the waste ends up in open dumps, most notably in cities in the Global South that lack proper collection systems (Kaza et al., 2018). In developed countries, an environmentally conscious form of landfilling, known as "sanitary landfilling," is commonly employed. Sanitary landfills, designed with architectural upgrades, are environmentally safer compared to common landfills. A typical sanitary landfill comprises four layers: the bottom layer incorporates dense clay lining and a cover of high-density polyethylene (HDPE) sheets to prevent the leakage of toxic effluents; the second layer includes drainage channels directing toxic fluids to a treatment facility; the third layer acts as a gas collection layer, trapping landfill gases for further cleaning and use; and the topmost layer serves as the primary reservoir for solid waste. The landfill's opening is covered with soil to mitigate odors and prevent the discharge of pathogenic microorganisms. In contrast, a common landfill widely present in the Global South is essentially a deep cavity accumulating solid waste and has a top cover of soil. Over the years, common landfills have been observed to emit significant amounts of methane (CH_4), nitrous oxide (N_2O), and toxic heavy metals. The uncollected methane that is not oxidized in the landfill cover contributes to fugitive emissions from the site. A notable limitation in implementing sanitary landfills, especially in least developed countries, lies in the shortage of skilled labor, hindering the widespread usability of this advanced landfilling method (Das et al., 2019).

Gas collection efficiency mostly differs based on the type of landfill in place whether it is a landfill with limited care, an average performing landfill, or a well monitored state-of-the-art landfill. The main difference between the three landfill designs is the difference in the percentage of gas collection during different time intervals throughout the 100 years. Since gas production is linked to the decay rate of different waste fractions, the actual collection efficiency will also vary based on the type of waste deposited in the landfill and the specific technology employed at the site. The percentages represent the effectiveness of gas collection from one ton of waste over a hundred-year span. These values are categorized into four intervals since the efficiency of gas collection varies throughout the landfill's lifespan. The average efficiencies of the different landfill types are presented in Table 2.

Table 2:Average landfill gas collection efficiencies in three types of landfills throughout different time period intervals (Olesen & Damgaard, 2014)

Time Period (years)		0-5	5-15	15-55	55-100
Landfill type	Limited Care with landfill gas collection	30%	45%	55%	0%
	Avg Performing	35%	65%	75%	0%
	State-of-the-art	45%	80%	95%	0%

Typically, a gas collection system isn't installed during the first two years of landfill operation, resulting in lower efficiency compared to subsequent periods. Collection efficiency is expected to peak once the landfill's final cover is in place. Eventually, there comes a point, influenced by factors such as landfill size, where gas collection ceases due to diminishing returns, that was typically set around the 55-100 year mark (Olesen & Damgaard, 2014). The installation of daily, interim, and final covers in engineered and state-of-the-art landfills enhances the gas collection efficiency due to an enhanced degradation of the waste in the lower cells.

The landfill gas that is uncollected goes through partial oxidization in the topsoil and contributes to emission to the environment. However, this is a simplified assumption, as some gas might exit the landfill along with the leachate, or it could undergo degradation before reaching the top cover. The oxidation efficiency is a function of cover type (i.e. cover of landfill vegetation), climatic conditions, age of waste landfilled, and the flux of methane to the top cover. When methane loading decreases, it signifies a reduction in anaerobic decomposition processes within the landfill. Consequently, as anaerobic conditions diminish, aerobic conditions, which support oxidation processes, become more prevalent in the top cover layer (Olesen & Damgaard, 2014). As landfilling areas are becoming scarcer around the world, alternative energy-focused technologies dealing with residual waste are being studied and implemented.

- **Waste-to-Energy**

With an increase of area demand for new landfill sites by 2.8×10^6 m^2 per year, the WtE market is forecasted to increase by 28.6 billion USD between 2023 and 2028, with Europe contributing to 43% of that growth (Technavio, 2024). MSW is a resource that has high potential to be converted to energy and recovered into other valuable resources through WtE conversion and other valorization techniques (Nanda & Berruti, 2021). WtE are technologies that can convert waste into energy. Their benefits are twofold: they reduce waste generation and disposal, and they fulfill part of the growing energy demand worldwide.

In the thermochemical technique, three main technologies have been extensively studied: incineration, pyrolysis, and gasification. Thermal techniques are effective in reducing the volume of waste, and destroying hazardous substances (Sajid et al., 2022). Among thermal conversion technologies, incineration is the most widely adopted (Kumar & Samadder, 2022). In developing countries, this technology is regarded as the most dependable and cost-effective for mass burning of untreated MSW to generate electricity. In developed countries, some pre-treatment should normally occur to maximize the energy recovered. As per Chen & Christensen (2010), the removal of non-combustible fractions also improved the lower heating value (LHV) of the waste. The LHV of MSW should be higher than 4.96 MJ/kg for being incinerated without auxiliary fuel consumption. In the study by Kumar & Samadder, (2022), one of the scenarios involved the use of RDF as an input to the incinerator process. It was found that the use of RDF formed from the combustible components of MSW can be an effective fuel for the generation of electricity from the incinerator. As for the co-products of incineration, there are reports on utilization of incineration ash as asphalt concrete layer, foam/lightweight material, cementitious binder, and glass ceramic composite.

2.2.2. Municipal Solid Waste Management of organics

This section focuses on the MSWM techniques for organic waste materials. For the biological treatment, the biodegradable component of waste undergoes some sort of degradation under either aerobic or anaerobic conditions.

- **Anaerobic processes**

In anaerobic conversion, the most common technology is AD (Kumar & Samadder, 2022). The composition of the feed highly affects the efficiency of biological conversion. On one hand, processes such as enzymatic hydrolysis and fermentation are used to convert biomass to ethanol. These types of reactions can lead to higher bioethanol yields for the following feedstocks: agricultural residues, dedicated plants, and distillers' grains. On the other hand, stillage, sewage sludge, MSW, de-oiled seed cakes, and food wastes showed higher activities in AD and produced greater biogas yields (F. Cheng & Brewer, 2021).

- **Aerobic processes**

In aerobic processes, composting is a widely used activity that generates compost as a product. Composting necessitates a careful mix of carbon-rich components, often referred to as "browns," like dry leaves, alongside nitrogen-rich components, known as "greens," such as food waste. Within the compost pile, microbes aid in the transformation of carbohydrates from the carbon-rich materials into energy for the metabolic and respiratory processes. Additionally, proteins derived from nitrogen-rich materials are used

by microbes to support their growth and reproduction. The compost product is often used as a soil amendment (US EPA, 2015). When compared to AD that produces composting, AD offered higher loading rates with better pathogen destruction giving a higher yield. As per Malmir et al., (2020), AD was favorable over composting. Composting usually requires large areas, is affected by weather conditions, and leads to the spread of malodorous compounds.

2.2.3. Municipal Solid Waste Management of recyclables

The management of recyclables plays a critical role in sustainable waste management strategies. Due to the high LHV of the recyclables, incineration technology has potential to recover energy in the form of electricity and/or heat. However, incineration bypasses the opportunity to recover secondary products and recycle materials. Mechanical recycling is a well-established method that involves the collection, sorting, cleaning, and reprocessing of materials into new products without altering their chemical structure. Paper and cardboard have the highest material recycling rate of nearly 60 % among all recyclable category, but they can only be recycled nearly five times before their quality degrades (CEPI, 2023; Viau et al., 2020). Metals like aluminum and steel can be repeatedly melted and reformed without degradation in quality, making mechanical recycling highly efficient and cost-effective for these materials. Similarly, glass can be infinitely recycled without loss of purity or quality, provided it is properly sorted and uncontaminated (Viau et al., 2020). The majority of plastic waste ends up in landfills, gets incinerated, or leaks into the environment, with only 9% effectively recycled, as outlined in a recent OECD report (OECD, 2022). This can be attributed to the diversity and contamination of plastic materials, which makes sorting a critical and complex step, often requiring sophisticated technology to clean the waste stream and separate different types effectively. The presence of contaminants can lower the quality of recycled plastics, making them less desirable for manufacturers and reducing the economic viability of recycling efforts.

Chemical recycling involves breaking down materials into their basic chemical components, which can then be used to produce new materials. Due to its high hydrocarbon content, plastic waste is the most common feed to chemical recycling processes. It is particularly advantageous for plastics that are complex and contaminated, which are unsuitable for mechanical recycling. However, the limited commercial availability, high costs, and energy requirements associated with chemical recycling pose significant challenges, and the technologies are still in its developmental stages for many materials (Porshnov, 2022). By setting goals for recycled targets and investing in advanced recycling technologies, the competitiveness and profitability of the market for secondary products can be improved.

2.3. Municipal Solid Waste Management worldwide

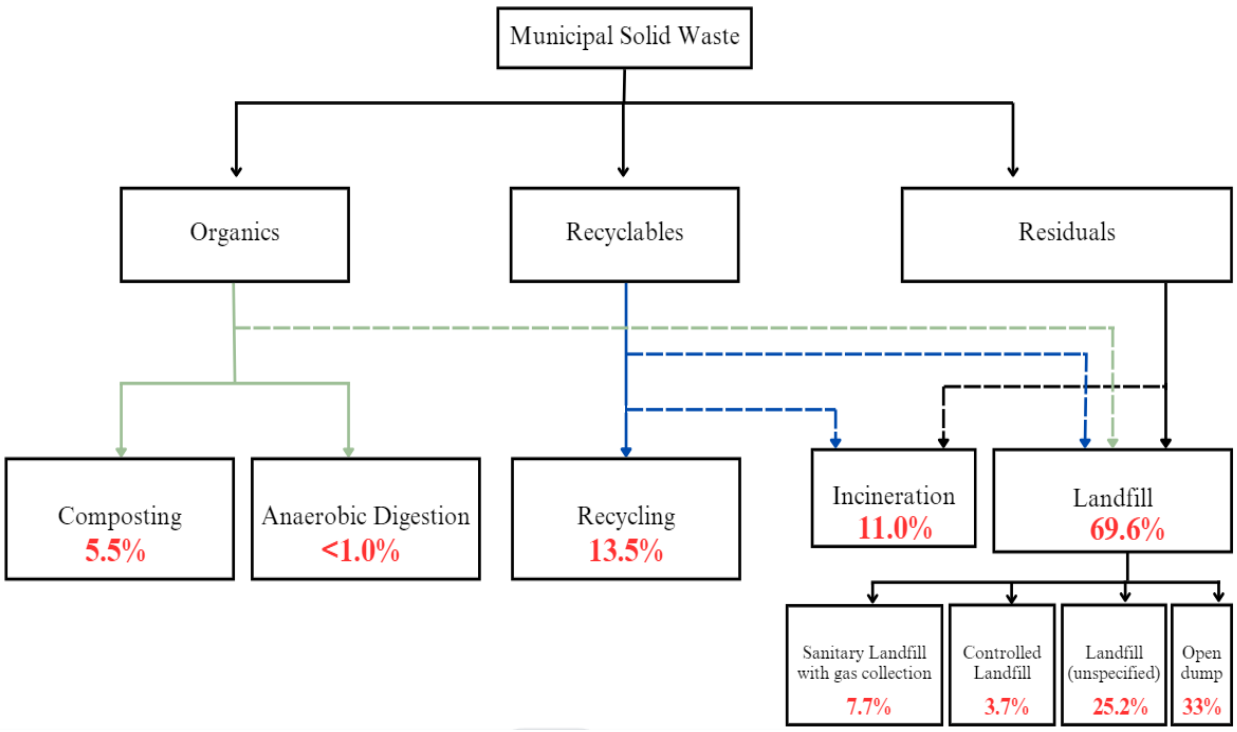

Figure 1: Distribution of treatment pathways of Global Municipal Solid Waste in 2018 (Kaza et al., 2018)

As far as MSW management is concerned, there are large differences in management practices worldwide. The distribution of different treatment pathways of MSW on a global scale is depicted in Figure 1. Even though all waste management hierarchies consider the landfilling of waste as their least preferred option, more than half of the MSW still ends up in landfills, with different landfilling disposal methods that are practiced across the world (Mensah et al., 2023). The majority of MSW (33%) is landfilled in open dumps, which is a common practice method in middle and lower-income countries. For instance, up to 90% and 45% of the MSW is dumped in Africa and Latin America, respectively (UNEP, 2024). Open dumps increase the contaminants' concentration in soil, runoff and groundwater contamination, and Global Warming Potential (GWP). The GHG emissions (per ton of MSW) of different landfilling operating conditions were compared and the following results were obtained: open dumps resulted in about 1,000 kg CO_2 eq, conventional landfilling resulted in 300 kg CO_2 eq, and landfills with energy recovery contributed to 16 kg CO_2 eq. Hence, open dumping resulted in a GWP at least 60 times higher than that of a landfill with energy recovery, with food waste accounting for nearly half of the emissions (Ferronato & Torretta, 2019). Some countries lack legislative guidelines to control the number of unsanitary landfills, while others, such as the USA, banned the open dumping of waste in the Resources Conservation and Recovery Act (FedCenter,

2017). In developed and some developing countries, regulations require landfills to monitor their GHG emissions and to install an engineered system that consists of a lined bottom, leachate collection, and groundwater monitoring system. For instance, in North America, some provinces of Canada and states in the USA set a landfill capacity threshold by which the installment of landfill gas recovery system becomes a requirement (ECCC, 2022).

Some countries are decreasing their reliance on landfills, and instead investing in other technologies that can treat and recover valuable by-products from MSW. For example, landfilling is almost non-existent in countries such as Belgium, the Netherlands, Denmark, Sweden, Germany, Austria and Finland. Instead, incineration plays an important role alongside recycling in these countries. A 2019 study showing the MSW per capita that is treated by incinerators in different regions of the world found that Denmark is the leading country with nearly 410 kg of MSW incinerated per capita in 2019. It is followed by Japan and other European countries, such as Germany, Denmark, Switzerland. This pattern can be attributed to the small territorial area of the respective countries, which leads to the exploration of alternative MSWM technologies due to a space constraint for landfilling the MSW (Dadario et al., 2023).

For the recyclables portion of the MSW, the focus is on an increased diversion rate worldwide. With only 9 % of the waste being recycled in 2019, new programs and regulations are helping improve recycling schemes and recycling efficiency (OECD, 2022). Global EPR regulations are currently on the rise, mandating producers to manage the collection and recycling of the waste instead of delegating this responsibility to governments. The EPR started with the Packaging and Packaging Waste Directive set in 1994 in the EU whereby the legislation governed packaging, end-of-life vehicles, batteries, and electronic equipment. The revised version of the Directive requires all members of the EU to establish EPR systems for packaging waste by 2024 (European Commission, 2024). Other major EPR regulations are coming into effect across the world, and most notable in the following regions/countries: EU, USA, Canada, South Africa, Singapore, India Chile, and Colombia (BanQu, 2023). Nevertheless, to increase the number of MSW that goes into recycling, which was only of 13.5 % in 2018 (Figure1), new diversion policies, technologies, collection schemes, and environmental awareness will need to be instilled in different regions worldwide. Especially, the chemical recycling market is forecasted to increase at a compound annual growth rate of 25.8% between 2024 to 2034, dominated by the pyrolysis technology that enables the handling of mixed waste streams and hard-to-recycle plastics (Future Market Insights, 2024).

As for the management of separately collected organic waste, composting is the most common technology used worldwide with 5.5% of the MSW getting composted, as seen in Figure 1. Conversely, less than 1% of the global MSW is anaerobically digested (Kaza et al., 2018). The low percentage of AD

implementation can be attributed to a lack of incentives and policies that support such technologies. Currently, Europe and the USA dominate biogas production, while Asia has the highest number of anaerobic digesters installed, mainly consisting of small-scale units. The biogas product from AD can be converted into biomethane by removing CO_2 from the gas. Various countries have set policy targets to increase the percentage of renewable energy used in the transportation sector (Vasco-Correa et al., 2018). The use of biogas and biomethane greatly varies around the globe, with Europe leading in biogas production, followed by China and the USA. The main reason for the leading status of Europe is due to the development of policies that promote renewable energies. Notably, the Renewable Energy Directive 2018/2001/EU, established in 2016, set ambitious targets for 2030: at least 14% of energy should be from renewable sources in the transport sector, with a sub-target of 3.5% stemming from advanced biofuels and biogas (Iglesias et al., 2021).

Even when landfilling is perceived as the least preferred option, it is most of the time unavoidable, and governments often face increasing demand for new landfill sites narrowing attention on the exploring MSWM options. For instance, in Canada, the transitioning to alternative waste management methods, especially in more remote regions, can be logistically challenging and costly. Landfills may be more politically acceptable in certain regions due to public perceptions and concerns.

2.4. Municipal Solid Waste Management in Canada

Canada was the second highest per capita generator of MSW globally in 2023 (Filipenco, 2023). In Canada's waste management hierarchy, energy recovery is preferred over landfilling. Any type of material that cannot be diverted for reuse and recycling purposes is either landfilled or processed in WtE technologies such as incinerators and AD.

Landfilling is still the major treatment pathway for MSW in Canada. The emissions from landfills accounted for 19% of the total methane emissions in Canada in 2021. To regulate methane emissions from landfills, the Strengthened Climate Plan proposed new federal regulations requires more landfills to install systems that capture and flare or utilize methane gas produced by decomposing organic waste. In accordance with the regulations under the Canadian GHG Offset Credit System, a federal protocol has been issued specifically for projects involving the recovery of landfill gas. Landfill owners and project developers who meet the eligibility criteria can potentially earn revenue from selling the offset credits. Environment and Climate Change Canada (ECCC) is also funding multiple programs to conduct projects that aim at reducing GHG emissions at landfills. The country has been taking measures to reduce landfilled waste and to increase diversion of waste. The Canada-wide Strategy on Zero Plastic Waste set a 30% waste reduction target by 2030 (Canada, 2023).

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As part of the province's shift towards a Zero Plastic Waste model, the first priority action disclosed in the plan consists of an EPR model, where companies bear the responsibility and associated costs of recycling their packaging, rather than residents. This transition is scheduled to be phased in over a two-year period from July 2023 to 2025. In Ontario, Canada's most populous province, current landfill space is declining, and new landfills have not been approved for over a decade (Mueller, 2013). Effective July 1, 2023, the implementation of Ontario Regulation 174/23 brought amendments to Ontario's Blue Box Regulation. This regulation mandates producers to annually report to the Resource Productivity & Recovery Authority (RPRA) the quantity of blue box material supplied in the preceding year. The reported supply quantity is utilized to determine the producer's "management requirement," specifying the amount of blue box material they are obligated to recover in the subsequent year. The recovery rate for each material is determined by dividing the total tons marketed of a specific material by the total tons generated of a specific material (Ontario, 2021a).The total tons generated is the weight of material supplied to the market in a given year, and the marketed tons represent the weight of material supplied to recovery facilities after sorting in a material recovery facility (MRF). The new recovery targets that are set by the province are shown in Table 3. There is a transition period between 2026 to 2029, and then new targets for 2030 onwards.

Table 3: Recovery Targets set by the province of Ontario (Ontario, 2021)

Material category	Recovery percentage 2026 - 2029	Recovery percentage 2030 onwards
Paper	80	85
Rigid Plastic	50	60
Flexible Plastic	25	40
Glass	75	85
Metal	67	75
Beverage Containers	75	80

2.5. Environmental impacts methods

2.5.1. Methodological tools to assess environmental impacts of Municipal Solid Waste Management

Modeling frameworks, such as LCA, are often used to compare waste management methods/technologies for a particular metric of interest (Anshassi et al., 2019, Dastjerdi et al., 2021). A pivotal focus within sustainability research lies in the assessment of the environmental impacts associated with products and services. The realm of tools available for quantifying such impacts is expansive, encompassing various methodologies. While they share common goals of evaluating environmental sustainability, each approach has distinct focuses and methodologies, as evidenced by the literature.

Among these, the Carbon Footprint Assessment stands out as a widely utilized tool with a specific focus on quantifying GHG linked to a product or activity. This method provides a simplified metric, commonly expressed in carbon dioxide equivalents (CO_2 eq), thereby facilitating effective communication and comparison. The significance of carbon footprint assessments in addressing climate change was underscored by Weidema et al., (2008). When it comes to assessing the environmental impacts of waste management projects using the Carbon Footprint tool, GHG can be quantified using the methane commitment (or theoretical yield gas) method or the waste-in-place method. In the first method, the forecast of any future methane emissions associated with the waste deposited in the inventory year is estimated based on assumptions for future landfill operation practices. In the second method, the methane released within the inventory year is quantified based on data from previously deposited waste. Despite the wide availability of tools to calculate GHG, criticism also arises due to its narrow focus on carbon, potentially overlooking other crucial environmental aspects.

Moving forward, Environmental Impact Assessment (EIA) emerged as a procedural tool designed to ensure that decision-making processes for activities with significant environmental influence consider relevant environmental aspects. Nevertheless, its limitation lies in its evaluation of individual projects, neglecting the broader context of existing and planned developments in a region. Typically, EIAs concentrate on the potential environmental effects of specific projects, such as industrial plants, with the system boundary focusing only on the production process It serves as an early-stage assessment aimed at informing decision-making and potentially shaping project design to reduce adverse environmental effects. The primary goal is to address and control these impacts to ensure compliance with environmental standards and regulations (Tukker, 2000).

Another methodological tool in environmental analysis is the Ecological Footprint, which quantifies the total surface area of terrestrial and aquatic ecosystems required to supply resources and absorb emissions (Biagetti et al., 2023).While this method primarily addresses resource consumption, it fails to reflect associated environmental pollution. Notably, the Ecological Footprint does not broadly capture the spectrum of environmental impacts, such as acidification, eutrophication, ecotoxicity, and human toxicity. These impacts imply processes that may irreversibly damage bio productive capacity, impacting ecosystem services, nutrient cycles, and biodiversity (Castellani & Sala, 2012). The method only allows for a direct comparison between natural capital demand and supply, establishing an ecological balance (Biagetti et al., 2023).

Highlighting the progress in environmental assessment methodologies, LCA has emerged as an optimal instrument for evaluating ecological burdens and human health impacts throughout the complete lifecycle of products, processes, and activities. Nevertheless, there is still a lack of comprehensive health

data of various pollutants, chemicals, and substances, especially for emerging compounds and long-term exposure effects (Haes et al., 2002). Biagetti et al. (2023) asserted its effectiveness in modeling the entire system from which products are derived or in which processes and activities operate. The European Commission has acknowledged LCA as the "best framework for assessing the potential environmental impacts of products" since 2003 (Biagetti et al., 2023).

2.5.2. Life Cycle Assessment

The utilization of LCA in this study is motivated by its capability to compare scenarios, quantify impacts, and normalize results for comparability, alongside its adherence to ISO standards (Dastjerdi et al., 2021; Klöpffer, 1997). LCA, as a comprehensive tool, conducts an in-depth analysis of the environmental impacts associated with a product, process, or activity throughout its entire value chain. Among the model-based tools, LCA facilitates the mapping and optimization of flows at each stage of a system's lifecycle (Howard-Grenville & Paquin, 2008). In 2006, the ISO 14040 and ISO 14044 standards were published, and another amended version of each standard was published in 2020. They provided a comprehensive framework for conducting LCA studies. These standards outlined the principles, requirements, and guidelines for conducting life cycle assessments. Following the ISO 14001 framework, LCA consists of four key steps: goal and scope definition, inventory analysis, impact assessment, and interpretation (Klöpffer, 1997).

In the goal and scope definition phase, the study's LCA's objective and the system's scope are clearly defined. This section outlines technical, geographic, and temporal boundaries of the system. The functional unit, which quantifies a product, system, or service, forms the basis for calculating impact categories (Arzoumanidis et al., 2020). The researcher also addresses rules and assumptions, such as the allocation method for co-products and chosen cut-off criteria (Klöpffer, 1997). Moreover, considerations for the intended audience are crucial, as LCA may serve various purposes, including decision making in product and process development, purchasing, information structuring, eco-labeling, environmental product declarations, and regulatory decisions (Tukker, 2000). Moving to the life cycle inventory analysis (LCI), each step of the life cycle is examined to account for inputs and outputs. This involves defining emissions and resource consumption associated with energy, transportation, and auxiliary products used as inputs. Outputs encompass co-products, emissions to air, water, and soil, waste-heat, and solid wastes. The subsequent step, life cycle impact assessment (LCIA), facilitates a comparative assessment of product or service systems. This involves selecting impact categories and the appropriate impact assessment method based on the study's context. Finally, in the interpretation step, the results of the inventory and assessment are discussed, and conclusions and recommendations are given in the context of the case study (Klöpffer, 1997). This step adds depth to the LCA process, offering insights into the implications of varying parameters and enhancing the robustness of the assessment.

The assumptions used within the methodology could differ based on the product or service that is being examined. For instance, when a product is examined, the boundary could extend to the disposal of the product. Thus, there is an opportunity to apply LCA to MSWM whereby the approach undertaken by the author would differ from a basic generic LCA.

2.6. Life Cycle Assessment of Municipal Solid Waste Management

In the last few years, there has been a growing interest in performing the LCA of MSWM across the world. The disparity among studies is notable on a geographical scale. A literature review performed in 2019 by Khandelwal et al., (2019) presents the number of LCA studies found on MSWM between 2013 and 2017 across different locations in the world, but it only focused on the results of the literature search of "LCA of MSW". Asia and Europe are leaders in that field, with 72 and 53 studies performed, respectively. As per the study of Khandelwal et al., (2019), only 10 studies were performed in North America. More specifically, North American studies are largely centered in the USA with very few studies found in Canada.

A literature review of the MSWM LCA studies focusing on the USA and Canada is performed. The literature search focused on studies between 2015 and 2023 and excluded any study on the management of construction and demolition waste, hazardous and e-waste, and sewage sludge. The results are summarized in Table 4. Among the 15 studies selected, 12 of them are from the US and only 3 are performed in Canada. Moreover, most of the studies focus on the environmental impacts of the residual portion of MSW or organic waste. However, only the study by Malmir et al., (2020) takes into account an integrated MSWM approach where each of the MSW undergoes separate treatment. Similarly, the work focusing solely on recyclables has been scarce but is gaining more attention recently due to the number of policies that are being implemented to increase diversion in North America. As for the technologies considered in the studies, incineration appears to be included in almost all the LCAs, where it is compared to the landfilling alternative. Fewer studies include other thermal technologies, such as gasification and pyrolysis. The LCA software employed differs among the studies. Six of the studies use SimaPro tool. The remaining studies use a variety of tools such as EASETECH, Swolf, GaBi, LandGEM, GREET, and IWM-2.

Table 4: Summary of LCA studies on MSWM in Canada and the US from 2015-2023

Study reference	Location	Software tool	Objectives	Technology
(Berge et al., 2015)	USA	EASETECH	1) To evaluate the environmental impacts associated with the Hydrothermal Carbonization of food wastes and the combustion of the generated hydrochar for energy production.	Hydrothermal carbonization.

(H. Wang et al., 2015)	USA	GaBi	1) To investigate whether a pyrolysis plant using MSW in North Carolina would be environmentally friendly.	Pyrolysis Anaerobic digestion Incineration Landfill
(Coventry et al., 2016)	USA	LandGEM and models by authors	1) To compare environmental impacts of four different MSW treatment options.	Landfill Gasification Advanced thermal recycling (grate furnace)
(Soltani et al., 2016)	Canada	SimaPro	1)To develop a framework that addresses the challenges of choosing a mutually sustainable waste treatment strategy in Metro Vancouver when the stakeholders have conflicting preferences.	Landfill Incineration Co-combustion of RDF in cement kilns.
(Thyberg & Tonjes, 2017)	USA	EASETECH	1) To determine if separate food waste recovery and management is environmentally sounder than waste-to-energy incineration.	Incineration Composting Anaerobic digestion
(Isola et al., 2018)	USA	SimaPro	1) To understand the sensitivity of the portable AD to feedstock and organic loading rate changes, effect of scale, and heat source as well as identifying operating conditions which provided the best biogas yield and lowest impact.	Anaerobic Digestion
(Hou et al., 2018)	USA	SimaPro	1)To assess the environmental impacts of various plastic film waste treatment systems.	Landfill MRF Incineration
(Winslow et al., 2019)	USA	GHG, Regulated Emissions, and Energy Use in Transportation (GREET)	1) To evaluate the environmental and financial impacts of four potential LFG management and waste hauling operation scenarios through the use of LCA techniques and an economic analysis.	Landfill to electricity Landfill to fuel
(E. Lee et al., 2020)	USA	SimaPro	1) To conduct a comparative LCA and LCC to determine the environmental and economic impacts and benefits of high solids anaerobic co-digestion of biosolids, FW, and YW with different waste compositions.	Anaerobic digestion, Incineration Composting Landfilling
(Malmir et al., 2020)	Canada	IWM-2	1)To compare different scenario of MSWM in Montreal, considering WtE technologies. 2) Use the LCA results in a three objective optimization algorithm to minimize total energy consumption and CO_2 emissions.	Landfill Combustion Anaerobic digestion Composting Recycling
(Y. Wang et al., 2021)	USA	LCA model by authors	(1) Develop an LCA model for a representative U.S. MSW landfill based on state-of-the-practice landfill design and regulatory-compliant LFG management. (2) Investigate the effects of gas collection and control regulations, landfill size and design, and waste composition on LFG emissions and overall landfill environmental performance.	Pyrolysis Anaerobic digestion Incineration Landfill
(Alamu et al., 2021)	USA	SimaPro	1)To assess the waste-to-energy process in the United States using a case study of the incineration plant in Baltimore, Maryland.	Incineration
(Ouedraogo et al., 2021)	USA	LandGEM, HELP, GREET	1)To investigate and compare the environmental and human health impacts of two MSW disposal methods: gasification and landfilling without energy or LFG recovery, using an open access and freely available US-based database.	Landfilling Gasification
(Anshassi et al., 2022)	USA	Swolf	1) To compute the landfill gas collection efficiency required for a typical US landfill to result in a smaller GHG emissions footprint than MSWI treatment.	Incineration Landfilling
(Zhang et al., 2023)	Canada	SimaPro	1)To analyze the environmental impacts of three scenarios for managing plastic waste in the province of British Columbia in Canada by using the LCA technique.	Incineration Landfilling Mechanical recycling Chemical recycling

2.7. LCA Tools used in Municipal Solid Waste Management

2.7.1. Generic Tools

In comparison to a product-based LCA that studies the impacts of a product from cradle-to-grave, a waste-LCA assesses the impacts of the management of a material containing multiple waste fractions from end-of-life to grave or remanufacturing. Software tools available to perform an LCAs on waste are divided into generic and waste-specific types.

In generic LCA software, such as SimaPro, the estimation of electricity generated from WtE systems such as incineration is computed based on the LHV of the waste input, and then manually inserted as one of the parameters of the study. The tool is most of the time supported by another more technical-oriented tool that helps in the generation of technical data needed for the LCA. For instance, Aspen Hysys, a chemical-engineering process modeling tool, could be used to model the incinerator, pyrolysis, or gasification process, and the necessary mass and energy balances computed will enable the researcher to use the process-specific emissions generated by the system and use them in the LCA tool. Some other models focused on landfill gas emissions can be also used to complement the generic LCA tools. For instance, LandGEM is an Excel-based landfill gas emission model developed by US EPA, that estimates emission rates for MSW landfills. The model uses decay rates as well as gas emission factors developed using empirical data from US landfills. The waste composition used in the model is representative of aggregate data on US MSW composition, and thus cannot be modified by the user (Kumar & Samadder, 2022; US EPA, 2023).

Generic LCA tools, such as SimaPro, GaBi, and Open LCA, are designed with a product focus and do not track the physical and chemical properties of material flows. Instead, they only focus on the total quantities of materials used (Clavreul et al., 2014). As a result, most of the studies consider multiple cut-off assumptions which leads to the underestimation of emissions. As an example, in a study by Soltani et al., (2016) a scenario of RDF co-combustion of Vancouver's waste is modeled using SimaPro software, but indoor air emissions of the plant as well as technical considerations of the production line are not accounted for by the model.

2.7.2. Waste specific LCA tools

The use of process simulation tools such as Aspen in addition to LCA tools can be observed in literature. Using process simulation tools can enhance the robustness of models in LCA software. However, this approach necessitates proficiency in additional software and forfeits the benefits of tracking, controlling, and calculating physical flows directly within the LCA modeling platform (Lodato et al., 2021). Additionally, separating waste into various streams through source separation and monitoring the masses

and substances in subsequent treatment processes are crucial aspects of contemporary waste management (Clavreul et al., 2014). As a result, multiple waste management specialized tools are being developed around the world in order to conduct a thorough detailed LCA of waste management. The developed software applications are capable of better understanding and analyzing the impact of various parameters (i.e. composition of reference flow and changes in technologies) of the waste management model on different environmental impacts.

Compared to a generic LCA, a waste specific LCA model can include the following aspects into its modelling (Gentil et al., 2010):

1. First, it can calculate the environmental performance for managing waste with varying fractional compositions. The models should adapt to changes in the composition of waste fractions, such as fluctuations in the amounts of paper and plastic. In specific, with regards to the composition of the waste input, the researcher is now able to track the impact based on the physical and chemical properties of each of the materials present in the flow (Clavreul et al., 2014).
2. Secondly, the models should account for specific emissions associated with elemental components of waste, such as mercury content in newspaper.
3. Third, waste-specific models can compute the waste management processes' operating specific emissions (i.e. dioxin emission) which eliminates the need of finding operational emissions data from literature and inputting it into the software.

There are multiple solid waste management LCA tools that are developed and in use by practitioners. Research has been done to shortlist the tools that meet the following criteria:

- The model should have at least one impact assessment indicator.
- The model can model reference flows with different waste compositions.
- Models should have available documentation that was updated after 2020.
- The model has general life cycle modelling characteristics (i.e., substitution using system expansion).
- The tool can model material-specific properties (i.e. chemical properties and elemental composition) of waste.

The following tools meet the five criteria mentioned: WARM (2023), MSW-DST (2021), SwolfPy (2022), and EASETECH (2024). While the first three LCA models are designed in the USA, the latter originates from Denmark. Although there are over 30 European waste LCA models available, EASETECH was selected due to its accessibility, frequent updates, inclusion of more than 10 waste fractions, and transparent documentation outlining their functionalities. A brief comparison of some of the key parameters

of each of the 4 MSWM LCA tools under study is presented in Table 5. The parameters that are compared are the following: the tool's main objective, the modelling of the functional unit , the level of detail available in the LCI, the LCIA indicators and methods that are available, the number of waste fractions that can be selected as an input, and the feasibility to import processes from other databases in order to better answer the goal and scope of the LCA study.

The USA tool WARM is only focused on estimating the GHG emissions of a particular MSWM pathway. As for the functional unit, all the models except EASETECH, offer a generation-based functional unit, which means that the functional unit is defined as the amount of waste generated in a specific study area for a specific timeframe, accounting for the local characteristics of the generated waste. EASETECH offers greater flexibility in the functional unit modelling; it could be input, or output based (i.e. 1 m^3 of biogas generated from a MSWM technology). The LCI is the most extensive in EASETECH and SwolfPy, where around 1,000 to 1,500 substances are included in the inventory, and they are divided into sub-compartments to further specify the source of the exchange (i.e. urban, close to ground). In addition to that, the elemental waste composition varies among the different models. For the LCIA method step, EASETECH offers the greatest number of LCIA methods among the models; it has more than 10 methods including TRACI, IPCC, Recipe, and CML. Moreover, EASETECH has the highest amount of waste fractions (80) available in the waste composition tab. For this research, the ability to import processes from external databases is extremely important for the goal and scope of the LCA. Since the study is happening in Canada, it is important to find data that is the most representative of the geography, the technology, and the temporal boundary selected. As per the information available in Table 5, only EASETECH offers the user the flexibility of importing databases from Ecoinvent and ELCD (Blikra Vea et al., 2018) .

Table 5: Comparison of different MSWM LCA tools

	Main objective	**Functional unit**	**LCI**	**LCIA**	**Number of waste fractions**	**Feasibility to import processes**
WARM, USA, 2020	Developed by the US EPA, this tool assists solid waste planners and organizations in estimating GHG emissions resulting from various waste management approaches.	Generation-based	The most limited LCI (only GHG emissions and energy use results).	GHG emissions and energy reduction	54	No
EASETECH, Denmark, 2024	Comprehensive waste LCA and LCC tool developed at the Technical University of Denmark	One of the following: unitary, generation, or input and output-based.	More than 1,500 substances/exchanges (air, water, soil) and detail the substances/exchange in relation to sub-compartments (i.e. urban air close to ground, surface water).	Amont the following methods: ILCD., TRACI, IPCC.	80	Ecoinvent and ELCD
SwolfPy, USA, 2024	A dynamic life-cycle assessment framework designed for optimization, taking into account potential	Generation-based	More than 1,500 substances/exchanges (air, water, soil)	Landfill GHG emissions and diversion rate	41	No

	future changes in policy requirements, waste composition, and the energy system.		and detail the substances/exchange in relation to sub-compartments (i.e. urban air close to ground, surface water).	based on policies.		
MSW-DST, USA, 2021	Assessing the environmental trade-offs and costs across the life cycle of various waste management or materials recovery programs.	Generation-based	Second most limited LCI (only 29 substances/exchanges and two compartments).	Energy consumption, and emissions for 32 pollutants.	26	No

EASETECH is selected as the modelling tool in this study. The model assumes the following parameters for landfilling (Olesen & Damgaard, 2014):

- Accounts for ancillary materials for construction and operation of landfill, without accounting for the production of ancillary materials.
- Materials containing biogenic carbon (i.e., newspaper, cardboard, office paper, yard trash, food waste) do not degrade but instead permanently store, or sequester, that carbon. As a result, these materials are credited with a carbon offset.
- Time horizon of 100 years for LCI of landfill.
- Combined Heat & Power (CHP) system can be modelled as part of the landfill energy recovery.
- The landfill gas-to-energy is assumed to be happening from year 1 to year 55, and then venting is considered for the next years.

The following list includes the key parameters used in the modelling of incinerators on EASETECH (Anshassi & Townsend, 2021):

- The construction and decommission are not included.
- The option of modelling a CHP is included.
- The raw materials (i.e. lime, ammonia, activated carbon) used for the air pollution control (APC) system are considered.
- Specific transfer coefficients are used for each substance in the input waste stream (such as water, volatile solids, and energy) to determine their presence in the flue gas, bottom ash, fly ash, wastewater, and scrap metals.

- Co-products generated include non-ferrous and ferrous metals. The model includes processes for ferrous metals recovery (i.e. iron, steel) as well as non-ferrous metals recovery (i.e. aluminum, copper) from bottom ash residues.

As for the modeling of recycling activities, the following parameters are used on EASETECH (Anshassi & Townsend, 2021):

- The model does not consider the emissions associated with the construction of the MRF and no information is provided around the MRF lifetime.
- The boundaries can be extended to the transport and reprocessing stage of the materials separated by the waste management system, and can include avoided impacts from virgin production, which is considered a substitution process in which a material is substituted by a marketable one.
- The model allows the user to select a substitution ratio for the different materials undergoing recovery.
- It does not consider a forest carbon offset from paper recycling. WARM is the only tool that includes this offset, where the recycling of paper eliminates the necessity to harvest trees and consequently leads to greater soil carbon storage. Models that do not account for this offset assume that the biological system of carbon stocks of forests is in equilibrium.

For organic waste management, EASETECH has models for both AD and composting. It also offers the most material-extensive properties among all the tools, as it includes 12 elements only characterized for biomass as well as 53 material-specific properties for each waste fraction. Lastly, the calculation of biogas and of bioproducts (i.e. digestate and compost) are waste-specific (Lodato et al., 2021).

One major limitation to the waste management LCA software is that most of them do not include thermal treatment options other than incineration in their processes. The main reason for this is the widespread use of incineration as the main thermal technology to treat solid waste and the data limitation of the other options. Currently, there are only a limited number of pyrolysis plants worldwide that handle MSW often alongside biomass or industrial waste. LCA studies on MSW pyrolysis have employed diverse system boundaries, scales, technological assumptions, and modeling approaches, making it difficult to provide definitive comparisons or conclusions about technological efficacy (T. F. Astrup et al., 2015; Dong et al., 2018; Zaman, 2013). All in all, the modeling tool that could be selected by the researcher could impact the results obtained due to multiple determining factors such as the inclusion of key substances/exchanges.

2.8. The need for this study

2.8.1. Gaps in LCA of Municipal Solid Waste Management in Canada

MSWM LCA studies are scarce in Canada. A total of nine studies were found in literature, and they are summarized in Table 6. In a study by Mohareb et al. (2008), Integrated Waste Management Model (IWM) was used to compare different waste management scenarios in Ottawa in 2003. However, one of the gaps was that the fossil fuel emissions that were displaced by the generation of power associated with some of the waste handling methods, such as incineration, landfill gas capture for energy and AD, were not incorporated into the figures of the GHG emissions, but only in the net energy consumption indicator figures. This is also the case in another study by Malmir et al., (2020) in which the impact assessment step only included energy consumption and GHG emissions, without considering other impact categories. In this study, the IWM-2 model did not consider offsetting the combustion of fossil fuels rather than biogas and, consequently, emission saving.

Only two studies were performed in Ontario. In the study by Assamoi & Lawryshyn, (2012), the waste compositions were based on a detailed waste audit done for Vancouver but the study was conducted in Toronto, and the model was created without any LCA tool but instead the author developed their own spreadsheet. In the second study, scenarios involving organic waste management in an AD facility were considered. The location in Ontario was not specified, and the LCI was gathered from different plants in the province (Ncube et al., 2021). The study only focuses on AD without comparing it to alternative treatment options (i.e. composting) that are currently adopted in the province.

Two studies performed in Vancouver investigated a scenario whereby RDF is used as a fuel in the cement industry (Reza et al., 2013; Soltani et al., 2016). Both studies solely focused on the residuals of the MSW, without considering the other waste categories of MSW. In the study by Soltani et al., (2016), the LCA was followed by a life cycle cost analysis and a game theory approach. The results were based on sustainability indices for each of the LCC and LCA results to select the best scenario for the city.

Two of the studies addressed diversion initiatives but none of them tackled the EPR targets. In the study by Zhang et al., (2023) on plastic recycling, the avoided burdens from the substitution of virgin material were not included in the result. Also, in a study performed in Toronto, there were different scenarios considering waste prevention activities such as plastic bag reuse, online newspaper reading, and bottle refilling programs (Cleary, 2014). Nevertheless, they only targeted waste prevention at a household level and not recent EPR diversion initiatives focusing on the increase in sorting efficiencies and decrease in materials generated from suppliers to the marketplace.

The variability in waste composition and MSWM practices across different provinces in Canada reinforces the need to perform LCA studies specific to each case. For example, AD treatment technology was proven to have the lowest efficiency to treat food waste in Montreal city. This outcome was explained by the relatively low food waste quantity in the city, which does not seem high enough for the maximum simultaneous reduction of energy consumption and CO_2 production by the technology (Malmir et al., 2020). In the study in metro Vancouver by Soltani et al., (2016), the LCA coupled with game theory led to the selection of mass-burn WTE as the most sustainable options for Metro Vancouver. However, multiple assumptions selected in this study resulted in this outcome. Therefore, it is important to carefully consider different alternatives and perform an LCA using data as accurate and reliable as possible.

Table 6:Comparison of different parameters studied in MSWM LCA publications performed in Canada between 2008-2023

Study Reference	Tool	Functional unit	Temporal boundary	Scope	Geographical boundary	LCIA method
Mohareb et al., (2008)	IWM	NA	2003	From collection of waste to material recovery.	Ottawa	NA
Assamoi & Lawryshyn, (2012)	NA	Tonnes of MSW from the City of Toronto between 2011 and 2040	2011 to 2040	Residual waste after material separation at the material recovery facility until energy recovery for landfill/incineration .	Toronto	IPCC (2006)
(Reza et al., 2013)	Gabi	The productio n and utilization of one ton of RDF	2015	From collection of waste from transit stations and continues to mechanical treatment in the RDF facility.	Vancouver	NA
(Lai et al., 2014)	WAR M	Total amount of waste generated over this 17-year period (20 14-2031) in the Region of Waterloo	2014-2031	Not specified	Waterloo	NA
(Cleary, 2014)	SimaP ro 7.3.3	Tons managed per year	2008	From waste collection to treatment and disposal. The boundary includes the impacts associated with the recycling of waste as well as the electricity displaced due to landfill gas generation.	Toronto	Recipe
Soltani et al., (2016)	Sima Pro 2.0	1 kg MSW	2013	Cradle to gate: Disposal of waste at treatment plants or landfill to mechanical treatment, incineration, and recovery of materials.	Vancouver	Recipe for mid-point impact
Malmir et al., (2020)	IWM 2	Total waste generated in MTL in 2017	2017	Point at which a material is discarded into the waste stream to the point at which it was either	Montreal	NA

				converted into a useful material or, it was finally disposed.		
(Ncube et al., 2021)	Simapro 9.11	MWh (electricity) production.	2021	From arrival or organic waste at the AD facility to the production of biogas and its conversion into electricity and heat (AD-CHP).	Ontario, facility not specified	Traci
Zhang et al., (2023)	Open LCA	Management of plastic waste by 2030	2019 to 2030	End-of-life treatment technology only.	Vancouver	CML-IA Baseline method

2.8.2. Knowledge Contributions of this Study

One intriguing aspect of LCA studies in urban MSWM is the variability in results across different research efforts. These variations can be attributed to several factors, including geographical location, waste composition, data sources, and system boundaries. This variability underscores the importance of conducting localized LCAs tailored to the region's specific waste management context. The results will differ because the waste composition differs among different cities due to differences in consumption behaviors, waste collection and transportation programs, infrastructure availability, and funding.

To the best of the author's knowledge, this study presents the second LCA conducted on MSWM for the different MSW categories (residuals, recyclables, and organics) in Ontario, with the only one other study being performed in Toronto. Among other LCA studies carried out in Canada focusing on MSWM using waste-specific LCA tools, this research stands out as the most comprehensive to date. Previous studies utilizing waste-specific tools, such as IWM, have not accounted for the fossil fuel emissions offset by the generation of power through certain waste handling methods, such as AD (Malmir et al., 2020). Furthermore, this study is distinguished by its integrated approach to MSWM, encompassing concurrent scenarios for three waste categories: organics (composting and AD), residuals (landfilling and incineration), and recyclables (EPR strategies). The findings from this study are expected to inform stakeholders involved in diversion initiatives and those exploring landfill alternatives within the Region of Waterloo, providing critical insights into the environmental implications of various waste management options.

Chapter 3: Case study: Region of Waterloo

3.1. Description of study area

The Region of Waterloo, a region with a size of 1,300 km^2 and a population exceeding 630,000 as of 2022, stands as one of Ontario's most rapidly expanding regions. The region's main characteristics include its interconnected communities, its robust transit systems, and its proximity to the Grand River watershed. It is situated within Ontario's greenbelt; the world's largest, protecting farmland, forests, wetlands, rivers, and lakes in southwestern Ontario. The Region of Waterloo is considered a mid-sized community, offering the conveniences of a major urban hub while preserving the character of smaller rural communities. Its principal urban centers include Waterloo, Kitchener, and Cambridge, and the townships include the towns of North Dumfries, Wellesley, Wilmot, and Woolwich (Region of Waterloo, 2021b).

The Region of Waterloo consists of seven cities and townships. Waterloo, Kitchener, and Cambridge are the three main cities. North Dumfries, Wellesley, Wilmot, and Woolwich are the townships of the Region and are classified either as medium urban or as rural towns. To be able to simplify the assumptions, a table computing the density and percentage of population residing in each town is presented in Table 7. As per the table, North Dumfries, Wellesley, Wilmot, and Woolwich only represent 13% of the total population of the Region. Similarly, the density of population in Cambridge, Kitchener, and Waterloo are at least 15 times larger than the other towns' densities. Therefore, the MSW composition of urban regional cities are assumed to be representative of the Region of Waterloo. Moreover, audits performed by the RPRA confirm that the Region of Waterloo is classified as urban regional (RPRA, 2021).

Table 7: The spatial distribution of the Region of Waterloo by population in 2021 (Statistics Canada, 2022)

City/town	Type	Area (km^2)	Pop (2021)	Density (ppl/km^2)	Percentage of total population (2021)
Cambridge	Urban regional	113	138,479	1,225	24%
Waterloo	Urban regional	64	121,436	1,897	21%
Kitchener	Urban regional	137	256,885	1,878	44%
North Dumfries	Rural	187	10,619	57	2%
Wellesley	Rural	278	11,318	41	2%
Wilmot	Rural	264	21,429	81	4%
Woolwich	Rural	326	26,999	83	5%
Total		1,369	587,165	429	100%

- **<u>MSWM in the Region of Waterloo</u>**

Currently, the Region of Waterloo's responsibility is to manage the collection of garbage, bulky items and appliances, yard waste, kitchen waste, and seasonal holiday waste (such as Christmas trees and lights)

collection. Additionally, it oversees the management of the Cambridge compost site for yard waste, and the Region of Waterloo's landfill. They also conduct regular monitoring of five closed landfills, all while maintaining their commitment to safeguarding the air, soil, and water quality at all the sites through rigorous environmental controls.

The following Table 8 shows the composition of the MSW categories of the Region of Waterloo, and the different definitions used by the Region to refer to the different categories.

Table 8: MSW categories terms used by the Region of Waterloo

MSW waste type	**MSW categories as per the Region of Waterloo**	**Composition of MSW categories in the Region of Waterloo**
Recyclables	Blue box	• Glass • Metal • Paper • Plastic
Organic waste	Green bin	Kitchen waste
Yard waste	Yard waste	Yard waste
Garbage	Garbage	Residuals of MSW

As of March 2024, the collection of Blue Box materials is managed by Circular Materials. The responsibility has now shifted to PROs for blue box material sorting, processing, and recycling of material, as well as resident education and promotion.

The Region has a residential curbside collection service that consists of weekly collections of blue box recycling waste and green bin food waste, and a biweekly collection to the garbage bags known as "black bins", bulky items, and yard waste.

Food waste represents a valuable resource that can be repurposed to create a beneficial product known as compost. The green bin material that is collected curbside is taken to the Waterloo transfer station and temporarily stored in bunkers. Then, it is gathered and transported to the City of Guelph's Organic Waste Processing facility. The shredded material is transferred to a series of tunnels whereby oxygen is pumped through the floor, which aids in aerobic decomposition. The facility's temperature is maintained above 55 °C to ensure optimal conditions for decomposition and accelerate the composting process. After 14 days, the material is transferred to another set of tunnels where airflow, moisture content, and temperature are controlled, and the material remains there for an additional seven days. Contaminants are then removed and are matured in a maturation hall for a minimum of 21 days, whereby compost is turned at various stages. Finally, the material goes through a final screen and the compost is tested to ensure it is of high quality to be used for agricultural activities.

The bagged leaves, garden clippings, and Christmas trees gathered from curbside pickups and from transfer stations are transported to a composting area located at the waste management site in Cambridge where the material is processed and formed into windrows, then degraded to ultimately transform into compost (Region of Waterloo, 2021).

In the MRF, the recyclables coming from the blue box go through the following steps: pre-sorting, magnetic belts, glass breaker, plastic perforator, shaker table, optical reader, final sorting, and compression into bales. The different materials are then sent to multiple destinations for recycling and recovery.

The landfill is home to the remainder of the waste, where the landfill gas collection system installed in 1993 enabled 37 million kWh of electricity to be generated from the site in 2021, a capacity able to power between 4,000 to 6,000 houses in the Region of Waterloo. As a by-product, leachate is also produced on-site. To limit the leachate contamination in the groundwater, expansion cells have been constructed since 1994 with a fully clay-lined design as well as a bottom leachate collection system that meets modern design standards. The leachate is then sent to a waste water treatment plant in the region (Region of Waterloo, 2024). In 1993, a strategy was put in place in the Region of Waterloo to gather landfill gas from both the existing sections and newly developed zones of the landfill. The primary objectives of this gas collection system are to reduce emissions into the atmosphere, prevent subsurface gas migration, and mitigate off-site odors. This gas is captured via a network of pipes linking vertical gas extraction wells and horizontal collection trenches (Region of Waterloo, 2024a). As per the Waste Management Team in the Region of Waterloo, an average collection efficiency of 80% is used for reporting purposes in 2024.

The landfill is classified as an engineered landfill due to its gas collection system, its leachate system, and the cover system put in place to control emissions from degradation. Daily measures are taken to cover waste at the Waterloo landfill. This is done to prevent waste propagation, to prevent pests from invading the garbage, and to mitigate unpleasant odors. The landfill employs a variety of methods for daily cover, among which is the installation of a 15 cm layer of thick soil. Additionally, after a certain volume or depth has been deposited, intermediate covers consisting of approximately 30 centimeters of soil are applied. These serve as a temporary cap until waste deposition resumes in those sections. Upon reaching maximum capacity, each landfill cell is sealed with one meter of compacted clay before being topped with a layer of topsoil and seeded with grass to restore the area (Region of Waterloo, 2024a). Since 1995, the Region has collaborated with Toromont Energy to utilize landfill gas for electricity generation. The Region is responsible for managing the gas collection system and supplying the landfill gas to Toromont Energy. Meanwhile, Toromont owns and runs an electrical generating station, selling the electricity and emission credits to Ontario Power Generation.

- **Waste generation numbers in the Region of Waterloo**

In 2021, the MSW generation in the Region of Waterloo was 153,400 metric tons. The breakdown of the waste categories is shown in Table 9.

Table 9: MSW breakdown in 2021 in the Region of Waterloo, by author

Waste breakdown from residential collection in 2021	Amount (Metric Tons) *(Region of Waterloo, 2021a)*	Percentage
Blue box	36,816	24%
Green bin	27,612	18%
Yard waste	21,476	14%
Garbage	67,496	44%
Residential waste	153,400	100%

Almost 44 % of residential waste is landfilled, and the residential diversion rate reached 56 % in 2021. This diversion rate is one of the highest on Ontario, and it surpasses the Ontario wide diversion rate of 49% in 2021 (RPRA, 2024a). Among the key focuses of the strategic plan of the Region is the preparation for a smooth transition to the EPR provincial regulatory framework to enhance diversion and recycling in Ontario.

The waste flow of the Region of Waterloo in 2021 is depicted in Figure 2. The weights of materials doing to different waste categories are extracted from Table 13, which stems from annual reports published by the Region of Waterloo. The information around the different materials available in the blue box, and their respective percentages, is sourced from audits performed the Continuous Improvement Fund (CIF) on urban regional cities of Ontario in 2021. Hence, some uncertainty might be associated with the values. Similarly, the recycling efficiencies at the MRF are computed based on a mass balance of the materials coming in and leaving the facility. The values of materials coming in are assumed to be similar to those of the composition of the blue box materials by the CIF. However, this might not hold true due to losses that occur during collection and transportation. The values of materials leaving the facilities are sourced from the MRF's 2021 database. A detailed explanation of the numbers obtained is included in the LCI section of Chapter 4.

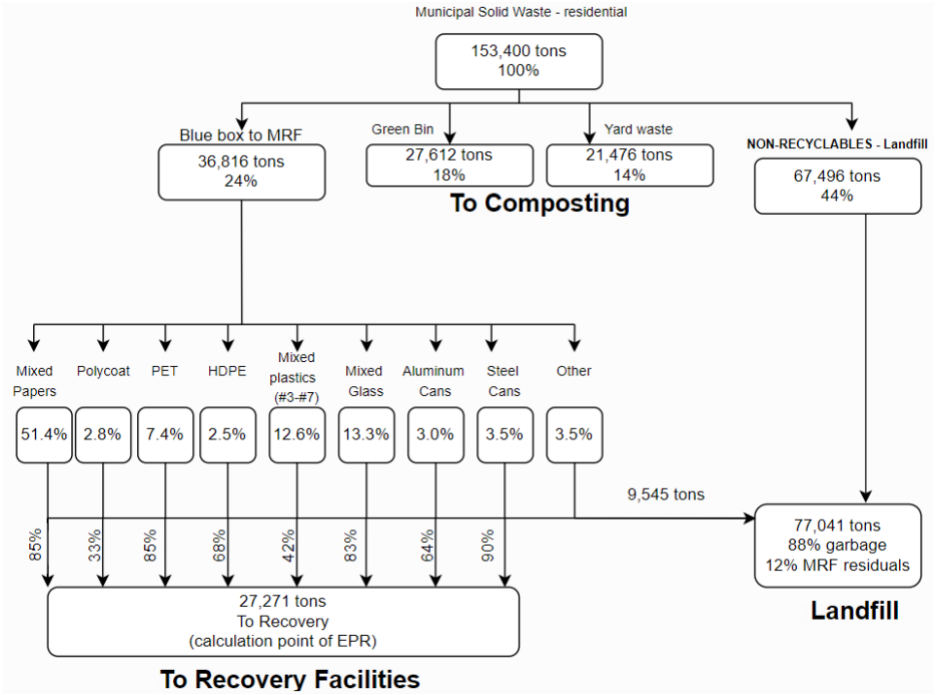

Figure 2:Waste flow of Region of Waterloo in 2021

3.2. Scenarios modelled in this study

The following three scenarios are included in this study:

1) The baseline system is a business-as-usual MSWM system in the Region of Waterloo in 2021 where: organic waste undergoes composting, recyclables are sorted then undergo processing to produce secondary materials, and residuals are disposed in a landfill with energy recovery. The waste flow corresponds to that of Figure 2.
2) This scenario considers an incinerator for residual waste treatment, and an anaerobic digester for organic waste, with all other processes kept similar as Scenario 1. Scenario 2 has a similar waste flow as Scenario 1 (Figure 3). However, the pathways of garbage waste and organic waste are different.

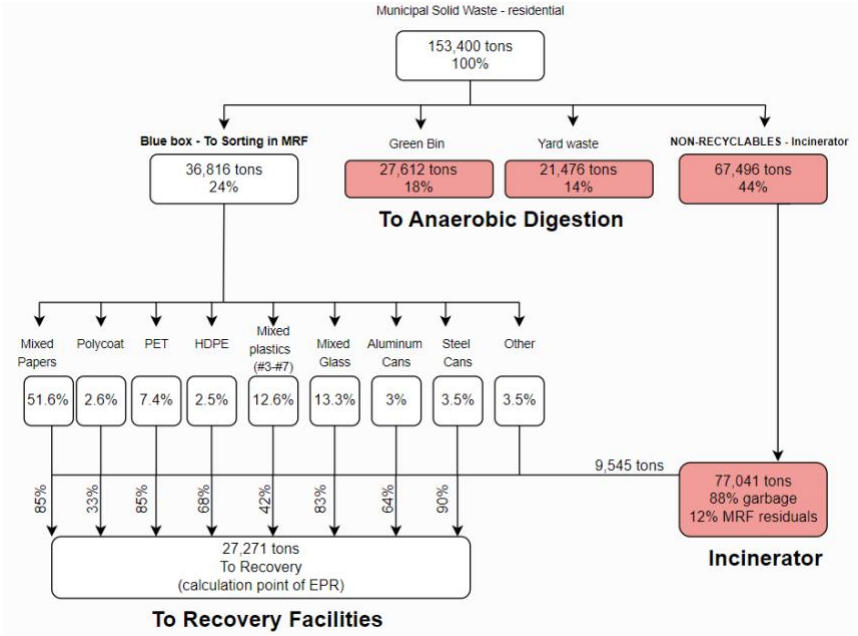

Figure 3: Waste Flow under WtE scenario

3) The third scenario considers the EPR proposed recovery targets set by province to be implemented between 2026 and 2029. The recovery target is defined as the number of materials marketed to suppliers after sorting, divided by the number of materials generated to the marketplace. In that scenario, the number of materials marketed is assumed to increase in order to meet the recovery targets set by the province. This is achievable by increasing the recycling efficiencies at the MRF. The news waste flow is depicted in Figure 4.

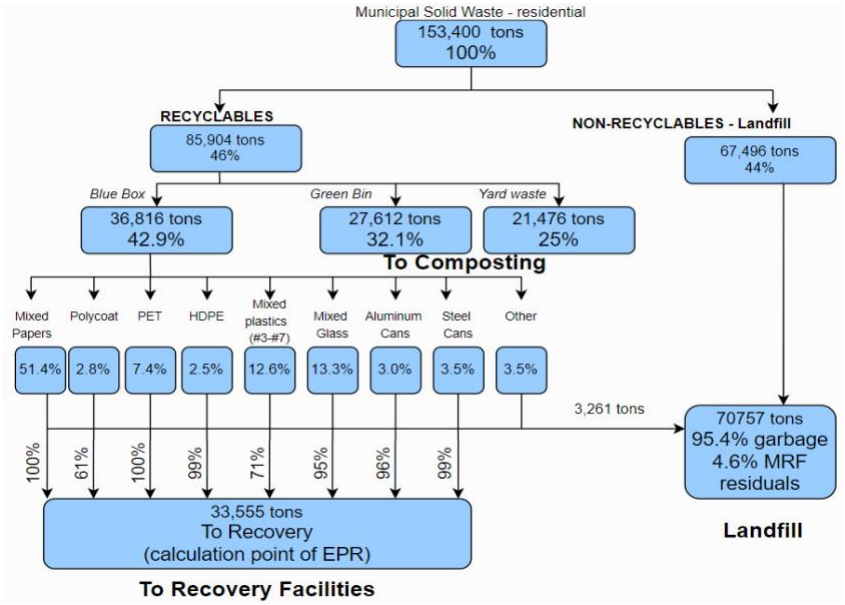

Figure 4:Waste Flow under EPR scenario (Note: assuming the generated flow is similar to that in 2021)

Chapter 4: Life Cycle Assessment

In this study, LCA is used as a methodological tool to assess the environmental impacts of MSWM scenarios in the Region of Waterloo as per the guidelines set in ISO 14044. The following sections are included in the LCA: goal and scope definition, inventory analysis, life cycle impact assessment, and interpretation .

4.1. Goal and Scope

4.1.1. Goal of the Study

The overall goal for carrying out this study is to quantify the environmental impacts of different MSWM pathways to treat MSW in the region of Waterloo, using a waste specific LCA modelling tool EASETECH V3.5.0 developed by the Technical University of Denmark (DTU). The study looks at three scenarios: the BAU state of MSWM in the Region, a second scenario considering WtE technologies, and a last scenario where the Region achieves the EPR diversion targets set by the province.

The results of this LCA are intended to provide direction for the MSWM stakeholders in Canada to focus on key drivers of environmental impacts in disposal and treatment of MSW. This will aid in identifying the key impact areas that future research should focus on. It is of particular interest to the Region of Waterloo waste management division, as well as to other regions with a similar waste management context.

4.1.2. Scope of the study

The life cycle system of MSWM, alongside the assumptions used in this study, are clearly defined in this section of the thesis. Then, the scope of the LCA is discussed.

- **Function, functional unit, key parameters, and reference flow**

The function of the service is the management of residential MSW of the Region of Waterloo. This includes recyclables, organics, and residual waste.

The Functional unit, which quantifies this function is "The management of 1 ton of Municipal Solid Waste from residential housing in the Region of Waterloo in 2021."

The Reference flow is 1 ton of MSW based on composition studies from Continuous Improvement Fund (CIF) data of urban regional cities in Ontario in 2021.

The key parameters needed to determine the reference flow are outlined below:

- Waste composition: Data for waste composition is gathered from the CIF website. Since 2012, the CIF and the Stewardship of Ontario funded different waste audits that target the residential seasonal MSW portion of the region. The different regions chosen are divided based on their density and the

following divisions were examined in the audits: large urban, urban regional, medium urban, and rural regional. The Region of Waterloo is classified to be an urban regional region as per the data calls released by the RPRA. The RPRA Datacall is the source of data that allocates funds under the Blue Box program and calculates the net Blue Box system cost (*RPRA,* 2023). The data from the CIF audits show the mean disposed per household per week (kg/hh/wk) of garbage, recycling, and organic streams during the four seasons of the year. The waste composition is divided into seven major sections: printer paper, paper packaging, plastics, metals, glass, municipal hazardous & special waste, and other materials.

- Climatic conditions: The climate of the Region of Waterloo has large seasonal differences, with warm, humid summers and cold winters. The waste composition varies between seasons, but the mean waste composition is employed in this study.

4.2. System boundaries

4.2.1. Geographical boundaries

The model represents the MSWM system of the Region of Waterloo. Nevertheless, the treatment pathways sometimes happen outside the region. For instance, the composting facility is in Guelph, and the recovery facilities for the blue box materials are dispersed in Quebec, North-Eastern USA regions, and Mid-western USA cities. Therefore, the boundary extends to the regions responsible for treating and recovering the MSW of the Region of Waterloo.

4.2.2. Temporal boundary

The temporal boundary of the study is in 2021, and the results are assumed to be still valid until 2031. So, the timeframe is assumed to be short-term. This timeframe is chosen based on the following two factors:

1. MSW composition data: The data collected represents the trends in the year 2021. The year 2021 was chosen over more recent years because the audit performed by CIF was more detailed for the year 2021 and included more waste fractions and more information on the composition. So, only one-year data is used to generate the results.
2. Lifetime of technology in place: The lifetime of the treatment technology is an important parameter that should be considered as it directly impacts the long-term environmental impacts of MSWM practices. A longer operational lifespan can lead to higher cumulative environmental impacts, such as GHG emissions, resource depletion, and land use, while a shorter lifespan may necessitate more frequent construction and operational phases, resulting in additional resource consumption and emissions. As of 2021, the lifetime of the landfill has been expected to be 25 years, then the landfill will be at capacity by around the year 2045. In parallel, for Scenario 2, the anaerobic digester's lifetime is assumed to be 20 years, but the lifespan decreases to 8 years when the system is a

combined heat and power technology (Fusi et al., 2016). Similarly, in the region of Peel, in Ontario, the incinerator built is expected to have a 30 years of lifespan (Noor Javed Staff Reporter, 2015). Thus, any incinerator is expected to have a similar lifetime. For the purpose of this study, the results obtained are assumed to be applicable for a period of 10 years starting from 2021. This choice was selected due to a multitude of factors including the maturity of the technologies studied, the change in waste composition and waste management policies, and the life span of the current landfill.

4.2.3. Technological boundaries

The life cycle of waste is divided into five main stages: collection, storage, disposal or valorization, secondary raw material and/or energy recovery. This study follows a zero-burden approach for the inlet waste stream, which assumes that all the environmental burden of the incoming waste is shifted onto the waste management system. A consequential LCA approach is followed, whereby marginal data is used to capture the changes and impacts associated with small shifts in demand or supply within a system. System expansion is used to account for eco-functionalities within the system. It involves enlarging the boundaries of the analyzed system and accounting for the avoided environmental burden by deducting it from the total impacts. (Thomassen et al., 2008). Any secondary materials or energy produced by the waste management system were credited through system expansion by assuming they would replace the primary materials or energy sources representative of the geographical boundary in place.

The boundaries start after the collection of MSW from the residential households in the Region until the final disposal of all solid residues and the substitution of virgin material, mineral fertilizer, and energy. The system boundaries of Scenario 1 (BAU) and Scenario 2 (WtE) are shown in Figures 5 and 6 respectively. The boundaries for Scenario 3 (EPR) are assumed to be similar to that of the BAU boundaries and are depicted in Figure 7. Waste collection operations are assumed to be the same for all scenarios and are omitted from the LCA. Waste collection refers to the transportation of waste from the households to the management facility. The data needed to estimate this number is not readily available, and to avoid misrepresentation of this parameter, it was not included in the study.

Emissions are divided into three main types: upstream, downstream, and operational emissions.

- Indirect upstream emissions result from the inputs of materials and energy (such as electricity and fuel) needed in the respective waste treatment technologies. The construction of the technologies that treat the waste are outside the scope of the study.
- Direct emissions are the result of process-specific emissions.
- Indirect downstream emissions are associated with electricity production and substitution, material production and substitution, and fertilizer production and substitution of compost and digestate.

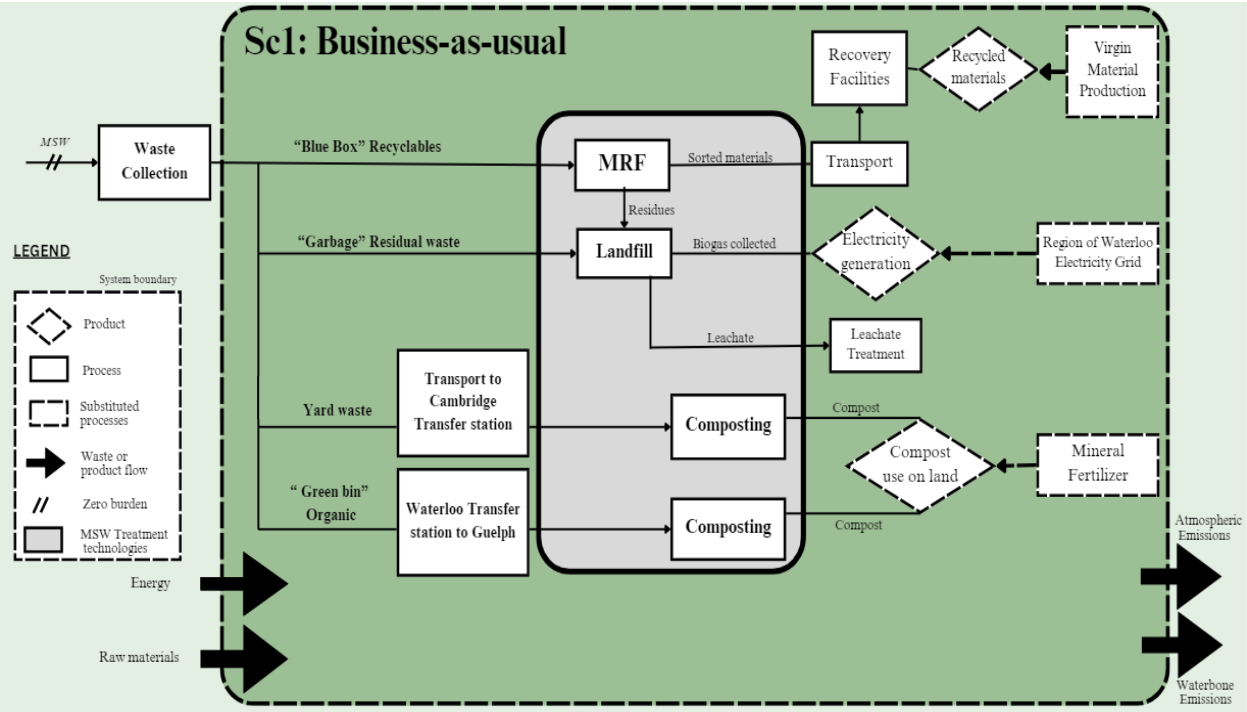

Figure 5: System boundaries of the LCA model, Business-as-usual MSWM in Waterloo

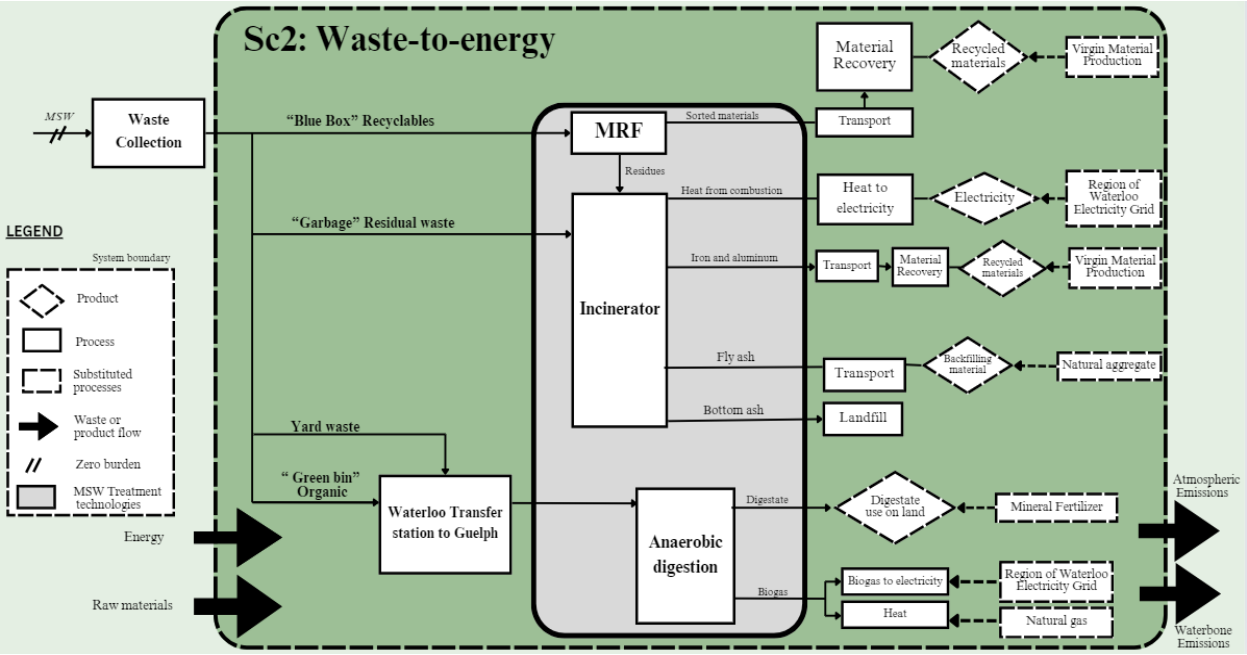

Figure 6: System Boundaries - WtE scenario 2

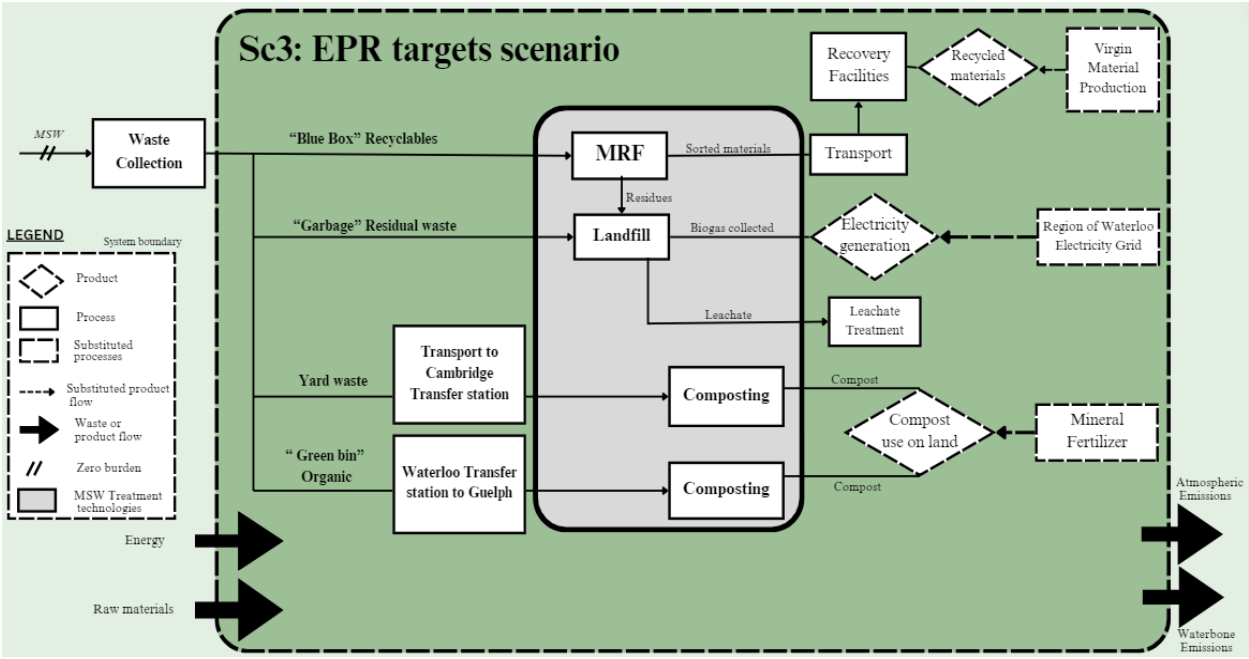

Figure 7: System boundaries of scenario 3: EPR targets

4.3. Sensitivity Analysis

A further sensitivity analysis is conducted in the life cycle interpretation step in order to study the effect of changing some parameters on the results of the study. The following three sensitivity analyses are performed:

- GWP characterization factor: The study assumes a GWP100 due to its relevance to the lifetime of the landfill of 100 years assumed in this study. Nevertheless, most of the organic waste degrades within the first 20-30 years, and most of the emissions happen during that timeframe. Thus, a GWP20 is also considered for the analysis.
- Energy mix: The average energy mix of Ontario in 2021 is considered in this study. However, to further understand the effect of high and low energy use, the energy mixes with high and low natural gas demand are further investigated. The high demand represents data from the peak natural gas demand during Summer 2021 while the lowest demand represents data from the Winter 2021 in Ontario.
- Energy generation pathway: the system assumed for the methane gas collected from the landfill as well as from the incinerator is electricity-based. However, by capturing and utilizing the heat produced during electricity generation, combined heat & power (CHP) systems can achieve higher overall energy efficiency compared to separate electricity and heat generation systems. Thus, a CHP system is further analyzed for each of the three scenarios of the study.

4.4. Impact assessment method and impact categories

The impact categories that are chosen for the study are selected based on the focus of the Canadian Environmental Sustainability Indicators that were developed with the aim of improving air quality, reducing GHG emissions, and ensuring cleaner water resources. The air quality indicators focus on assessing Canadians' potential long-term exposure to ground-level ozone and fine particulate matter (PM2.5), which are significant components of smog and among the most prevalent and detrimental air pollutants affecting human health. Additionally, the GHG indicator monitors annual emissions of the primary GHG responsible for climate change. The freshwater quality indicator provides insights into the state of surface water quality at designated monitoring sites across the nation (Environment Canada, 2006).

Thus, the following impact categories are studied in this LCA: GWP, photochemical ozone formation, particulate matter, and eutrophication. The emphasis is placed on the non-toxic impact categories instead of the toxic impact categories. While the toxic impact categories are uncertain in their approach of fate and exposure modelling and have highly variable characterization factors, the non-toxic categories have well established characterization factors and are based on widely acceptable concepts (Huijbregts et al., 2016).

The GWP impact category characterization model developed by the IPCC was selected for this study. Factors are expressed as GWP for a time horizon of 100 years (GWP100), in kg CO_2 eq. GWP accounts for the emission of GHG such as CO_2, CH_4, and N_2O. The impact assessment for the other impact categories was performed using the Traci 2.1 method developed by the US EPA. This method was chosen due to its relevance to geographical conditions in the United States, which shares closer proximity to Canada compared to Europe.

4.5. Life Cycle Inventory used in EASETECH model – BAU Scenario 1

This section of the thesis presents the data used for modelling the three product systems and describes key assumptions. The Ecoinvent database (version 3.9.1) and online reports and audits were used for data sourcing. When no data specific to the area under study or to the technology used in the Region, models available on EASETECH representative of Europe or the most appropriate available geographical location available in Ecoinvent were used.

4.5.1. MSW composition

The MSW composition is needed to model the different processes of MSWM on EASETECH.

The steps are available in the Supplementary Information 1 (MS Excel file). The audit from the CIF shows the urban regional material fractions of the waste for each season of the year 2021, available in the “CIF data urban regional” sheet of the document. The data is presented in kilograms per household per

week and is divided into the following waste types: printed paper, paper packaging, plastics, metals, glass, municipal hazardous and special waste, and other materials. Rather than focusing on the MSW variations among seasons, the focus is on the mean data for each MSW category (i.e. blue box, garbage, yard waste, and organics). Then, by using the data available in the Region of Waterloo Waste Management Report of 2021, the yearly waste generation (tons) of each of the different MSW categories (in Table 10) are turned into percentages as shown in Table 11.

Table 10: Urban Regional MSW composition from CIF audits - adapted to Region of Waterloo in 2021

Material Category	Weight (tons)
1. PRINTED PAPER	
Newspapers - Daily and weekly	1,155
Other Newspapers/Newsprint - Other	1,845
Magazines and Catalogues	1,137
Directories / Telephone books	6
Other Printed Paper (Obligated)	1,912
Other Printed Paper (Non-Obligated)	894
Total Recyclable Paper	6,950
2. PAPER PACKAGING	
Gable Top Containers - Food and other non-beverage	92
Gable Top Carton – Beverage non-dairy	121
Gable Top Carton – Dairy & Substitutes	268
Aseptic Containers - Food and other non-beverage	84
Aseptic Carton – Beverage non-dairy	242
Aseptic Carton – Dairy & Substitutes	38
Aseptic Containers - Alcoholic Beverage	2
Polycoat Beverage Cups	544
Spiral Wound Containers	123
Ice Cream Containers and Other Bleached Long Polycoat	172
Paper Laminate Packaging	1,032
Corrugated Cardboard	9,458
Boxboard/Cores/Molded Pulp	5,862
Other Paper Packaging (Non-Obligated)	461
Total Paper Packaging	18,499
3. PLASTICS	
#1 PET Bottles and Jars - Clear - Non-Beverage	764
#1 PET Bottles and Jars - colored - Non-Beverage	80
#1 PET Bottles and Jars - Black - Non-Beverage	6
#1 PET Bottles - Clear - Non-Alcoholic Beverage	1,361
#1 PET Bottles - Colored & Black- Non-Alcoholic Beverage	32
#1 PET Bottles - Clear - Alcoholic Beverage	52
#1 PET Bottles - colored & Black- Alcoholic Beverage	16
#1 PET Bottles and Jars ≥ 5 L - All	34
#1 PET Thermoform - Clear	905
#1 PET Thermoform - Colored	45
#1 PET Thermoform - Black	73
#2 HDPE Bottles and Jugs (Natural) - Non-Beverage	171
#2 HDPE Bottles and Jugs (Colored) - Non-Beverage	670
#2 HDPE Bottles and Jugs (Black) - Non-Beverage	28
#2 HDPE Bottles (Natural) - Non-Alcoholic Beverage	6
#2 HDPE Bottles (Natural) - Non-Alcoholic Beverage - Dairy	5
#2 HDPE Bottles (Colored & Black) - Non-Alcoholic	14
#2 HDPE Bottles (Colored and Black) - Non-Alcoholic	159
#2 HDPE Bottles and Jugs ≥ 5 L - All	36
#2 Other HDPE Containers	41
Flexible Film Plastic – LDPE & HDPE	2,317
LDPE/HDPE Film - Products (non-packaging)	1,538

#5 PP Bottles - Non-Beverage	94
#5 PP Bottles - Non-Alcoholic Beverage	12
#5 Other PP Containers	1,293
#5 Other PP Containers (Black)	170
#6 PS - Expanded Polystyrene	544
#6 PS - Expanded Polystyrene (Black)	28
#6 PS - Non-expanded Polystyrene - Non-beverage	290
#6 PS - Non-expanded Polystyrene (Black) - Non-Beverage	30
Plastic Laminates and Other Film Packaging	2,465
Other Rigid Plastic Packaging - Non-Beverage	988
Other Rigid Plastic Packaging - Non-Beverage (Black)	128
Other Rigid Plastic Packaging - Non-Alcoholic Beverage	8
Large HDPE & PP Pails & Lids	119
Other Plastics - (non-packaging/durable)	2,013
Total Plastics	16,535
4. METALS	
Aluminum- Food Containers	108
Aluminum Containers - Non-Alcoholic Beverage	784
Aluminum Containers - Alcoholic Beverage	253
Aluminum Foil & Foil Trays	481
Aluminum Aerosols	58
Other Aluminum (non-packaging)	24
Steel Food Cans	1,084
Steel - Non-Alcoholic Beverage	12
Steel Paint Cans	28
Steel Aerosol Container	187
Other steel (non-packaging)	717
Total Metals	3,736
5. GLASS	
Clear Glass - food and other products	2,379
Clear Glass - Non-Alcoholic Beverage	385
Clear Glass - Alcoholic Beverage	992
Coloured Glass - food and other products	261
Coloured Glass - Non-Alcoholic Beverage	150
Coloured Glass - Alcoholic Beverage	964
Other Glass - non-Blue Box	1,004
Total Glass	6,135
6. MUNICIPAL HAZARDOUS AND SPECIAL WASTE	
Batteries (Consumer-type Portable)	120
Total MHSW	120
7. OTHER MATERIALS	
Avoidable Food Waste	10,420
Unavoidable Food Waste	34,266
Yard Waste	22,555
Tissue/Towelling	5,227
Pet Waste	6,728
PPE (Masks/gloves)	115
Other Waste	22,111
Total Non-Recyclable Other Materials	22,223
Total Organic Other Materials	79,199
Grand Total	**153,400**

Table 11: MSW composition in the Region of Waterloo – in percentages

MSW generated	Percentage
Newsprint residual waste	1.956%
Books phone book	0.004%
Magazines	0.741%
Other paper	2.803%

Total printed papers	**5.5%**
Paper and carton container	0.82%
Milk carton	0.2%
Juice carton	0.079%
Cardboard and paperboard	9.987%
Total paper packaging	**11.1%**
PET plastic packaging	2.194%
Plastic packaging HDPE	0.737%
Non packaging plastic LDPE	2.513%
PP plastic packaging	1.023%
PS	0.209%
Expanded PS	0.373%
Non packaging plastic	1.312%
Soft plastic	1.607%
Hard plastic	0.811%
Total plastics	**10.8%**
Aluminum foil and container	0.070%
Beverage can (Aluminum)	0.676%
Aluminum foil	0.367%
Steel food can	0.733%
Non packaging metal (Fe)	0.467%
Metal packaging (Fe)	0.122%
Total metals	**2.4%**
Clear glass	2.449%
Glass packaging brown	0.896%
Other/special glass residual waste	0.655%
Total Glass	**4.0%**
Batteries	0.078%
Total hazardous	**0.08%**
Animal derived food waste	14.565%
Vegetable food waste	14.565%
Branches garden waste	14.703%
Tissue paper	3.408%
Animal bedding	2.193%
Animal excrement - dog	2.193%
Disposable sanitary products	0.075%
Other combustible	7.207%
Other non-combustible	7.207%
Total organic & others	**66.1%**
Grand TOTAL	100%

4.5.2. MSW tonnage across different waste categories

The four main MSW household categories are: Blue box (paper and plastics), Green bin (kitchen waste), Yard waste, and the residues that go into the garbage bin. This data is also collected from the CIF datasheet of years 2020/2021 available in the Supplementary Information 1 (CIF data urban regional and EASETECH inputs sheets) and used as an input in the mass transfer process of sorting, as shown in Table 12.

Table 12: MSW materials pathways across different waste categories

Material Type	Residuals	Blue box	Green bin	Yard waste
Newsprint	8%	92%		
Magazines	10%	90%		
Other paper	53%	47%		
Paper and carton container	51%	49%		
Milk carton	8%	92%		
Juice carton	3%	97%		
Cardboard and paperboard	14%	86%		
PET plastic packaging	15%	85%		
Plastic packaging HDPE	19%	81%		
Non packaging plastic LDPE	73%	27%		
PP plastic packaging	42%	58%		
PS	46%	54%		
Expanded PS	41%	59%		
Non packaging plastic	64%	36%		
Soft plastic	75%	25%		
Hard plastic	44%	56%		
Aluminum foil and container	25%	75%		
Beverage can (aluminum)	10%	90%		
Aluminum foil	77%	23%		
Steel food can	14%	86%		
Non packaging metal (Fe)	72%	28%		
Metal packaging (Fe)	34%	66%		
Clear glass	9%	91%		
Glass packaging brown	7%	93%		
Other/special glass residual waste	79%	21%		
Batteries	98%	2%		
Animal derived food waste	38%		62%	
Vegetable food waste	38%		62%	
Branches garden waste	5%			95%
Tissue paper	98%	2%		
Animal bedding	100%	0%		
Animal excrement - dog	100%	0%		
Disposable sanitary products	96%	4%		
Oher combustible	97%	3%		
Other non-combustible	97%	3%		

4.5.3. Blue box Nyle Ludolph Recycling Facility-MRF

To be able to compute the sorting efficiency of the Nyle Ludolph Center, the following steps are followed. The Region of Waterloo Waste Management Team provided the information shown in Table 13, corresponding to the amount of material that leaves the MRF after the sorting process takes place.

Table 13: Data from the Region of Waterloo Waste Management team on the materials that leave the MRF

Materials shipped from Waterloo transfer station and MRF	**Amount (Tonnes)**
Aluminum cans	714
HDPE bottles	619
Mixed glass	4,051
Mixed paper	16,084
Mixed plastics	1,951
PET bottles	2,332
Polycoat containers	310
Steel cans	1,156
Total diversion (tonnes)	28,648

In Table 14, a mass balance is performed on the materials entering and leaving the MRF. The purpose of the mass balance is to determine the difference in mass between the input and output, which is the weight of materials leaving the MRF and going to the landfill. The tons of materials leaving the MRF are extracted from Table 13. The materials entering the MRF correspond to the material collected, assuming no losses occur during collection and transportation. Then, the residuals are calculated by doing the percentage change between the materials going in and out. The following equation is used:

$$Residuals\ (\%) = \frac{In\left(\frac{ton}{yr}\right) - Out\ (\frac{ton}{yr})}{In\ (\frac{ton}{yr})} \qquad \textit{(Equation 1)}$$

The residuals represent the percentage of recyclables that are sent to landfill for final disposal.

Table 14: Mass balance between materials entering the MRF and materials leaving the facility

Material Category	**IN (tons/yr)**	**OUT (tons/yr)**	**Residuals (tons/yr)**	**Residuals (%)**	**Sorting efficiency (%)**
Mixed paper	18,913	16,084	2,829	15%	85%
Polycoat containers	1,014	310	704	69%	33%
PET bottle	2,734	2,332	402	15%	85%
HDPE BOTTLE	915	619	296	32%	68%
Mixed plastic	4,643	1,951	2,692	58%	42%
Mixed glass	4,887	4,051	836	17%	83%
Aluminum cans	1,111	714	397	36%	64%
Steel cans	1,289	1,156	133	10%	90%

Since the material information available in Table 14 only encompasses the mass balances of the main material categories without considering the sub-categories of the MSW composition, some assumptions have been made to compute the residuals. Each material category mentioned in Table 14 is assumed to be associated with one or more of the material fractions of the MSW input of the model. The sorting efficiency of each material included in a certain sub-category is assumed to be the same for all of the materials within that sub-category. For instance, 85% sorting efficiency of the mixed papers is used for all materials within this category: newsprint, magazines, cardboard and paper, and other types of paper mixtures. This assumption could be invalid in instances where some materials are more easily sorted and accepted for recovery than others due to several reasons. For example, in the mixed plastic stream, the PET is the easiest plastic to recycle, while polystyrene is one of the hardest to recycle. Thus, accounting for a similar allocation in the mixed plastic stream can lead to overestimation/underestimation of certain material types that are being sorted out of the MRF (Ecocycle, 2024). However, since no data is readily available on specific materials sorting percentages, the even allocation will be discussed in the data quality section of this study.

Another input process that is used in the MRF of Waterloo is the electricity needed to run the recycling activities, which is summarized in Table 15. As per information from the MRF waste management team, the amount of electricity billed in 2021 was around 1.6 million kWh. By dividing this value by the total amount of waste diverted in 2021, then the power of electricity needed for 1 ton of waste is 45 kWh/ton.

Table 15: Electricity needed in the MRF for sorting activities

	Electricity in MRF	**Reference**
Electricity billed (Jan to Aug)	1,104,641	*Region of Waterloo*
Electricity (kWh per year) estimate	1,656,962	*Calculation by author*
Electricity per kg of waste input (kWh/kg)	0.045	*Calculation by author*
Power needed for sorting (kWh)	10.71	*Calculation by author*

4.5.4. Recyclables transportation post sorting

After the sorting of the blue box waste at the MRF, each product is then sent to separate locations to process and recover the material that could then be used in the production of other products. The data is provided by the Waste Management Team of the Region of Waterloo and is summarized in Table 16. Everything is sent to recovery centers in Quebec, Ontario, or the USA, apart from the mixed glass that is kept on-site to be used for landfill operations. Some of the destinations are unspecified, and some assumptions are chosen. For the aluminum cans, the exact destination is not disclosed, so the information is found in a news article published by CBC (Pierce, 2020). For the mixed papers and steel cans, it is assumed that they are sent to

paper and steel mills close to the Region of Waterloo. All of the distances are approximate from Google Maps.

A transportation process complying with the Euro3 European Emission Standard along with the emissions from the production of diesel oil is used in all transportation modelled in this study. It is not representative of Canada's transportation emission standards, but it is assumed that the transportation has little impact on the LCA results relative to the impacts of other processes such as landfilling and WtE. When sensitivity analysis was done on some of the studies, the results that excluded the transportation of waste to the incinerator facility did not significantly change the results (Ramos et al., 2018; Turconi et al., 2011). The process with Euro standards was thus used because previous studies proved that the transportation GWP impact is minimal (S.-H. Lee et al., 2007; Quirós et al., 2015).

Table 16: Recyclables pathway after the MRF

Materials shipped from MRF	**Destination**	**Distance from MRF to destination (km)**	**Reference**
Aluminum cans	Northeastern/Mid Eastern US (**Assumption:** Kentucky)	960	*(Pierce, 2020)*
HDPE bottles	Listowell ON	54	*Region of Waterloo MRF Team*
Mixed glass	On-site used for landfill operations	0	*Region of Waterloo MRF Team*
Mixed paper	Different locations (third party handling) (**Assumption**: Brantford)	60	*Author*
Mixed plastics	Northern Ontario_ Listowel	54	*Region of Waterloo MRF Team*
PET bottles	Northern Ontario, Shelburne	85	*Region of Waterloo MRF Team*
Polycoat containers	Cowansville, QC, and Detroit Michigan	730	*Region of Waterloo MRF Team*
Steel cans	**Assumption**: Gerdau, Cambridge	35	*Author*

4.5.5. Blue box materials : Recycling & Substitution Processes

In the following processes, two major steps are required in the model: the recycling process and the avoided production process. Substitution operates on the principle that when a system generates a co-product, it avoids a production process in another system, which leads to avoided emissions and resource extractions, which should be deducted from the analysis of the studied product system (Wardenaar et al., 2012). In the recycling step, the impacts associated with the transformation and recycling of the sorted blue box products are accounted for by the study. The technical substitution ratio (A) is inserted in this step, and it represents the losses incurred by the recycling process by referring to the efficiency of the sorting and remanufacturing steps. In the substitution process, it is assumed that the recycled material is an avoided burden because there is no longer any requirement to conventionally produce a new raw material, and thus any emissions associated with that conventional production are considered as a saving. The avoided virgin production is a value that is less than or equal to 1 and is dependent on the functionality of the recycled material versus the replaced material as well as on the market conditions, and it is modeled by the market response (B). In this step, system expansion is used, and negative signs are used in EASETECH to account for the avoided virgin production of materials.

In all the recycling processes modeled, the electricity, heat, and natural gas were imported from Ecoinvent to be representative of the respective regions where the recovery of materials is happening. When available, processes specific to the Region where the recycling and production of virgin material is happening, are used.

4.5.5.1. Mixed Papers recycling

The mixed papers are comprised of printed paper as well as other types of paper packaging such as carton boards and boxboard containers. The recycling process generally differs between newsprint and cartons. Thus, two models were created on EASETECH to separately represent the recycling & substitution processes of each.

First, the paper to cardboard recycling is modeled using a process available on EASETECH and representative of Sweden in 2006. The LCI is included in Table 17. The process takes as input mixed papers and carboard materials and generate solid packaging carboard as output. The fiber preparation and board making are included in the data. The technological efficiency (A) is set to be at 92%. All the residues are assumed to be incinerated with electricity and heat recovery. It is assumed that the incinerator happens in plant.

Similarly, the substitution of cardboard represents the production of board from wood in an integrated mill in Sweden between 2005 and 2007. As per the literature, the third quartile of the range of distribution of the substitution between recycled and virgin paper is less than 1:1 (Viau et al., 2020). Thus, the market response (B) is assumed to be 90%. There is a loss of quality at each recycling loop for paper and the number of loops is limited to five.

Table 17: LCI of paper to cardboard recycling (per 1 Functional unit)

Flow	Value	Unit	Notes	Reference
INPUTS				
Paper Recycling to cardboard				
Paper	34	kg	-	*CIF Urban Regional data 2021*
Process Water	522	kg	Treatment of surface water with ion exchangers	*RER ELCD Database*
Electricity	47	kWh	Consequential approach in modelling. The energy mix of Ontario in 2021 was created.	*Ecoinvent 3.9.1*
Petroleum	2	kg	Crude petroleum oil production specific to Canada	*Ecoinvent 3.9.1*
OUTPUTS				
Recycled paper	31	kg	Based on 92% recycling efficiency	*Mass balance on EASETECH, based on recycling efficiency from plant in Sweden.*
Waste paper to incineration	3	kg	8% residues	*Mass balance on EASETECH, based on recycling efficiency from plant in Sweden.*
Substituted process				
Cardboard production	-27.9	kg	Assuming a 90% market substitution ratio	- *Substitution ratio (Viau et al., 2020)* - *Substitution process is from a mill in Sweden (Stora Enso, EMAS Environmental Statement 2005, Skoghall Mill)*

For the newsprint recycling, fine paper is produced from mixed papers using a process available on EASETECH and representative of Denmark in 2007. The LCI is presented in Table 18. It is assumed that the technological efficiency is of 84%. For the second step for the mixed papers recycling with substitution, a process specific to Quebec is used. The activity starts at the reception of pulpwood and ends with packaged paper sheets ready for shipping.

Table 18: LCI of mixed papers recycling (per 1 Functional unit)

Flow	Value	Unit	Notes	Reference
INPUTS				
Paper Recycling to fine paper				
Paper	56	kg	_	*CIF Urban Regional data 2021*
Process Water	840	kg	Treatment of surface water with ion exchangers	*Process is from RER ELCD Database and value is from EASETECH (EU Best Available Technique)*
Electricity	22.4	kWh	Consequential approach in modelling. The energy mix of Ontario in 2021 was created.	*Process is from Ecoinvent 3.9.1 and value is from EASETECH (EU Best Available Technique)*
Petroleum	0.002	kg	Crude petroleum oil production specific to Canada	*Process is from Ecoinvent 3.9.1 and value is from EASETECH (EU Best Available Technique)*
Calcium carbonate	11.2	kg		*EASETECH (EU Best Available Technique)*
Sodium hydroxide	0.001	kg		*EASETECH (EU Best Available Technique)*
Spruce wood	17.36	kg		*EASETECH (EU Best Available Technique)*
OUTPUTS				
Recycled paper	47	kg	Based on 84% recycling efficiency	*Mass balance on EASETECH, based on recycling efficiency from factories in Denmark*
Waste paper to incineration	9	kg	16% residues	*Mass balance on EASETECH, based on recycling efficiency from factories in Denmark*
Substituted process				
Paper production uncoated	-27.9	kg	Assuming a 90% market substitution ratio.	- *Substitution ratio (Viau et al., 2020)* - *Substitution process is from Ecoinvent 3.9.1 representative of a mill in CA-QC.*

4.5.5.2 Polycoat containers recycling & substitution

The next material modeled on EASETECH is the polycoat containers. To accurately model the recycling and substitution of polycoat, a material split step is necessary. This step ensures that the three main components of this type of container (aluminum, paper, and plastic) are accounted for in the study, and the impacts are calculated based on the weight percentages. There is around 70% paper, 20% plastic, and 10 % aluminum in polycoat containers (Blunt, 2018).

- **Aluminum**

First, for the aluminum fraction, since no recycling process related to the recycling of aluminum in the North American context was found in Ecoinvent, the process is selected from EASETECH and it representing European context. The LCI is included in Table 19. The emission profile is from a state-of-the-art Italian plant, Ecoinvent database and the Italian National Agency for New Technologies, Energy and Sustainable Economic Development. The technological efficiency is equal to 93%.

The process used to model the substitution is specific to Canada. The output of this unit process is packaged aluminum ingots, wrought alloy, and it is representative of Canada. The market response (B) of aluminum

is set as 100% (Rigamonti et al., 2010). Most authors have suggested that there was no alteration in intrinsic characteristics during the recycling of these materials. Consequently, it is generally believed that they are capable of infinite recycling, with their properties remaining unchanged through recycling processes. Nonetheless, the introduction of contaminants in metals can greatly impact the capacity of recycled metals to replace primary metals (Viau et al., 2020).

Table 19: LCI of aluminum (10%of polycoat containers; per 1 Functional unit)

Flow	Value	Unit	Notes	Reference
INPUTS				
Aluminum Recycling				
Aluminum waste	0.220	kg	Part of polycoat material	*CIF Urban Regional data 2021*
Natural gas	0.827	MJ	Representative of Quebec	- *Data from EASETECH from Italian study by (Rigamonti, 2007)* - *Process from Ecoinvent 3.9.1*
Electricity	0.002	kWh	Representative of Quebec	- *Data from EASETECH from Italian study by (Rigamonti, 2007)* - *Process from Ecoinvent 3.9.1*
OUTPUTS				
Recycled aluminum	0.2	kg	Based on recycling efficiency off 93%	*Mass balance on EASETECH, based on recycling efficiency from study done in Italy (Rigamonti et al., 2009)*
Waste aluminum to landfill	0.02	kg	Residues of 7%	*Mass balance on EASETECH, based on recycling efficiency from (Rigamonti et al., 2009)*
Substituted process				
Aluminum production	-0.2	kg	Assuming a 100% market substitution ratio	*Ecoinvent 3.9.1, aluminum ingot production in Canada*

- **Mixed Papers**

Second, the mixed paper recycling processes used are similar to the one described in Table 18. The only change regards the input of mixed paper originating from polycoat, which amounts to 1.5 kg. Hence, the LCI values change, and are presented in Table 20.

Table 20: LCI of mixed papers (70% of polycoat containers; per 1 Functional unit)

Flow	**Value**	**Unit**	**Notes**	**Reference**
INPUTS				
Paper Recycling to fine paper				
Paper	1.5	kg		*CIF Urban Regional data 2021*
Process Water	22.5	kg	Treatment of surface water with ion exchangers	*Process is from RER ELCD Database and value is from EASETECH (EU Best Available Technique)*
Electricity	0.6	kWh	Consequential approach in modelling. The energy mix of Quebec in 2021 was created.	*Process is from Ecoinvent 3.9.1 and value is from EASETECH (EU Best Available Technique)*
Petroleum	0.000054	kg	Crude petroleum oil production specific to Canada	*Process is from Ecoinvent 3.9.1 and value is from EASETECH (EU Best Available Technique)*
Calcium carbonate	0.3	kg	_	*EASETECH (EU Best Available Technique); ELCD process*
Sodium hydroxide	0.00003	kg	_	*EASETECH (EU Best Available Technique); ELCD process*
Spruce wood	0.5	kg	_	*EASETECH (EU Best Available Technique); ELCD process*
OUTPUTS				
Recycled paper	1.3	kg	Based on 84% recycling efficiency	*Mass balance on EASETECH, based on recycling efficiency from factories in Denmark*
Waste paper to incineration	0.2	kg	16% residues	*Mass balance on EASETECH, based on recycling efficiency from factories in Denmark*
Substituted process				

Paper production uncoated	-1.1	kg	Assuming a 90% market substitution ratio	- *Substitution ratio (Viau et al., 2020)* - *Substitution process is from Ecoinvent 3.9.1 representative of a mill in CA-QC.*

- **Plastic**

Third, the plastic part is assumed to be PP, and the process of PP recycling is modeled using a process available on EASETECH, which is representative of Denmark. The LCI is presented in Table 21. The incoming plastic waste is washed, shredded, grinded, dried, extruded and granulated. The overall material loss in the process is 9.7% of the collected waste, therefore the technological efficiency (A) is 90.3%. The output is granulated polypropylene fibers, which substitute for similar material produced from virgin resources. All the residues are assumed to be incinerated in an incinerator accepting paper and plastics as inputs and delivering heat and electricity as outputs. The next step, involving the substitution process is specific to Canada. The market response (B) is set as 90% because the loss of material grade is assumed to be of 10 % based on the literature (Viau et al., 2020).

Table 21: LCI of PP (20% of polycoat; per 1 Functional unit)

Flow	Value	Unit	Notes	Reference
INPUTS				
PP Recycling				
Polycoat plastic waste	0.438	kg	Part of polycoat material	*CIF Urban Regional data 2021*
Natural gas	0.390	MJ	Representative of CA-ON	*EASETECH, Swerec plant, Sweden*
Electricity	0.333	kWh	Representative of CA-ON	*EASETECH, Swerec plant, Sweden*
Water	1.139	kg	Representative of CA-QC	*EASETECH, Swerec plant, Sweden*
Diesel oil - truck	0.0002	kg	Representative of EU standards	*EASETECH, converted from EDIP, IPU-NF-E2752*
OUTPUTS				
Recycled PP	0.395	kg	Based on 90% recycling efficiency	*Mass balance on EASETECH, based on recycling efficiency from SWEREC plant Sweden.*
Waste PP to incineration	0.043	kg	Based on 90% recycling efficiency	*Mass balance on EASETECH, based on recycling efficiency from SWEREC plant Sweden.*
Substituted process				
Granulate PP production	-0.356	kg	- Ecoinvent process representative of rest of Europe (RER). - Assuming a 100% market substitution ratio	- *Ecoinvent 3.9.1, production in Canada.* - *Substitution ratio from (Viau et al., 2020).*

4.5.5.3. PET recycling

The LCI used for PET recycling is included in Table 22. The process of PET recycling is modeled using a process available on EASETECH and is representative of USA in 2010. The input is PET post-sorting, and the output is recycled PET flakes. The technological efficiency (A) is set as 80%. The PET granulate substitution is imported from ELCD (European reference Life Cycle Database) database and is representative of the Rest of Europe (RER). The market response (B) is selected to be 81%. The price variation between the primary PET and the secondary PET is used to evaluate the substitution ratio between the two materials (Rigamonti et al., 2010; Viau et al., 2020).

Table 22: LCI of PET recycling process (per 1 Functional unit)

Flow	Value	Unit	Notes	Reference

INPUTS				
PET recycling				
PET plastic waste	20	kg	Waste out of MRF	CIF Urban Regional data 2021
Natural gas	40	MJ	Process specific to CA-ON	• Value from EASETECH , from USA, Franklin Associates, 2011. • Process from Ecoinvent 3.9.1
Electricity	7.3	kWh	Process specific to CA-ON	• Value from EASETECH , from USA, Franklin Associates, 2011. • Process from Ecoinvent 3.9.1
Water	6.3	kg	Process of treatment of water with ion exchangers.	ELCD, RER , v 3.2
Diesel oil - Train	4118	kg*km	Process used modelled for Danish specifications but can be applied to any diesel locomotive in general.	EASETECH, from USA, Franklin Associates, 2011.
Diesel oil- truck	17028	kg*km	Euro 6 standards	EASETECH, from USA, Franklin Associates, 2011.
Sodium hydroxide	0.38	kg		Process ELCD, RER Value from EASETECH from USA Franklin Associates 2011
Liquified Petroleum Gas (LPG)	0.002	kg	LPG are utilized for energy production	EDIP97 database
OUTPUTS				
Recycled PET resin	16	kg	Based on recycling efficiency of 80%	Mass balance on EASETECH, based on recycling efficiency from
Waste PET to incineration	4	kg	Residues : 10%	Mass balance on EASETECH, based on recycling efficiency from
Substituted Process				
PET granulate production	-13	kg	Assuming an 81% market substitution ratio, process representative of RER	• Process from ELCD, RER , v 3.2 • Substitution ratio : (Rigamonti et al., 2010; Viau et al., 2020)

4.5.5.4. HDPE recycling

The LCI of the HDPE is summarized in Table 23. The recycling process is representative of the USA. The HDPE input mainly comes from the MRF, and the output is HDPE pellet. Data from the source reports a technological efficiency of 93%. All the residues are assumed to be incinerated in an incinerator accepting paper and plastics as inputs and delivering heat and electricity.

The substitution process is imported from Ecoinvent and is the following and is representative of RER. The market response (B) is set as 90% because the loss of material grade is assumed to be of 10 % based on the literature (Rigamonti et al., 2010).

Table 23: LCI of HDPE recycling (per 1 Functional unit)

Flow	Value	Unit	Notes	Reference
INPUTS				
HDPE recycling				
HDPE plastic waste	4	kg	Waste out of MRF	CIF Urban Regional data 2021
Natural gas	0	MJ	Process specific to CA-ON	• Value from EASETECH , from USA, Franklin Associates, 2011. • Process from Ecoinvent 3.9.1
Electricity	1.8	kWh	Process specific to CA-ON	• Value from EASETECH , from USA, Franklin Associates, 2011. • Process from Ecoinvent 3.9.1
Water	0.0	kg	Process of treatment of water with ion exchangers.	ELCD, RER, v 3.2
Diesel oil- truck	4	kg*km	Euro 6 standards Value is uncertain, no information is provided.	• Value from EASETECH, from USA, Franklin Associates, 2011. • Process modelled using TEMA2010 Danish software for transport emissions.
Sodium hydroxide	0.00	kg		• Process ELCD, RER • Value from EASETECH from USA Franklin Associates 2011
Liquified Petroleum Gas (LPG)	0.015	kg	LPG are utilized for energy production	• Process EDIP97 database • Value from EASETECH from USA Franklin Associates 2011
OUTPUTS				

Recycled HDPE	16	kg	Based on recycling efficiency of 80%	Mass balance on EASETECH, based on recycling efficiency from
Waste HDPE to incineration	-12	kg	Residues: 10%	Mass balance on EASETECH, based on recycling efficiency from
Substituted Process				
HDPE granulate production	-13	kg	Assuming an 81% market substitution ratio, process representative of RER	• Process from ELCD, RER, v 3.2 • Substitution ratio : (Rigamonti et al., 2010)

4.5.5.5. Mixed plastics recycling

The mixed plastics stream's composition is not specified by the MRF. In general, mixed plastics are harder to recover. The modeling of mixed plastics recovery is done by assuming that the stream is composed of a mix of PP PS, plastic laminates, LDPE/HDPE film, and PET Thermoform. The LCI is presented in Table 24. The process used to model this recycling activity is the representative of a recycling facility in Sweden in 2006. It is assumed that the process of recycling would be to some extent similar to that happening in Canada. The input is a mix of plastic materials, and the output is polyethylene high density granulate. The loss of material in the process is low (3%) after subtraction of non-plastics and non-recyclable plastics (laminates and PS), therefore the technological efficiency is set to 97%. All the residues are assumed to be sent to an incineration plant. All data on energy and resource use and emissions is based on the amount of incoming material to the recycling plant.

Table 24: LCI of mixed plastics recycling (per 1 Functional unit)

Flow	Value	Unit	Notes	Reference
INPUTS				
Mixed Plastics Recycling to Polyethylene high density granulate				
Mixed plastics waste	11	kg	Waste out of MRF	CIF Urban Regional data 2021
Petroleum	0.01	MJ	Process specific to CA	Value from SWEREC plant Sweden ; Process from Ecoinvent 3.9.1
Electricity	0.93	kWh	Process specific to CA-ON	Value from SWEREC plant Sweden ; Process from Ecoinvent 3.9.1
Water	0.02	kg	Process of treatment of water with ion exchangers.	SWEREC plant Sweden
Diesel oil- truck	0.02	kg	Euro 2 standards	Value from SWEREC plant Sweden; Process from EDIP
OUTPUTS				
Recycled Polyethylene high density granulate	10	kg	Based on recycling efficiency of 97%	Mass balance on EASETECH, based on recycling efficiency from
Waste residues to incineration	1	kg	Residues 3%	Mass balance on EASETECH, based on recycling efficiency from
Substituted Process				
HDPE granulate production	-8	kg	Assuming a 90% market substitution ratio, process representative of RER	• Process from Ecoinvent 3.9.1 • Substitution ratio : (Rigamonti et al., 2010)

4.5.5.6. Glass recycling

The glass is used on-site and sent to the landfills for operational purposes. The LCI is summarized in Table 25. The EASETECH process of aggregate production is selected to model the substitution. In this module, the avoided transportation and excavation of natural aggregates are included. In that case, it is the glass that

is being sent instead of the bottom ash, but the avoided operational activity of natural aggregate is assumed to be valid in that scenario of glass recycling.

Table 25: LCI Glass recycling (per 1 Functional unit)

Flow	Value	Unit	Notes	Reference
INPUTS				
Glass recycling				
Glass waste	26.6	kg	Waste out of MRF	CIF Urban Regional data 2021
OUTPUTS				
Substituted Process – aggregate production				
Truck 28t-32t	-0.02	kg*km	EURO 5	Value from (Allegrini et al., 2015) ; Process from EASETECH
Electricity	-0.02	kWh	Process specific to CA-ON	Value from (Allegrini et al., 2015); Process from Ecoinvent 3.9.1
89 kW combine, diesel combustion	-532	L	Data regarding direct emissions originates from the LIPASTO project, where they are revised/updated yearly; they are thus considered highly reliable. The data regarding diesel provision originate from the ILCD database and considered highly reliable.	Value from (Allegrini et al., 2015)

4.5.5.7. Aluminum recycling

The LCI of aluminum recycling (Table 25) is similar to that presented in Table 19. However, the electricity and natural gas processes were imported from Ecoinvent to represent those available in the Northeastern region of the US. As for the aluminum ingot substitution model, no process specific to the US was found on Ecoinvent, and hence the process used was representative of Canada.

Table 26: LCI of aluminum recycling (mostly from aluminum cans) per 1 Functional unit

Flow	Value	Unit	Notes	Reference
INPUTS				
Aluminum Recycling				
Aluminum waste	4.3	kg	_	CIF Urban Regional data 2021
Natural gas	16.2	MJ	Representative of the US	Process from Ecoinvent 3.9.1 Value from (Rigamonti, 2007)
Electricity	0.04	kWh	Representative of the US	Process from Ecoinvent 3.9.1 Value from (Rigamonti, 2007)
OUTPUTS				
Recycled aluminum	4.0	kg	Recycling efficiency 93%	Mass balance on EASETECH, based on recycling efficiency from study done in Italy (Rigamonti et al., 2009).
Waste aluminum to landfill	0.3	kg	Residues: 7%	Mass balance on EASETECH, based on recycling efficiency from study done in Italy (Rigamonti et al., 2009).
Substituted process				
Aluminum production	-4.0	kg	Assuming a 100% market substitution ratio	Ecoinvent 3.9.1, aluminum ingot production in Canada

4.5.5.8. Steel recycling

The LCI of steel is presented in Table 27. During recycling, aluminum components are first shredded and then a magnetic separator is used to remove impurities ready to be sent to a steel smelter. Only the energy needed in the electric arc where the actual recycling takes place was included. The electric arc had an

efficiency of 84%, so the technical efficiency (A) was set equal to 84%. It is assumed that all residues are sent to a landfill.

The substitution process is representative of Canada. The process represents the manufacturing of large, alloyed steel slabs. The market ratio is also set at 100%, as explained in the aluminum substitution section with regards to metals recycling.

Table 27: LCI of steel recycling (per 1 Functional unit)

Flow	Value	Unit	Notes	Reference
INPUTS				
Steel Recycling				
Steel waste	7.5	kg		CIF Urban Regional data 2021
Electricity	3.8	kWh	Representative of Ontario	- Data from EASETECH from Italian study by (Rigamonti, 2007) (the model is based on process of recycling in Ecoinvent). - Process of electricity from Ecoinvent 3.9.1
OUTPUTS				
Recycled steel	6.3	kg	Based on recycling efficiency off 84%	Mass balance on EASETECH, based on recycling efficiency from study done in Italy (Rigamonti et al., 2009)
Waste steel to landfill	1.2	kg	Residues of 16%	Mass balance on EASETECH, based on recycling efficiency from (Rigamonti et al., 2009)
Substituted process				
Steel production	-6.3	kg	Assuming a 100% market substitution ratio	Ecoinvent 3.9.1, steel production in Canada Quebec

4.5.6. Composting

The composting of the yard waste takes place in Cambridge while the kitchen waste is transported to a composting facility in Guelph. The distance between Waterloo and Guelph is assumed to be 30 km, as per Google Maps, and is used as an input in the transportation process.

4.5.6.1. Composting Model for yard waste

The process models a typical enclosed windrow composting facility situated in the US, with an unspecified waste processing capacity. The LCI of the different inputs and outputs of the process is summarized in Table 28. Initially, the waste undergoes shredding in and is moistened to achieve a moisture content of approximately 50%. The composting operation occurs within enclosed windrows positioned on a designated composting pad. The facility is outfitted with a ventilation system, where emitted gases are routed to a biofilter for odor management. Periodically, the windrows undergo turning by means of a windrow turner. A trommel screen is employed to produce finely sifted compost following the curing process. The composting facility yields high-quality compost suitable for enhancing soil. Any materials rejected during screening are assumed to be disposed of in landfills.

Data of post-degradation total solids distribution is derived from transfer coefficients documented in alternative composting technologies mentioned by Andersen et al., (2010) and Boldrin et al., (2011). Then, it is assumed that 40% of the wet weight of the compost product is comprised of water. This moisture

content is considered a fair assumption as the ministry of Environment of Ontario recommends a moisture content ranging between 40% to 50 % (Ontario, 2021b).

Compost Substitution Model

The substitution process consists of two main processes in EASETECH. The first one is the modeling of the product that is to be substituted: the compost used on land. A process representative of the average crop rotation in Denmark during 2015 is used. The agricultural profile describes the emissions to air, surface water, groundwater and soil accumulation from land application of composted organic fraction of MSW on coarse sandy soil with average Danish crop rotation with nitrogen application rate. Data on the amount of diesel required for sludge spreading as well as the emission rate of methane are provided from literature (Ambus et al., 2001; Bernstad & la Cour Jansen, 2011).

The use on land of compost was assumed to displace marginal mineral fertilizers. The substitution factors are modified since it is assumed that mineral fertilizers and composts are not perfect substitutes. The nitrogen found in compost is primarily in organic form, yet plants require nitrogen in a mineral form, specifically as ammonia and nitrate, for growth. Therefore, it's crucial to differentiate between the organic and inorganic nitrogen content when determining the substitution ratio between the compost or digestate being used as a substitute and the fertilizer being replaced. The substitution ratios used are the following: 65% for Nitrogen, while for Phosphorus and Potassium it was 100% (Viau et al., 2020).

Table 28: LCI of yard waste (per 1 Functional unit)

Flow	Value	Unit	Reference
INPUTS			
Composting			
Yard waste	140	kg	*CIF urban regional data 2021*
Wheel loader, diesel	0.14	L	*(Komilis & Ham, 2004)*
Electricity	21	kWh	*EASETECH, composting in USA*
Compost use on land			
Farm tractor, diesel	0.023	L	*Bernstad, A. and J. la Cour Jansen (2011)*
OUTPUTS			
Compost	60.5	kg	*Mass Flow - EASETECH*
Water reject	60.5	kg	*Mass Flow - EASETECH*
Fraction of N	0.071	kg	*Mass Flow - EASETECH*
Fraction of P	0.030	kg	*Mass Flow - EASETECH*
Fraction of K	0.201	kg	*Mass Flow - EASETECH*
Substitution of fertilizer by compost			
Farm tractor, diesel, N fertilizer	-0.0007	L	*Bernstad, A. and J. la Cour Jansen (2011)*
Farm tractor, diesel, P fertilizer	-0.0003	L	*Bernstad, A. and J. la Cour Jansen (2011)*
Farm tractor, diesel, K fertilizer	-0.0020	L	*Bernstad, A. and J. la Cour Jansen (2011)*
Substitution of K_2O fertilizer	100	%	*(Viau et.al, 2020)*
Substitution of P_2O_5 fertilizer	100	%	*(Viau et.al, 2020)*
Substitution of N fertilizer	65	%	*(Viau et.al, 2020)*

4.5.6.2. Composting model for kitchen waste

The process models a typical composting tunnel facility situated in Italy in 2006. The LCI of the inputs and outputs is presented in Table 29. The plant is specific, but the technology could be common to other plants. In the enclosed channel composting facility, kitchen waste goes through a screening process, and then is placed into channels equipped with a conveyor belt at the bottom to help move the compost along from the start to the end of the channel. Ventilation air is sent from below into each of the channels and water is sprayed constantly to keep the composting activity within a certain moisture level. The waste stays in the channels for 11 weeks before being transferred to an open area to mature. The degradation of volatile solids during composting and total solids distribution were estimated by DTU Environment based on mass balance. The electricity consumption was estimated based on real consumption data from the facility, but the process was modified and imported from Ecoinvent in order to be representative of Ontario's electricity mix. The moisture content is selected to be of 40 %, which is considered a fair assumption as the ministry of Environment of Ontario recommends a moisture content that ranges between 40 to 50 % (Ontario, 2021b).

Compost Substitution Model

The substitution of fertilizer is modeled using the same data and assumptions as those used for the yard waste composting model explained in section 4.6.6.1.

Table 29: LCI table for composting of kitchen waste (per 1 Functional Unit)

Flow	Value	Unit	Reference
INPUTS			
Composting			
Animal derived food waste	90	kg	*CIF urban regional data 2021*
Vegetable derived food waste	90	kg	*CIF urban regional data 2021*
Wheel loader, diesel	0.18	L	*EASETECH – plant in Italy*
Electricity	9.54	kWh	*EASETECH – plant in Italy*
Compost use on land			
Farm tractor, diesel	0.004184	L	*Bernstad, A. and J. la Cour Jansen (2011)*
OUTPUTS			
Compost	72	kg	*Mass Flow - EASETECH*
Water reject	94	kg	*Mass Flow - EASETECH*
N	0.109	kg	*Mass Flow - EASETECH*
P	0.046	kg	*Mass Flow - EASETECH*
K	0.251	kg	*Mass Flow - EASETECH*
Substitution of fertilizer by compost			
Farm tractor, diesel, N fertilizer	-0.0011	L	*(Bernstad & la Cour Jansen, 2011)*
Farm tractor, diesel, P fertilizer	-0.0005	L	*(Bernstad & la Cour Jansen, 2011)*
Farm tractor, diesel, K fertilizer	-0.0025	L	*(Bernstad & la Cour Jansen, 2011)*
Substitution of K_2O fertilizer	100	%	*(Viau et al., 2020)*
Substitution of P_2O_5 fertilizer	100	%	*(Viau et al., 2020)*
Substitution of N fertilizer	65	%	*(Viau et al., 2020)*

4.5.7. Landfill Process

The landfilling process is modeled using an extended set of linked processes. It is important to note here that the process of landfill construction was omitted from the model. It is assumed that the impact of construction is not of main importance given the lifetime of the landfill. In other words, the impacts are allocated over the lifetime of the landfill and are not expected to be significant for the temporal boundary of the study taking place in 2021. The LCI table is included at the end of this section.

4.5.7.1. Landfill Gas Generation & Collection

The landfill takes as an input the residual waste of the MSW stream, as well as the residuals of the recyclables after sorting in the MRF. Organic matter degrades and leads to the formation of the landfill gas mainly comprised of methane and CO_2. The decay rates for different waste fractions are dependent on the moisture content in the landfill. These rates apply for moderate climatic conditions. Gas generation is modeled using a first order degradation model, and thus most of the gas will be produced in the first years after landfilling, depending on the decay rate. The different decay rates of all the material fractions available on EASETECH are extracted from the US EPA report (Olesen & Damgaard, 2014). Four modules have been built in EASETECH. One for each of the conditions: arid, moderate, wet, and bioreactor. The difference in climate conditions can speed up or slow down the decay rate. In the case of Waterloo, it is considered that the conditions are moderate. The temporal cutoff for the inventory is selected to be 100 years. Thus, all methane gas generated up until this time is included in the LCIA.

The next steps after gas generation are divided into two main processes. The first output is methane gas that is either collected and utilized or uncollected and oxidized. The second output is the leachate generation module.

First, the gas collected needs to have a prior process on EASETECH. A process named "Addition of substances" is required to be modeled as it consists of the addition of material substances to the composition matrix. In a landfill, new organic substances are generated as the waste decays, but they are not part of the original flows, therefore this process accounts for these substances (US EPA, 2008). As per the Waste Management Team in the Region of Waterloo, the average collection efficiency is 80%. The following Table 30 includes the collection efficiencies used for the model of the Region's landfill.

Table 30: Landfill Gas Collection Efficiencies chosen for Waterloo Landfill at different time intervals within 100 years

Time Period (Years)	0-5	5-15	15-55	55-100
Collection efficiency (%)	35%	65%	80%	0%

- **<u>Energy Generation</u>**

After landfill gas collection, some of the gas might leak through pipes, which leads to losses in energy recovery. However, the gas that is leaking prior to utilization is assumed to represent just an insignificant small percentage of the total gas collected (usually around 2 %). This gas is vented to the atmosphere and is modeled on EASETECH through the venting process whereby CH_4, CO_2, and other substances are emitted to the atmosphere.

The gas that is collected and utilized is combusted and used for energy generation. It is assumed that the electricity produced is injected into the Region's grid and provides part of the supply to the residents (Region of Waterloo, 2024a). The electricity generated is computed using yearly data for 2021 from the Region of Waterloo's landfill (available in appendix A).

$$Average\ power\ output\ per\ volume\ of\ methane\ gas\ \left(\frac{kWh}{m^3\ CH_4}\right) = \frac{Avg\ power\ output\ (kWh)}{CH_4\ content\ (\%) \times Gas\ flow\ (\frac{m^3}{hr})} \qquad \text{(Equation 2)}$$

The equation 2 above shows the steps needed to convert the data available in appendix A into a value that can be used as an input to the external process of electricity substitution on EASETECH. The average power output that is generated per m^3 of methane gas is computed by dividing the average power output by the product of the methane gas flow and the methane content of the gas. As such, the average amount of electricity that was produced in 2021 is 3.82 kWh/m^3 CH_4. A negative sign is added to the process in order to account for the avoided burden from the substitution process that happens from the electricity generation of the Region of Waterloo's landfill. This generation substitutes part of the Region's electricity grid. The electricity of Ontario mix is modeled on EASETECH by importing Canadian-specific databases from Ecoinvent 3.9.1. The data on the electricity mix in 2021 is presented in Table 31. It is extracted from the report published by Ontario Energy Board, and it shows the energy supplied by type for that year (OEB, 2022). The information is converted into kWh and used to create a region-specific electricity mix. The non-contracted source represents a variety of fuel types that are not categorized due to a lack of information. Thus, for the modeling on EASETECH, the non-contracted source representing 1.2% is allocated equally to the wind and solar sources of Ontario.

Table 31: Ontario's electricity mix in 2021 (OEB, 2022)

Electricity Source	**Ontario's electricity mix (%)year** *(OEB, 2022)*	**EASETECH input (kWh)**
Nuclear Energy	55.30	0.55
Water Power	23.3	0.233
Natural Gas	8.1	0.081
Wind	9	0.096
Solar PV	2.5	0.031
Bioenergy	0.5	0.005
Non-Contracted	1.2	-

Some emissions associated with the energy generation process have been modelled as process-specific. These include carbon monoxide, nitrogen oxides, sulphur dioxide, particles, dioxin, Polychlorinated biphenyl, hydrogen chloride, and hydrogen fluroide. The majority of the emissions are extracted from literature and more specifically from the US EPA and the Department for Environment Food and Rural Affairs in the United Kingdom (Olesen & Damgaard, 2014).

- **Landfill Gas Uncollected – Oxidation of methane in Top Cover**

The modeling of oxidation in EASETECH is divided into three processes that are divided by the time period during which oxidation happens. As the performance of the landfill improves and more monitoring measures are followed, oxidation rates for methane and trace substances subsequently increase.

Environment and Climate Change Canada (ECCC) suggested a default value for methane oxidation in landfill covers to be set at 10% of generated methane. Florida State University examined methane oxidation rates in various soil types and landfill covers, finding a range of 11% to 89% oxidized methane across studies. The average oxidation rate was 36% with a standard error of 6% (Abbassi & Abdel Mohsen, 2019). For this study, the oxidation rates selected are presented in Table 32. In the first five years of the landfill's lifetime, the oxidation rate in the topsoil is assumed to be 10 % while the waste is under daily cover. When the intermediate cover is placed, the oxidation rate increases to 20 %. When the final cover is installed after around 15 years of operation, the mean value of oxidation rate found from literature was used for the model, which represents a 36% oxidation rate (Olesen & Damgaard, 2014).

Table 32: Oxidation rate used for Waterloo Landfill on EASETECH, by author

	0-5 yrs (daily cover)	5-15 yrs (intermediate cover)	15-100 yrs (final cover)
Oxidation rate for average performing landfill	10 %	20 %	36 %

4.5.7.2. LCI: Leachate Generation, collection, and treatment

Leachate Generation

The volume of leachate produced depends on the rate of water infiltration into the landfilled waste. Calculations for leachate generation are based on selected timeframes, waste layer thickness, and waste density. The net infiltration of leachate values used on EASETECH are modeled using Visual HELP software. Due to diverse climatic conditions, infiltration rates and leachate output can differ significantly. Given the variability in infiltration rates within distinct climate conditions, it's advisable to model scenario-

specific cases. For this study, it is assumed that the Region of Waterloo is a medium precipitation area, ranging between 500-1200 mm/year (Environment and Climate Change Canada, 2024).

A net infiltration rate of 300 mm/yr was applied throughout the landfill's lifespan of 100 years. The waste layer height default is set at 10 meters, with a bulk density of 1 tonne/m³ in EASETECH software, representing densely compacted landfill waste. Leachate substance concentrations for different timeframes are sourced from literature and modeled over a century (Olesen & Damgaard, 2014).

Leachate collection

It is assumed that 99.9% of the leachate is collected in the first 80 years, and 87% in the last 20 years. The efficiency of the landfill's geomembrane liner is expected to decrease over the years. Lower collection efficiencies have therefore been applied after 80 years (Olesen & Damgaard, 2014).

Leachate treatment

The leachate treatment in EASETECH is modelled using the data from a wastewater treatment plant situated in Denmark. The plant uses primary sedimentation and a secondary treatment process utilizing a biological nitrogen removal process. Primary and secondary sludge is used in anaerobic digesters and the biogas is utilized for electricity and heat consumption on site. Digested sludge is dewatered, dried, and incinerated. Emissions to air cover the air emissions during wastewater treatment, during biogas utilization and emissions during sludge incineration. Emissions to water cover the effluent from the wastewater treatment and the reject water from dewatering the sludge. It is assumed the dewatered sludge is applied to industrial soil after incineration (Olesen & Damgaard, 2014).

The data for energy for biological and mechanical treatment and pumps and the data for water use are taken from literature (Olesen & Damgaard, 2014). In addition, electricity is substituted in that process due to the anaerobic digestion of the sludge of the wastewater treatment plant, whereby organic matter is converted into biogas. The production of methane is indicative of organic matter degradation and chemical oxygen demand (COD) removal. Higher CH_4 production rates generally correlate with more effective COD removal. The percentage of COD utilized, expressed as COD removal rate, is assumed to be of 94.5% and is taken from Yoshida et al., (2015). The rate of energy used for electricity production (90%) and the energy content per kg of COD (3.48 kWh/kg COD) are taken from literature (Olesen & Damgaard, 2014). The electricity substituted is assumed to substitute part of the Region of Waterloo's grid.

4.5.7.3. Carbon storage of slow-degradable portion of MSW

The slow-degradable waste is stored and is assumed to have no interactions with the surrounding environment. Consequently, the sole environmental impact associated with this module is the assumption

that all slow degradable carbon is contained, thus regarded as sequestered. This implies a carbon-saving effect, counted as a negative emission of carbon (Olesen & Damgaard, 2014).

4.5.7.4. LCI table of landfill

The input and output flows of the landfilling module are summarized in the LCI Table 33. The input consists of the MSW from both residential black garbage as well as the MRF residuals generated post-sorting. Additionally, some substances are added to account for the new organic substances generated as the waste decays, which are not part of the original flows. The treatment of leachate requires energy inputs, which are summarized in the table. The outputs consist of the following: electricity from waste decay and electricity from leachate treatment in a wastewater treatment plant coupled with AD.

Table 33: LCI for landfilling per 1 ton of total MSW managed (per 1 Functional unit)

Flows	Values	Unit	Reference
INPUTS			
Landfilled waste per ton of MSW managed in the Region			
Newsprints	19.6	***kg***	*CIF audit urban regional data - 2021*
Papers	16.8	***kg***	*CIF audit urban regional data - 2021*
Paper and carton containers	6.9	***kg***	*CIF audit urban regional data - 2021*
Magazines	1.7	***kg***	*CIF audit urban regional data - 2021*
Milk cartons (carton/plastic)	1.4	***kg***	*CIF audit urban regional data – 2021*
Juice cartons (carton/plastic/aluminium)	0.5	***kg***	*CIF audit urban regional data - 2021*
Cardboard and paperboard	26.9	***kg***	*CIF audit urban regional data - 2021*
Plastic packaging (PET)	6.1	***kg***	*CIF audit urban regional data - 2021*
Plastic packaging (HDPE)	3.3	***kg***	*CIF audit urban regional data - 2021*
Plastic packaging (PP)	7.7	***kg***	*CIF audit urban regional data - 2021*
Plastic packaging (PS)	1.6	***kg***	*CIF audit urban regional data - 2021*
Plastic packaging (Expanded PS)	2.8	***kg***	*CIF audit urban regional data - 2021*
Soft plastic	36.4	***kg***	*CIF audit urban regional data - 2021*
Hard plastic	6.2	***kg***	*CIF audit urban regional data - 2021*
Aluminum foil and containers	0.4	***kg***	*CIF audit urban regional data - 2021*
Beverage cans (aluminium)	2.9	***kg***	*CIF audit urban regional data - 2021*
Aluminium foil - Residual waste	3.7	***kg***	*CIF audit urban regional data - 2021*
Food cans (tinplate/steel)	1.6	***kg***	*CIF audit urban regional data - 2021*
Non-packaging metal (Fe)	3.5	***kg***	*CIF audit urban regional data - 2021*
Metal packaging (Fe)	0.5	***kg***	*CIF audit urban regional data - 2021*
Clear glass	6.0	***kg***	*CIF audit urban regional data - 2021*
Glass packaging (brown) - Residual waste	2.1	***kg***	*CIF audit urban regional data - 2021*
Other/special glass - Residual waste	5.4	***kg***	*CIF audit urban regional data - 2021*
Batteries	0.8	***kg***	*CIF audit urban regional data - 2021*
Animal-derived food waste - Residual waste	55.4	***kg***	*CIF audit urban regional data - 2021*
Vegetable food waste	55.4	***kg***	*CIF audit urban regional data - 2021*
Branches, Garden waste, Aarhus 2007	7.4	***kg***	*CIF audit urban regional data - 2021*
Tissue paper - Residual waste	34.1	***kg***	*CIF audit urban regional data - 2021*
Animal bedding - Residual waste	21.9	***kg***	*CIF audit urban regional data - 2021*
Animal excrements-dog - Residual waste	21.9	***kg***	*CIF audit urban regional data - 2021*
Disposable sanitary products	0.8	***kg***	*CIF audit urban regional data - 2021*
Other combustibles	72.1	***kg***	*CIF audit urban regional data - 2021*
Other non-combustibles	72.1	***kg***	*CIF audit urban regional data - 2021*
Non-packaging plastic (id 7-19)	9.1	***kg***	*CIF audit urban regional data - 2021*
Addition of substances			
Phenol	0.05	***g***	*EPA 2008 AP 42, Fifth Edition, Volume I Chapter 2: Solid Waste Disposal*
CO	1.34	***g***	*EPA 2008 AP 42, Fifth Edition, Volume I Chapter 2: Solid Waste Disposal*
Dichlorobenzene	0.29	***g***	*EPA 2008 AP 42, Fifth Edition, Volume I Chapter 2: Solid Waste Disposal*
Ethylchloride	0.48	***g***	*EPA 2008 AP 42, Fifth Edition, Volume I Chapter 2: Solid Waste Disposal*

Chloromethane	0.01	***g***	*EPA 2008 AP 42, Fifth Edition, Volume I Chapter 2: Solid Waste Disposal*
Naphtalene	0.03	***g***	*EPA 2008 AP 42, Fifth Edition, Volume I Chapter 2: Solid Waste Disposal*
Hg	0.00	***g***	*EPA 2008 AP 42, Fifth Edition, Volume I Chapter 2: Solid Waste Disposal*
H2S	1.92	***g***	*EPA 2008 AP 42, Fifth Edition, Volume I Chapter 2: Solid Waste Disposal*
NMVOC	1.44	***g***	*EPA 2008 AP 42, Fifth Edition, Volume I Chapter 2: Solid Waste Disposal*
VC	0.19	***g***	*EPA 2008 AP 42, Fifth Edition, Volume I Chapter 2: Solid Waste Disposal*
TCE	0.19	***g***	*EPA 2008 AP 42, Fifth Edition, Volume I Chapter 2: Solid Waste Disposal*
PCE	0.48	***g***	*EPA 2008 AP 42, Fifth Edition, Volume I Chapter 2: Solid Waste Disposal*
Benzene	0.38	***g***	*EPA 2008 AP 42, Fifth Edition, Volume I Chapter 2: Solid Waste Disposal*
Chlorobenzene	0.10	***g***	*EPA 2008 AP 42, Fifth Edition, Volume I Chapter 2: Solid Waste Disposal*
Ethylbenzene	0.96	***g***	*EPA 2008 AP 42, Fifth Edition, Volume I Chapter 2: Solid Waste Disposal*
Propylbenzene	0.10	***g***	*EPA 2008 AP 42, Fifth Edition, Volume I Chapter 2: Solid Waste Disposal*
Dichloromethane	0.96	***g***	*EPA 2008 AP 42, Fifth Edition, Volume I Chapter 2: Solid Waste Disposal*
Chloroform	0.01	***g***	*EPA 2008 AP 42, Fifth Edition, Volume I Chapter 2: Solid Waste Disposal*
Carbon tetrachloride	0.00	***g***	*EPA 2008 AP 42, Fifth Edition, Volume I Chapter 2: Solid Waste Disposal*
Xylenes	1.92	***g***	*EPA 2008 AP 42, Fifth Edition, Volume I Chapter 2: Solid Waste Disposal*
Toluene	5.28	***g***	*EPA 2008 AP 42, Fifth Edition, Volume I Chapter 2: Solid Waste Disposal*
CFC11	0.05	***g***	*EPA 2008 AP 42, Fifth Edition, Volume I Chapter 2: Solid Waste Disposal*
CFC12	0.24	***g***	*EPA 2008 AP 42, Fifth Edition, Volume I Chapter 2: Solid Waste Disposal*
CFC113	0.02	***g***	*EPA 2008 AP 42, Fifth Edition, Volume I Chapter 2: Solid Waste Disposal*
HCFC21	0.48	***g***	*EPA 2008 AP 42, Fifth Edition, Volume I Chapter 2: Solid Waste Disposal*
HCFC22	0.14	***g***	*EPA 2008 AP 42, Fifth Edition, Volume I Chapter 2: Solid Waste Disposal*
Leachate treatment			
Process water	4.34E-05	***kg***	*EASETECH ; Yoshida, H. and Clavreul, J. (n.d.) Supporting Material. Unpublished manuscript*
Electricity	0.60	***kWh***	*EASETECH ; Yoshida, H. and Clavreul, J. (n.d.) Supporting Material. Unpublished manuscript*
OUTPUTS			
Electricity from gas collected	69.7	***kWh***	Average Output Electricity data from Region of Waterloo database in 2021
Electricity from leachate treatment	2.96	**kWh/kg COD**	EASETECH ; Yoshida, H. and Clavreul, J. (n.d.) Supporting Material. Unpublished manuscript

4.6. Life Cycle Inventory used in EASETECH model – Scenario 2

This section outlines the inventory used to model the WtE scenario, whereby the garbage waste goes to an incinerator with electricity recovery and the organic waste goes through an anaerobic digestor with heat and electricity generation as well as a digestate product. The sole processes changed are the landfill and the composting. Thus, the modelling and LCI of other processes are assumed to be similar to the ones described in the BAU modeling section.

4.6.1 Incinerator

The LCI of the incinerator process is presented in Table 34. The incinerator process on EASETECH describes a generic Danish incineration plant in 2012. The flue-gas cleaning system is based on a WtE plant situated in Denmark in 2011. The technology modelled is a grate incinerator with wet flue gas cleaning that takes the MSW as an input and generates fly ash, iron scraps, aluminum, wastewater, bottom ash and cleaned flue gas as outputs.

The flue gas cleaning system uses chemicals in order to get rid of the pollutants present in the gas prior to release. Nitrogen oxide is removed with selective noncatalytic reduction and dioxin, and mercury is removed with activated carbon. Moreover, the wastewater generated is assumed to go through wastewater treatment. The process for wastewater treatment is imported from Ecoinvent 3.9.1 and is representative of Quebec between 2010 to 2023.

In this study, no bottom ash was reused. Instead, the bottom ash was assumed to be landfilled in an area next to the incinerator. The incineration plant is characterized by a separation efficiency of 50% for Aluminum and 80% for iron. Iron scrap and aluminum are recovered from the bottom ash and are assumed to go to a recovery facility. Since the fly ash is assumed to be hazardous, and there are specific regulations for the handling of hazardous waste in Canada, the fly ash is assumed of be used as a backfilling material for salt mining. In Canada, some of the facilities ship their fly ash to hazardous landfills in the US while others re-use it in other sectors such as in construction and mining (LaFarge, 2023). The data of the process on EASETECH is representative of the technology in Germany in 2006 (T. Astrup, 2008; Fruergaard, Hyks, et al., 2010).

The flue gas enters a boiler in order to recover the main product: steam. The steam then goes through a turbine to generate the electricity. The electricity produced by the incinerator is assumed to be connected to the district electricity grid. The electrical efficiency is set equal to 27%. The power generation efficiency of the conventional incinerators is between 20% and 32% (Ding et al., 2021). In an LCA study of an incinerator scenario for MSWM in Toronto, the chosen incinerator electricity recovery efficiency was 20 %, which was considered conservative by the authors (Assamoi & Lawryshyn, 2012). Thus, the 27 % electricity efficiency is a middle case scenario in that case.

Table 34: LCI table for incinerator (for 1 Functional unit)

Flows	Value	Unit	Reference
INPUTS			
MSW	515	kg	*CIF urban regional study 2021*
TMT 15	0.20	kg	*(Møller et al., 2013)*
Sodium hydroxide	1.24E-02	kg	*(Møller et al., 2013)*
Hydrogen chloride gas (HCl)	2.88E-03	kg	*(Møller et al., 2013)*
Calcium carbonate, limestone, $CaCO_3$ > 63 microns	2.92	kg	*(Møller et al., 2013)*

Process water from surface water	204.45	kg	*(Møller et al., 2013)*
Polyethylene high density granulate	3.09E-04	kg	*(Møller et al., 2013)*
Hydrated Lime	0.17	kg	*(Møller et al., 2013)*
Activated Carbon	0.53	kg	*(Møller et al., 2013)*
Ammonia (NH_3)	0.79	kg	*(Møller et al., 2013)*
OUTPUTS			
Fly ash	13.6	kg	*EASETECH mass flow*
Steel	1.6	kg	*EASETECH mass flow*
Aluminum	1.1	kg	*EASETECH mass flow*
Bottom Ash	91.7	kg	*EASETECH mass flow*
Electricity	450	kWh	*EASETECH mass flow*

4.6.2. Anaerobic Digestion

4.6.2.1. Technology Description

The LCI of the AD is summarized in Table 35 in section 4.6.2.4. For the anaerobic reactor digestion of municipal organic solid waste, the model selected for the study is a thermophilic one stage wet reactor. In one stage process, the initial hydrolysis and acidification takes place in the same reactor vessel as the methane production. The wet process has moisture content above 90%. The digestion temperature is typically around 53 - 55 °C for thermophilic digestion.

The technology dataset is constructed from measured data from a number of European biogas plants in 2007.

The following processes are used to model the biogas production:

1. Energy use for heating the reactor to thermophilic temperature of 55 °C: Heat needed to increase the temperature of water and food waste to 55 °C, assuming outside average temperature in the Region of Waterloo is 8 °C (Mahler, 2023). It is assumed that 90 % of the wet weight is water, and 10% wet weight is comprised of organic waste. Thus, the following two equations represent the energy required for this heating process:

Energy required to heat the water (MJ/kg wet weight) = (55°C -8°C) x 4.2 J/g°C. x 0.9/1000

Energy required to heat the solids (MJ/kg wet weight) = (55°C -8°C) x 3 J/g°C x 0.1 /1000

2. Diesel to operate machinery at the plant.
3. Electricity needed for pumps and ventilators.

4.6.2.2. Biogas production

The process describes a generic Danish stationary engine combustion plant in 2013 and is modeled as per the Danish emission inventory for stationary combustion plants (Nielsen et al., 2018). It is assumed that 2 % of the methane is leaked while the rest is converted into biogas through a stationary engine combustion process. It is assumed that the system is a combined heat and power system with an average electrical efficiency of 39% and an average heat efficiency of 51% (Malet et al., 2023). The electricity produced

substitutes electricity of the grid in the Region of Ontario, which is modelled using a set of Ecoinvent processes specific to Ontario's grid. The heat produced substitutes natural gas, which is modelled using a process specific to Ontario, imported from Ecoinvent.

For the process specific emissions, the emission factors of the engine combustion are based on the CORINAIR system, which is the Emission Inventory tools by European Environmental Agency (EEA) and European Topic Centre on Air and Climate Change (ETC-ACC) (Corinair, 2024).

4.6.2.3. Digestate modelling

The moisture content of the waste coming into the reactor is increased to reach a value higher than 85 % (Rosenheim et al., 2015). The substitution process consists of two main processes on EASETECH. The first one is the modeling of the product that is to be substituted: the digestate used on land. The process used is representative of the average crop rotation in Denmark during 2015. The agricultural profile describes the emissions to air, surface water, groundwater and soil accumulation from land application of composted organic fraction of MSW on coarse sandy soil with average Danish crop rotation with nitrogen application rate. Data on the amount of diesel required for sludge spreading as well as the emission rate of methane are provided from literature (Ambus et al., 2001; Bernstad & la Cour Jansen, 2011; Bruun et al., 2006).

The use of digestate on land was assumed to displace marginal mineral fertilizer. The substitution factors are modified since it is assumed that mineral fertilizers and digestate are not perfect substitutes. The substitution ratios used are the following: 85% for Nitrogen, while for Phosphorus and Potassium it was 100% (Viau et al., 2020).

4.6.2.4. LCI of AD

The LCI of AD is presented in Table 39. Input flows represent the flows needed to undergo AD as well as to model the use on land of the digestate. The outputs represent the products of the AD process, mainly energy and digestate.

Table 35: LCI of anaerobic digestion of organic waste (per 1 Functional unit)

Flow	Amount	Unit	Reference
INPUTS			
Biogas production			
Organic waste	320	kg	*CIF urban regional audit*
Wheel loader	0.3	L	*EASETECH from average biogas plant in Europe*
Electricity	16	kWh	- *Value from EASETECH from average biogas plant in Europe* - *Process specific to Canada (Ontario) from Ecoinvent 3.9.1.*
Natural gas - heat up water	57	MJ	- *Value from EASETECH from average biogas plant in Europe* - *Process specific to Canada (Ontario) from Ecoinvent 3.9.1.*
Natural gas - heat up solids	5	MJ	- *Value from EASETECH from average biogas plant in Europe* - *Process specific to Canada (Ontario) from Ecoinvent 3.9.1.*
Digestate use on land			
Process Water	0.9	kg	*Mass flow on EASETECH*
Farm tractor, combustion of diesel	2.1	L	*(Bernstad & la Cour Jansen, 2011)*
OUTPUTS			
Electricity	103	kWh	*Mass and energy flow EASETECH*

Heat	486	MJ	*Mass and energy flow EASETECH*
Digestate	277	kg	*Mass flow EASETECH*
N content in digestate	2.50	kg	*Mass flow EASETECH*
P content in digestate	0.56	kg	*Mass flow EASETECH*
K content in digestate	0.85	kg	*Mass flow EASETECH*
Substitution of fertilizer by digestate			
Farm tractor, diesel, N fertilizer	-0.0250	L	*(Bernstad & la Cour Jansen, 2011)*
Farm tractor, diesel, P fertilizer	-0.0056	L	*(Bernstad & la Cour Jansen, 2011)*
Farm tractor, diesel, K fertilizer	-0.0085	L	*(Bernstad & la Cour Jansen, 2011)*
Substitution of K2O fertilizer	100	%	*(Viau et al., 2020)*
Substitution of P2O5 fertilizer	100	%	*(Viau et al., 2020)*
Substitution of N fertilizer	85	%	*(Viau et al., 2020)*

4.7. Life Cycle Inventory used in EASETECH model- Scenario 3

The EPR program in Ontario incentivizes producers to improve resource efficiency by optimizing the supply chain of their products from resource extraction to resource recovery. The EPR Ontario regulation made under the Resource Recovery and Circular Economy act in 2016 sets new recovery targets for the province. The recovery rate for individual materials is calculated by dividing the total weight of recyclable materials sorted and leaving a MRF by the total weight of specific individual materials supplied to the marketplace. Specifically for Blue Box materials, their recovery rates are computed by dividing the amount of material recycled through Ontario municipal recycling programs by the amount generated in Ontario households. All information required to compute the recycling efficiencies required to meet the targets is included in the Supplementary Information 2 Excel document, in the EPR scenario sheet. Estimates of material generation are from CIF audits on curbside waste composition, which is the most comprehensive dataset as it encompasses all materials recovered throughout the year, mandated by municipalities (Stewardship Ontario, 2013).

Table 36 presents the recovery targets included in the regulation. The targets are divided into two timeframes: the first targets set for 2026 are more conservative than the second ones set for 2030. The materials are divided into the following six categories:

1. Paper: any type of paper (i.e. magazines, newspapers, carton containers…).
2. Rigid plastic: any type of plastic that is molded (i.e. food or product container made of HDPE or PET).
3. Flexible plastic: This type of plastic is usually used for the handling and delivery of a thing; the product is ordinarily disposed of after a single use; the product is not used as packaging when it is with the end user (i.e. plastic bag, film, wrap, pouch, or laminate).
4. Glass: this category excludes the beverage glass containers.
5. Metal: this category excludes the beverage metal containers.
6. Beverage containers: These types of containers contain a ready-to-drink beverage product; they are made from metal, glass, paper or rigid plastic, or any combination of these materials; they are sealed by the manufacturer.

Table 36: EPR recovery rates 2030 targets in ON (Ontario, 2021a)

Material category	Recovery percentage (2026 – 2029)	Recovery percentage (2030 onwards)
Paper	80	85
Rigid Plastic	50	60
Flexible Plastic	25	40
Glass	75	85
Metal	67	75
Beverage Containers	75	80

In Table 37, the current recovery targets are computed. These targets represent the ones achieved in a BAU scenario. The glass material section is not included in the table since this material is currently not recovered and not sent to suppliers but is instead used on-site as material for landfilling. To model the scenario with the new EPR targets, one of the following parameters should be changed: weight of generated waste, which is representative of the waste supplied to the market by the producers within a specific year, and/or the weight of marketed waste that is collected from households, sorted in an MRF, and then sent for recovery to recycling facilities. For this study, the parameter that is modified is the marketed tons of MSW that is sent to recovery facilities. This amount is directly related to the recycling efficiency of the MRF during the sorting process of the waste. The required amounts of marketed material for each material category to meet the recovery requirements are summarized in Table 38.

Table 37: Current recovery targets calculated using the BAU data. The generated tons are from the CIF urban regional studies. The marketed tons are computed using the Region of Waterloo data of the tons of materials leaving the MRF post sorting. The recovery rate is found by dividing the marketed by the generated.

CURRENT MODEL - BAU				
Material category	**Generated (tons)**	**Marketed (tons)**	**BAU Recovery rate (%)**	**Recovery Target (2026-2029)**
Mixed papers	23763	16084	**68%**	80%
Rigid Plastic	8843	2980	**34%**	50%
Flexible plastic	6426	976	**15%**	25%
Metal	2686	1513	**56%**	67%
Beverage container	2756	1585	**58%**	75%

Table 38: Recovery targets under an EPR scenario. The marketed tons for each material category are increased to meet the recovery requirement

EPR model (Altering the marketed tons)				
Material category	**Generated (tons)**	**Marketed (tons)**	**EPR scenario Recovery rate (%)**	**Recovery Target (2026-2029)**
Mixed papers	23763	18979	80%	80%
Rigid Plastic	8843	4368	49%	50%
Flexible plastic	6426	1658	26%	25%
Glass	5601	4659	83%	75%
Metal	2686	1850	69%	67%
Beverage container	2756	2041	75%	75%

To achieve the targets summarized in Table 38, the flow of sorted materials is increased to reach the amounts shown in the "marketed" column of the Table. Thus, the recycling efficiencies at the MRF should also be increased. The efficiencies required to be met at the MRF are summarized in Table 39.

Table 39: Recycling efficiencies percentages needed at the MRF in order to reach the EPR recovery targets

Material category	Input of MRF (collected waste) (tons/yr)	Output of MRF (sorted waste=marketed) (tons/yr)	Recycling efficiency (%) at MRF	% of material going to landfill
Mixed paper	18913	18979	**100%**	0%
Polycoat containers	1014	620	**61%**	39%
PET bottle	2734	2728	**100%**	0%
HDPE bottles	915	910	**99%**	1%
Mixed plastic	4643	3317	**71%**	29%
Mixed glass	4887	4659	**95%**	5%
Aluminum cans	1111	1071	**96%**	4%
Steel cans	1289	1272	**99%**	1%

4.7.1. Life Cycle Inventory used in Scenario 3

The life cycle inventory used in Scenario 3 is included in the Supplementary Information 3 (MS Excel File). The only inventory tables included in the Excel sheet are related to the recycling processes that take place after sorting of the MSW. Since the only change is related to the recycling efficiencies of Scenario 3, the other inventories of the processes of landfilling and composting are similar to those presented in Scenario 1. As for the recycling processes, the flows and data sources included in the LCI tables are the same as those modelled in Scenario 1. However, the quantification of the flows changes due to an increase in the quantity of material recycled, as presented in Table 39.

Chapter 5: Results

This study performed LCA of three MSWM scenarios: the BAU scenario (Scenario 1), the WtE scenario (Scenario 2), and the EPR targets scenario (Scenario 3). First, the study evaluated the environmental impacts of these scenarios in terms of their carbon footprint, measured in kilograms of CO_2 eq based on the GWP indicator over a 100-year timeframe, as per the IPCC 2021 guidelines. The GWP100 was selected as the basis for comparison due to its widespread adoption in LCA studies and the LCI of the landfill considering a 100 years' cutoff for emissions. Second, the air quality and water quality indicators that are relevant to the Canadian Sustainability Indicators mentioned in section 4.4 are studied. In specific, the particulate matter formation, the photochemical ozone formation, and the eutrophication are assessed using Traci 2.1 model.

Considering the GWP100 indicator results among all scenarios, the impact of Scenario 2 is the highest with 88 kg CO_2 eq per FU. In Scenario 2, the process related to the combustion of waste in the incinerator heavily contributes to the GWP100 (303 kg CO_2 eq per FU). The avoided burdens from the electricity production (-84.5 kg CO_2 eq per FU) from the combustion process do not offset the impacts associated with the incinerator. Comparatively, achieving the EPR targets in Scenario 3 results in an impact of -80 kg CO_2 eq per FU, i.e. 130 % less than Scenario 1. By performing a process contribution analysis, it is found that the results achieved in Scenario 3 are attributable to the avoided burdens from the substitution of recyclables. Moreover, in Scenario 3, the assumption that a fraction of the biodegradable carbon is stored in the landfill, leading to delayed emissions, results in a significant decrease in GWP100 impact (-139 kg CO_2 eq per FU).

Considering the PM2.5 impact category, the three scenarios result in avoided burdens (-0.11 kg PM2.5 per FU in Scenario 1; -0.12 kg PM2.5 per FU in Scenario 2; -0.15 kg PM2.5 per FU in Scenario 3). The virgin material production of products results in PM2.5 due to the combustion sources in industrial facilities. Hence, the production of secondary materials offsets the negative impact from PM2.5.

Considering the photochemical ozone formation impact category, the impact is the highest in Scenario 2 (6 kg O_3 eq per 1 FU) and the lowest in Scenario 3 (-6 kg O_3 eq per 1 FU). By analyzing the hotspots of Scenario 2, it can be found that the incinerator process and the biogas generation of the AD contribute to 11 kg O_3 eq per 1 FU and 5 kg O_3 eq per 1 FU, respectively. The AD plant has a stationary engine combustion plant that generates biogas, which leads to NO_x emissions. The incinerator has a wet flue gas cleaning system and uses selective non catalytic reduction to reduce nitrogen oxides emissions but still results in the photochemical ozone formation impact mentioned. In Scenario 3, the two biggest hotspots are instead from recycling activities (5 kg O_3 eq per 1 FU) and the electricity generation in the landfill (3

kg O_3 eq per 1 FU). The process contribution analysis of Scenario 3 shows that the avoided burdens resulting from the substitution of virgin material production (-14 kg O_3 eq per 1 FU) outweigh the negative impacts discussed, resulting in an overall saving.

Considering the eutrophication impact category, the result is the highest in Scenario 2 (0.06 kg N eq per FU) and the lowest in Scenario 1 (-0.36 kg N eq per FU). The use on land of compost (Scenario 1) contributes to 0.07 kg N eq of the impacts, while the use on land of the digestate (Scenario 2) contributes to 1.02 kg N eq of the impacts. The difference is explained by a difference in N:P:K (6:1:2 for digestate v.s. 2:1:6 for compost) ratio among the two products as well as the higher bio-available nitrogen in the digestate compared to compost. Detailed results are presented in the sections below.

5.1. Global Warming Potential (GWP 100)

Figure 8 presents the characterized GWP100 results for the three scenarios. Scenario 2 is the scenario with the highest emissions of around 90 kg CO_2 eq. Scenarios 1 and 3, involving landfilling, resulted in avoided burdens of approximately -35 kg CO_2 eq and -80 kg CO_2 eq, respectively.

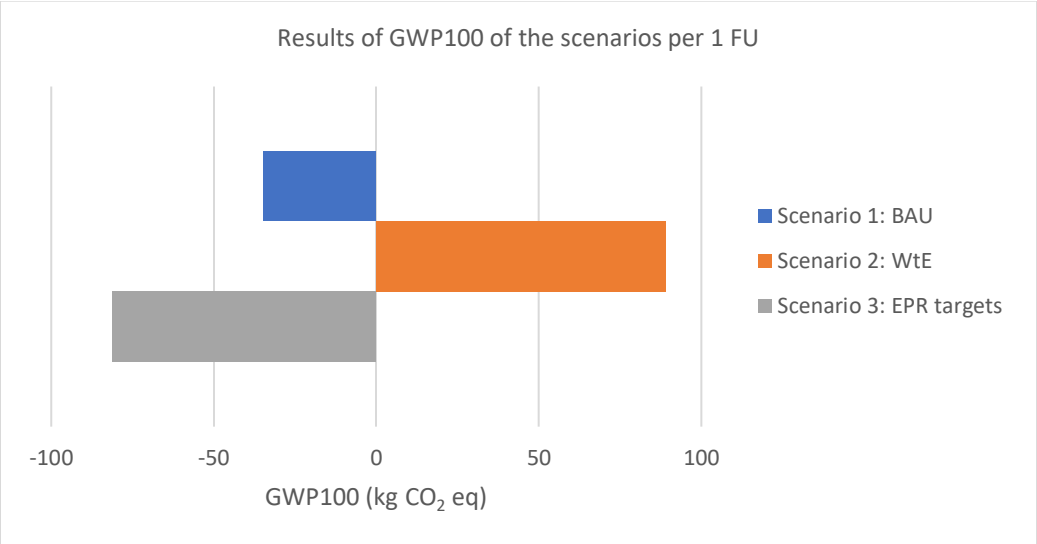

Figure 8: Results of GWP100 for the three scenarios (IPCC 2021 method)

5.1.1. Process Contribution Analysis of Global Warming Potential 100 for each of the scenarios

The process contribution analysis of Scenario 1 is shown in Figure 9. The analysis is presented using a waterfall chart, where all the negative environmental impacts are shown as a positive sign and color-coded in red, while all the savings have a negative sign and color-coded in blue. The net total impact is represented in the bar at the right end and is color-coded in black.

The majority of emissions within the Scenario 1 were from the following two sources:

1. Methane emissions from landfill sites (73% of total emissions), which emerge because of the organic material decomposition.
2. Recycling of blue box materials (16 % of total emissions). The recovery of blue box materials requires a substantial amount of energy, and thus contributes greatly to the GWP.

However, significant avoided burdens were observed due to the following two processes:

1. Long-term storage of slow-degradable carbon within landfills (49% of total savings): Under natural conditions, nearly all organic material would decompose aerobically, releasing carbon as biogenic CO_2. The carbon in the materials that do not fully decompose is effectively removed from the global carbon cycle, referred to as being stored. As per IPCC guidelines, the capture of biogenic CO_2 emissions from processes such as biomass combustion should be managed in the same manner as CO_2 capture from fossil fuel combustion. Hence, emissions and storage of both should be estimated and reported (IPCC, 2024). The waste composition of the Region of Waterloo has a significant amount of non-easily degradable carbon (i.e. paper, wood etc.), which gives the sequestration credit, whereas the degradation of fast degradable carbon, such as the carbon available in food waste, degrades and contribute to emissions.
2. The substitution of virgin material production through the recycling (45% of total savings): Substituting virgin materials with recycled ones reduces the emissions coming from extraction, processing, and manufacturing of new materials. By using recycled materials instead, the environmental burden associated with the initial extraction and production stages is avoided, leading to an offset in emissions and energy consumption. Recycling often requires less energy compared to the production of virgin materials. For instance, recycling aluminum requires significantly less energy than producing it from bauxite ore (Raabe et al., 2022). This reduced energy demand translates into lower GHG emissions, contributing to savings in GWP.

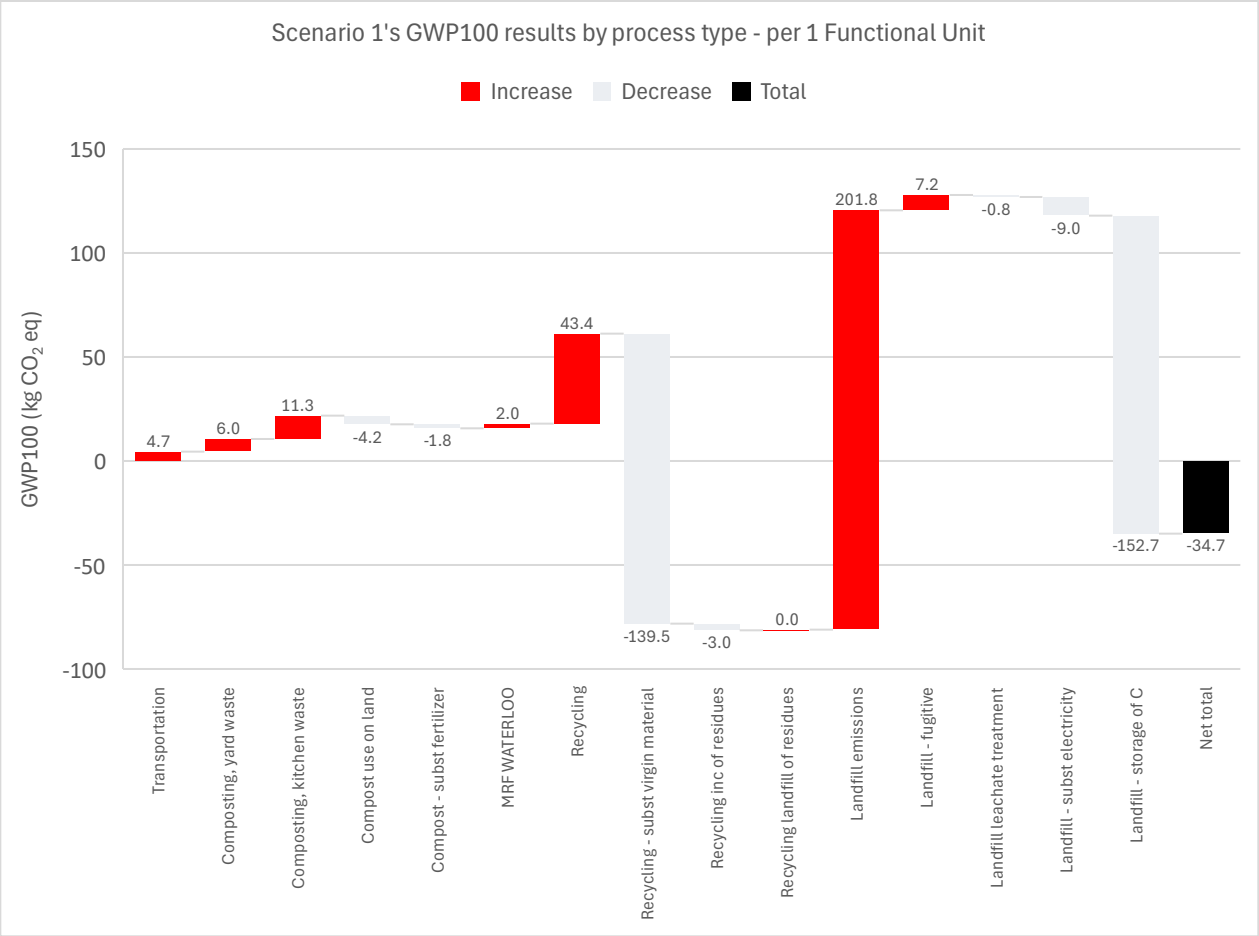

Figure 9: Process contribution analysis of the GWP100 of Scenario 1

The process contribution analysis of Scenario 2 is shown in Figure 10. The highest emissions within the WtE scenario were from the following two sources:

1. Emissions from incinerator combustion process (77% of total burdens).
2. Recycling of blue box materials at the recovery facilities (12 % of total burdens).

The biggest two savings were achieved through the following two steps:

1. The substitution of virgin material production through the use of recyclables (52% of total).
2. The substitution of electricity offsets the need for electricity from other sources included in the Region of Waterloo's energy mix (28% of total savings).

Since the MSW contains a significant amount of non-easily biodegradable materials, the inclusion of the carbon sequestration in the landfilling model of the BAU case study makes the landfilling of waste advantageous over its incineration. In the incineration scenario, the electricity savings are not sufficient to

offset the emissions arising from the combustion of MSW. However, it is important to note the difference in electricity savings between scenarios 1 (-9 kg CO_2 eq) and 2 (-84.5 kg CO_2 eq), which is derived from the fact that the incinerator can produce more energy due to energy content of the waste that contains a significant amount of materials with high LHV (i.e. plastics).

Moreover, the use of an AD to manage organic waste offers positive impacts on the GWP. The substitution of heat and electricity from CHP system of the AD leads to an overall saving of 35 kg CO_2 eq to the net GWP100 impact of this scenario. In addition, another 25 kg CO_2 eq of savings are achieved due to the substitution of fertilizer with the digestate. The yield of total solids available in the digestate is 1.5 times larger than that achieved with the compost (39 kg total solids from composting in the BAU scenario versus 101 kg total solids from AD in scenario 2). In addition, the substitution ratio assumed for the nitrogen fertilizer is higher in the case of the digestate (85%) versus the compost (65%) due to the higher bioavailability of the nitrogen in the digestate. Nevertheless, the savings achieved with the WtE scenario are not sufficient to offset the incinerator's emissions, which leads to a total net positive result of 89 kg CO_2 eq.

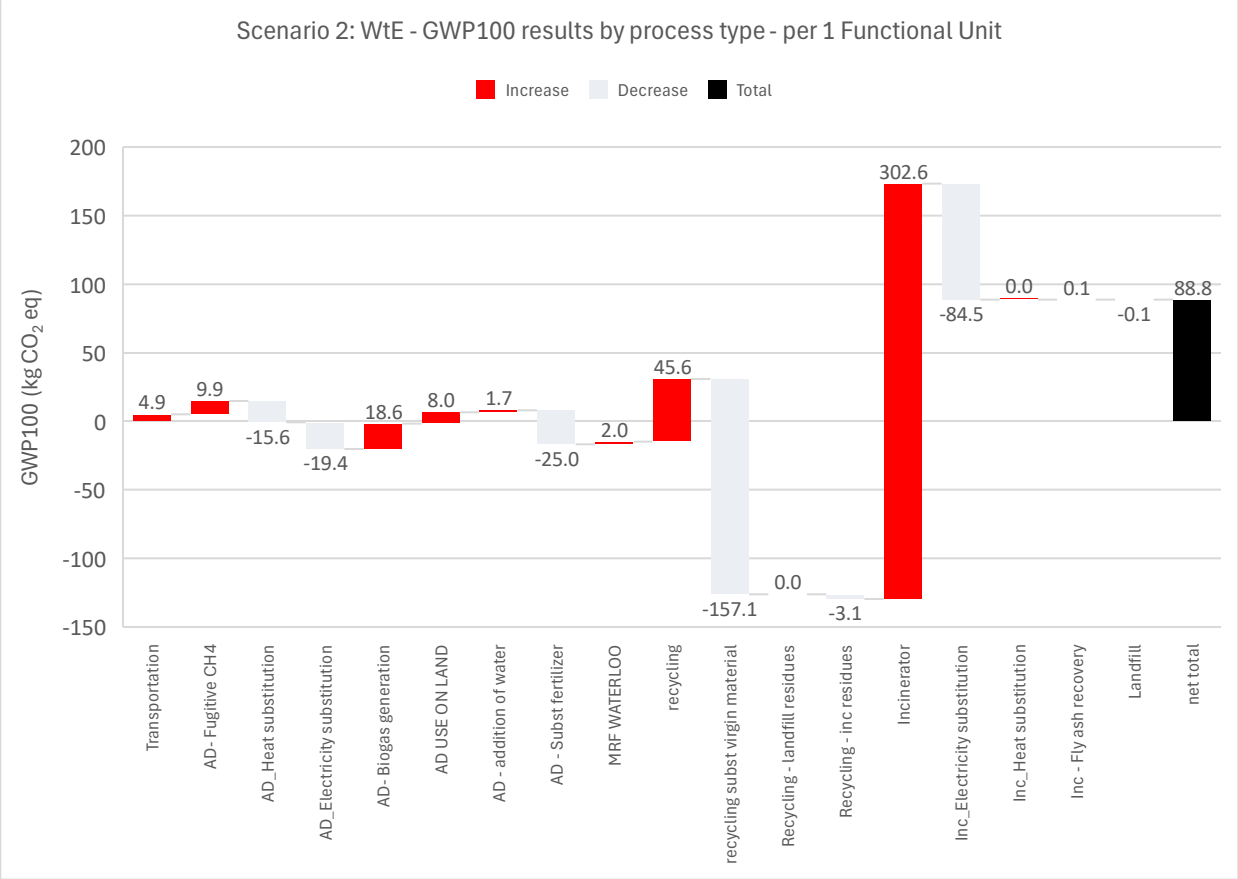

Figure 10:Process contribution analysis of GWP 100 results of Scenario 2

The results of Scenario 3 are presented in Figure 11. The offsets achieved in the EPR targets are 134% higher than those achieved in Scenario 1. The avoided impacts are attributed to the following two processes:

1. Increase in savings from substitution of virgin material production by 50 %, from -139 kg CO_2 eq to -209 kg CO_2 eq, relative to Scenario 1. More specifically, glass is not being recovered and substituted into a new product in Scenario 1. In Scenario 3, the glass is recycled into packaging glass, and the substitution of glass production provides significant savings to the results.
2. Compared to Scenario 1, the landfill emissions in Scenario 3 lead to a 21% reduction considering the GWP100 indicator. With an increase in tonnage of the marketed materials getting out of a MRF to recovery facilities, the weight of recyclables residues going to landfills is reduced. Thus, less non-easily biodegradable materials (i.e. paper products) are available in the landfills, which leads to further offsets.

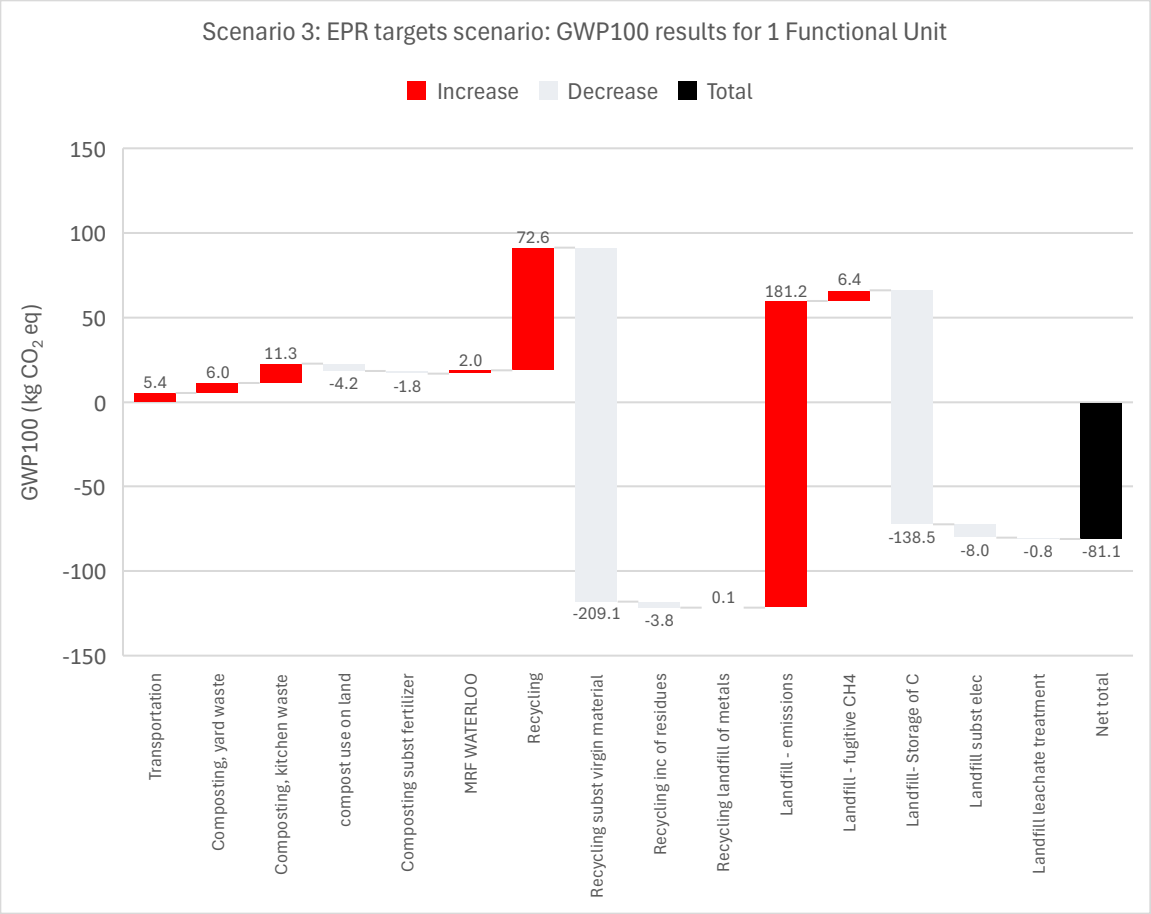

Figure 11:Process contribution analysis of Scenario 3- waterfall chart of GWP100 indicator for EPR targets scenario

5.1.2. Sensitivity analysis: Global Warming Potential 20 (GWP20)

Sensitivity Analysis 1: Results of GWP20 for the three scenarios

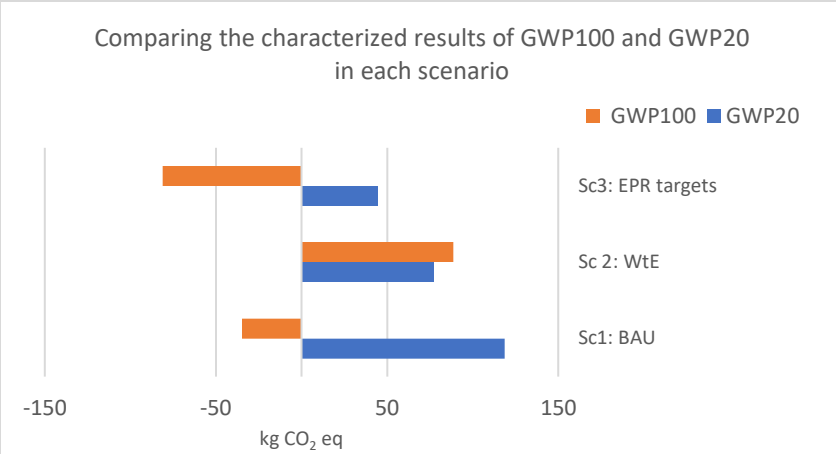

Figure 12: Sensitivity Analysis - Results of GWP100 and GWP20 of the three scenarios (IPCC 2021 method)

Figure 12 shows the first sensitivity analysis results. While the 100-year GWP is based on the "energy absorbed" by a GHG over a period of 100 years, the 20-year GWP is based on the energy absorbed by a GHG over a period of 20 years. With a GWP20, gases with shorter lifetimes in the atmosphere (i.e. CH_4 has a 12 years lifetime while CO_2 can stay for centuries) are prioritized because this indicator omits impacts that happen more than 20 years after the emissions occur (Mar et al., 2022). The GWP of Scenarios 1 and 3 become positive, signifying a negative impact on the environment. Additional savings are achieved with a GWP20 in Scenario 2.

Process Contribution Analysis of GWP20 for Scenarios 1 and 2

The process contribution analysis of the Scenario 1 is shown in Figure 13. The result of the GWP20 impact category is now positive, which signifies a burden on the environment. The highest emissions within Scenario 1 are attributed to the methane emissions from landfill sites (83% of total impacts). Over a 20-year period, one ton of methane has the same warming effect as 82 tons of CO_2. (ERCE, 2021). Thus, modelling the GWP impact of Scenario 1 with a 20-year time frame contributes to a burden of 120 kg CO_2 eq, while modelling the impact category with a 100-year time frame leads to -35 kg CO_2 eq. The pattern observed in Scenario 3 is like that observed in Scenario 1, so no process contribution chart was included for that scenario.

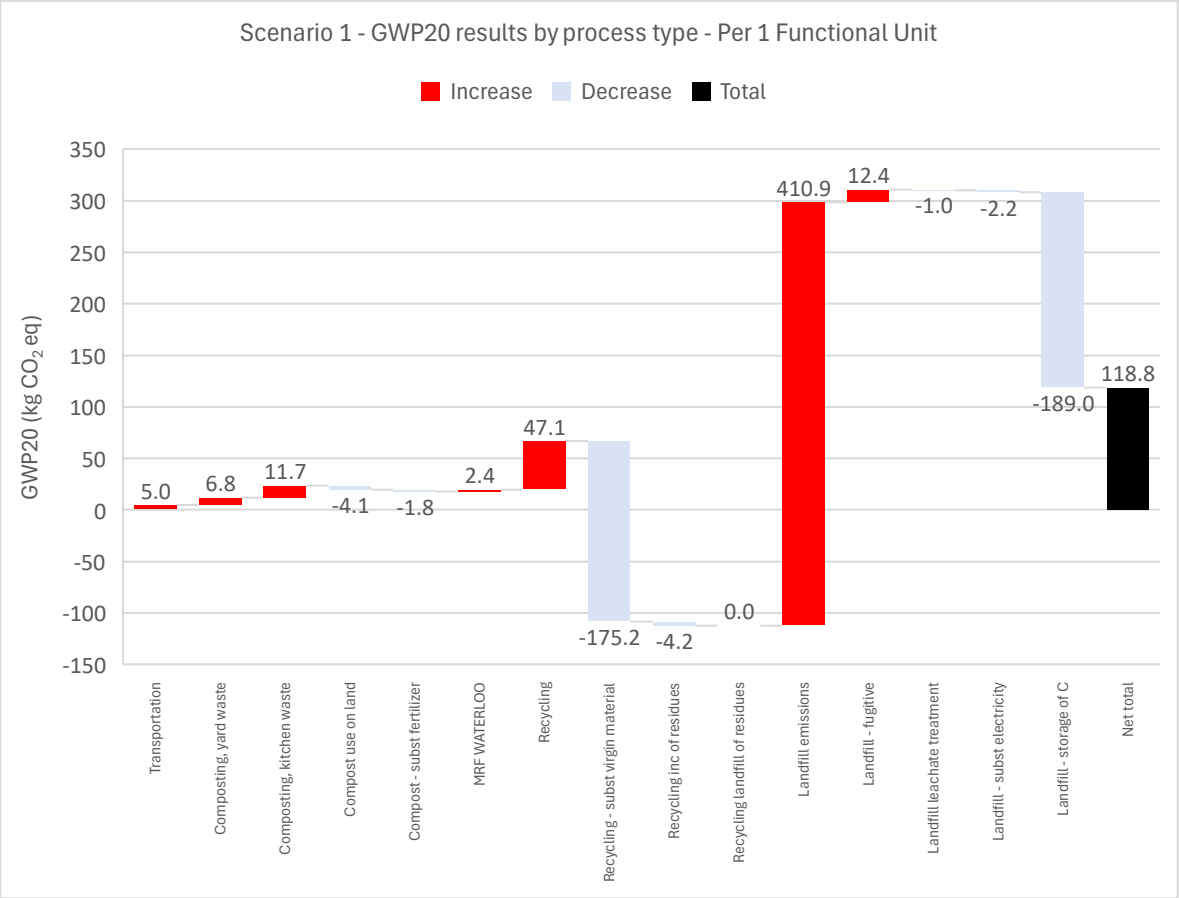

Figure 13:Process contribution analysis of GWP20 in Scenario 1

The process contribution analysis for Scenario 2 is presented in Figure 14. In that scenario, the result does not change much between the GWP100 and GWP20 (from 88.8 kg CO_2 eq to 77.3 kg CO_2 eq, respectively). The process of substitution of electricity and heat changes from -84 kg CO_2 eq with a GWP100 to -100 kg CO_2 eq with a GWP20. The substitution of virgin material production due to recyclables' recovery results in emissions savings from manufacturing plants, transportation of raw materials, or energy-intensive processes related to the production of virgin materials (i.e. plastic manufacturing, steel mill, paper mill). Over a 20-year timeframe, these emissions can contribute more significantly to the impacts compared to a 100-year timeframe.

The process of AD in Scenario 2 contributes to 18.6 kg CO_2 eq of the impacts for a GWP100, while it contributes to 42.9 kg CO_2 eq for a GWP20. The difference is attributed to the biogas generation process of AD, which releases CH_4 and N_2O to the atmosphere.

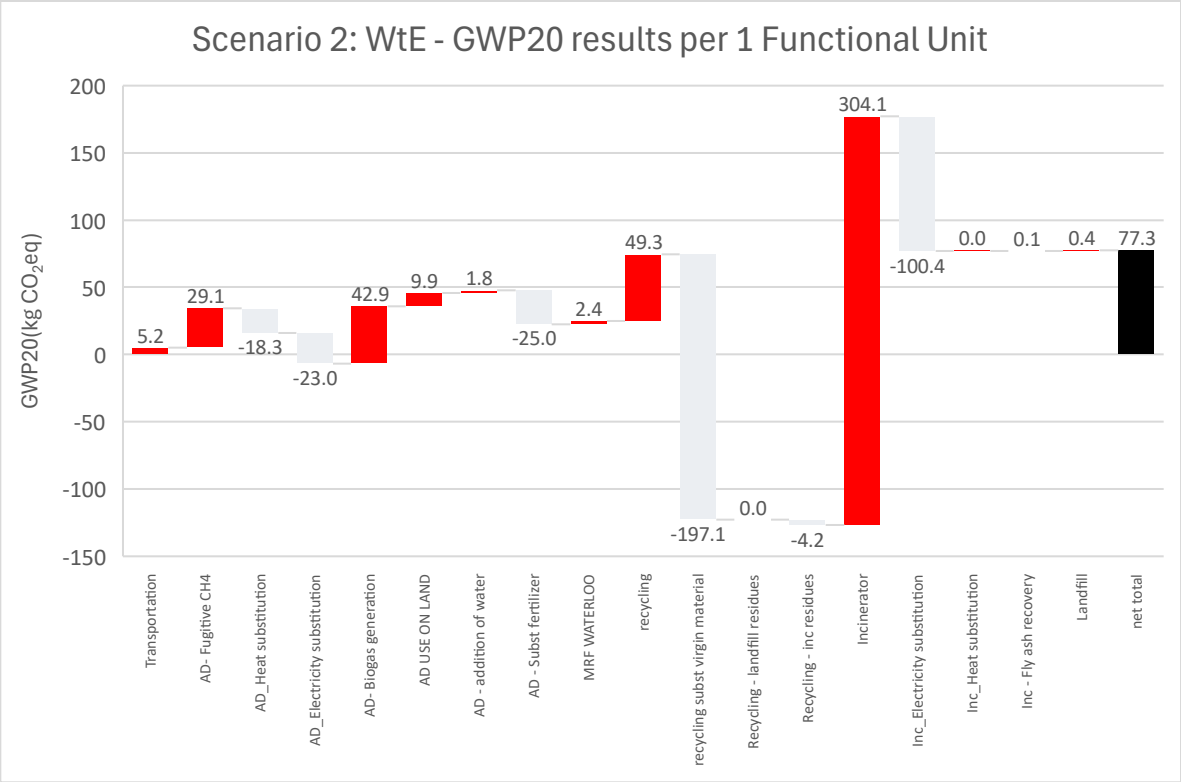

Figure 14:Process Contribution Analysis of GWP20 for Scenario 2

5.1.3. Sensitivity Analysis 2: High and Low Natural gas in the electricity mix of the Region

The second sensitivity analysis performed is on the energy mix of the Region. The demand of energy fluctuates around seasons and the peak and low demand are reported annually. The data is from 2022, and the peak demand happened in July while the lowest demand happened in May. Table 40 summarizes the data needed for the sensitivity analysis.

Table 40: Sensitivity analysis – changes in electricity mix of Ontario (high and low demand) (Ontario, 2023)

Demand – electricity mix	Peak natural gas sensitivity analysis (%)	Low natural gas sensitivity analysis (%)	Energy mix without Sensitivity analysis (%)
Nuclear Energy	48.3	57.1	55.4
Hydropower	22.6	28.1	23.3
Natural Gas	18.0	1.0	8.1
Wind	7.9	10.6	9.6
Solar PV	2.8	2.8	3.1
Bioenergy	0.4	0.4	0.5

The results of the sensitivity analysis for the GWP100 impact category for the BAU and WtE scenarios are presented in Figure 15. In Scenarios 1 and 3, the change in the energy mix did not really affect the results of the study. In contrast, in the WtE Scenario 2, a low natural gas demand results in a 19% increase in the GWP100 indicator relative to the scenario without sensitivity analysis, while a high natural gas demand results in a 40% decrease in the GWP100 indicator relative to Scenario 2 without a sensitivity analysis. This change is explained by the substitution of electricity process in each of the scenarios. In a high natural gas energy mix, the substitution happening in the LCA study results

in higher savings due to a higher substitution of natural gas. Conversely, in a low natural gas energy mix, the other sources are mostly renewable, and the savings from substitution of electricity become less significant.

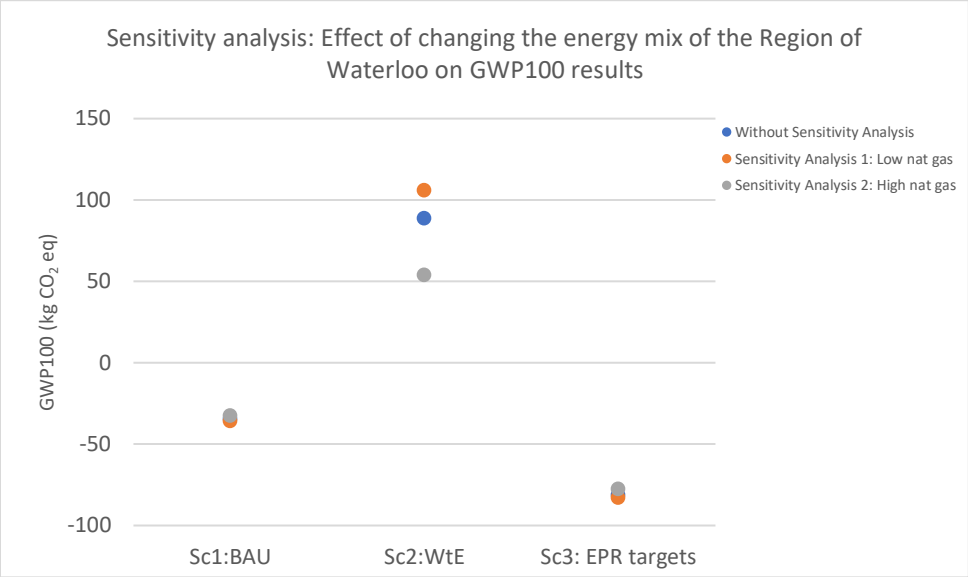

Figure 15: Sensitivity analysis 2: GWP100 results of low natural gas electricity mix (1% of mix) and high natural gas electricity mix (18%)

5.1.4. Sensitivity Analysis 3: Combined Heat and Power system

The third sensitivity analysis is performed on the energy system. The power generating system is modified to a CHP system in both the landfills and the incinerators modelled. CHP systems are advantageous due to their ability to maximize energy utilization. The efficiency of the technology increases significantly when the heat generated during combustion is utilized for both electricity generation and other thermal applications, such as heating or cooling. Figure 16 presents the results of the sensitivity analysis on the energy system used in the technologies treating the MSW of the Region of Waterloo.

For Scenarios 1 and 3 the CHP system is assumed to have the following efficiencies:

- 42 % for heat and 33 % for electricity (Ciuła et al., 2022).

For Scenario 2, the CHP system is assumed to have the following efficiencies:

- 60 % for heat and 20 % for electricity. In general, the electrical efficiency can range from 20 to 30 % while the heat efficiencies can reach a value of up to 85% (Fruergaard, Christensen, et al., 2010).

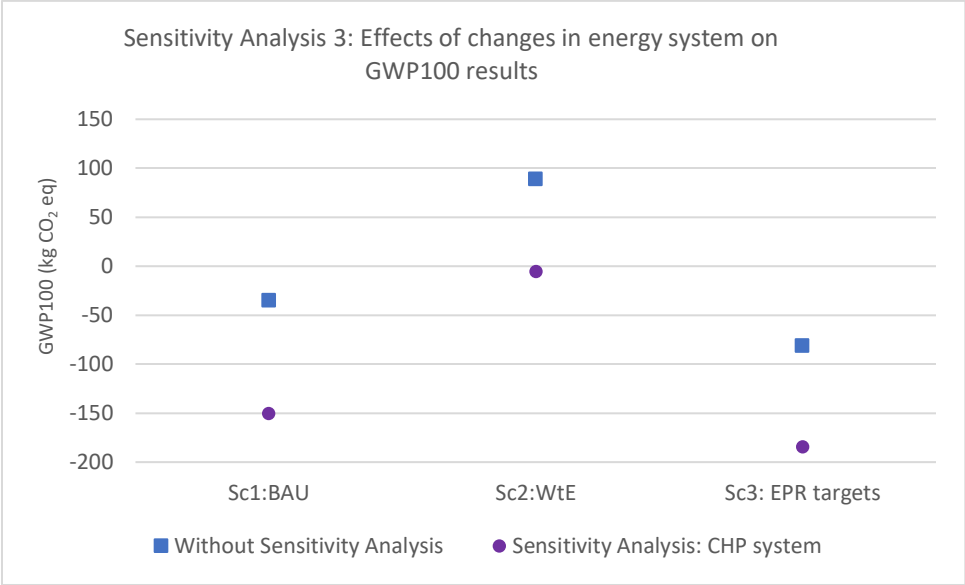

Figure 16: Sensitivity analysis 3: GWP100 results of CHP vs electrical system in the three scenarios

The different percentage changes between the results without sensitivity analysis and those considering a CHP system are presented in Table 41. The only processes that result in avoided burdens of GWP100 are from the energy generation and substitution of the landfill in Scenarios 1 and 3, and incineration in Scenario 2. Scenario 1 results in the highest percentage change of 334%. This finding indicates that the heat generated from the landfill gas displaces natural gas, contributing to an avoided burden.

Table 41: Percentage change of results without sensitivity analysis and results considering a CHP system

	Electrical-only system GWP100	Combined Heat & Power System GWP100	Percentage change
Scenario 1: BAU	-34.7	-150.4	-334%
Scenario 2: WtE	88.9	-5.1	-106%
Scenario 3: EPR targets	-81.1	-184.2	-127%

5.2. Impact category: Particulate Matter Formation (PM2.5)

The second impact category that is studied is the particulate matter formation (PM2.5). PM2.5 is closely monitored daily across Ontario. When this air quality indicator exceeds the limit, it exposes a risk to the population's health. The results of PM2.5 for the three scenarios are presented in Figure 17. All the scenarios result in avoided burdens in PM2.5.

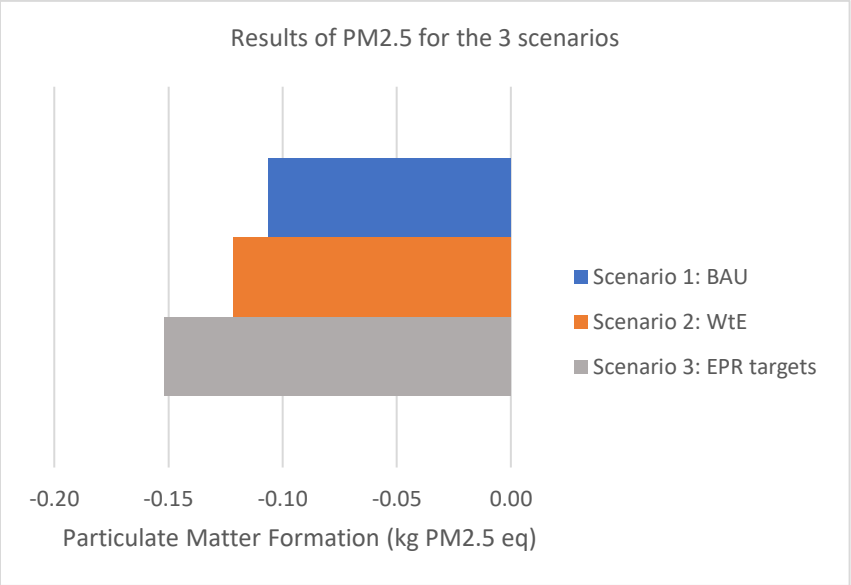

Figure 17: Results of particulate matter formation (kg PM 2.5 eq) for the three scenarios (per 1 FU)

5.2.1. Process contribution analysis

In all scenarios, the process contributing to the avoided burdens in PM2.5 is the substitution of virgin materials production due to the recycling of blue box materials. The PM2.5 primarily arise from combustion sources in industrial facilities producing raw materials (i.e. paper, plastics, steel), which explains the offsets achieved when these materials are substituted with recyclables. In Scenario 2 (Figure 19), higher savings relative to the baseline (Scenario 1) are achieved due to the following two reasons: higher recycling substitution savings due to higher number of materials that are recycled (incinerator by-products in addition to the blue box materials) and higher savings from the substitution of electricity production from the incineration of MSW. In Scenario 3 (Figure 20), the PM2.5 indicator results are 43 % higher than those achieved in Scenario 1. This result connotes that the higher weight of materials recovered due to an improvement in sorting rates at the MRF is the reason for higher substitution savings from the virgin material production.

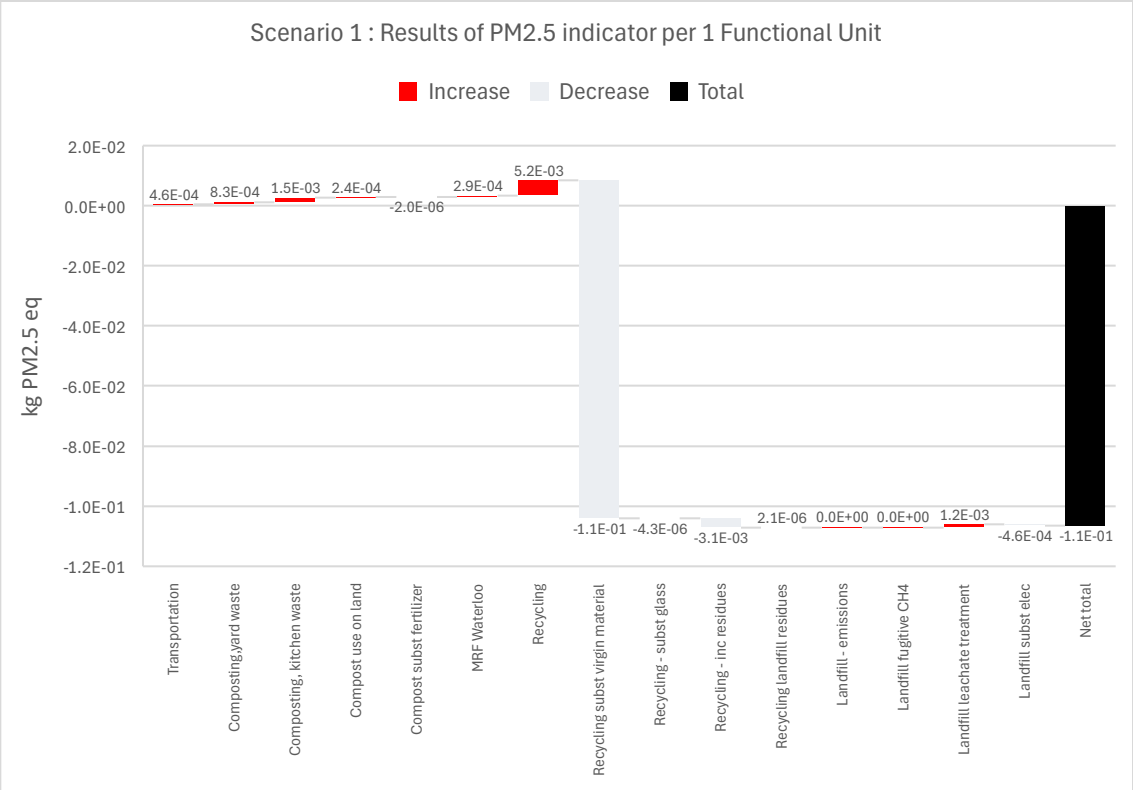

Figure 18: PM2.5 process contribution results of Scenario 1

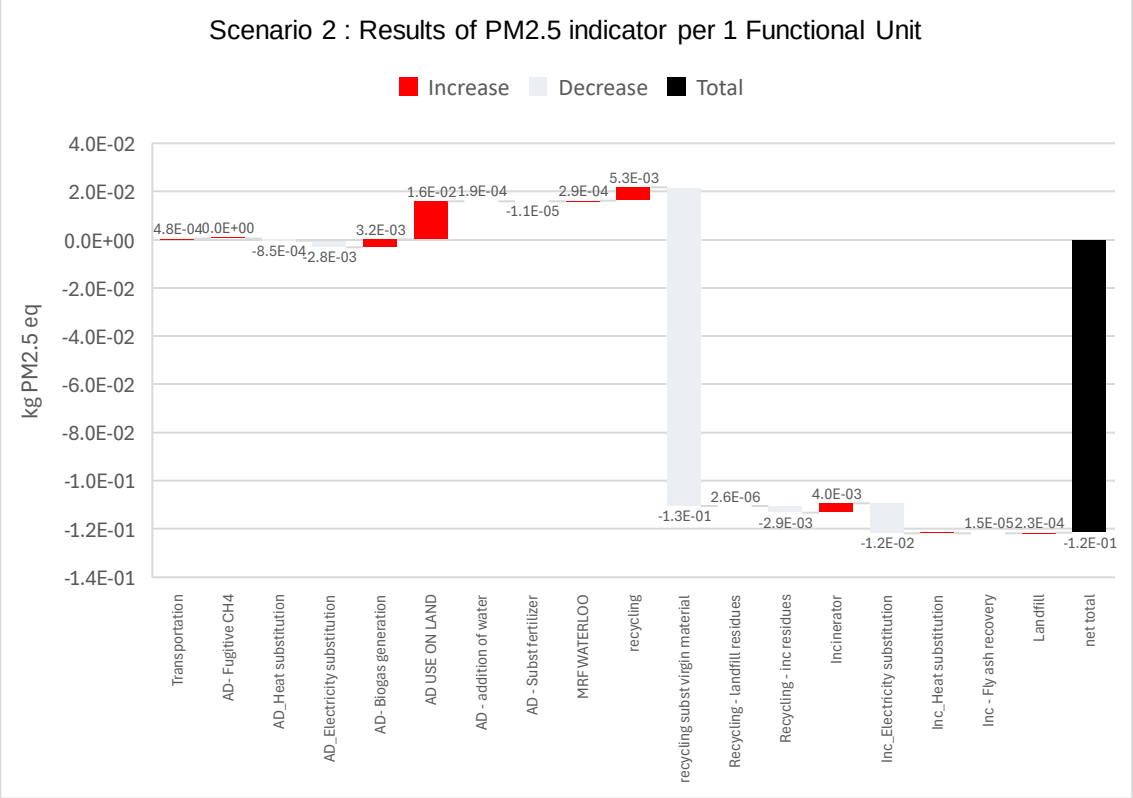

Figure 19: PM2.5 process contribution results of Scenario 2

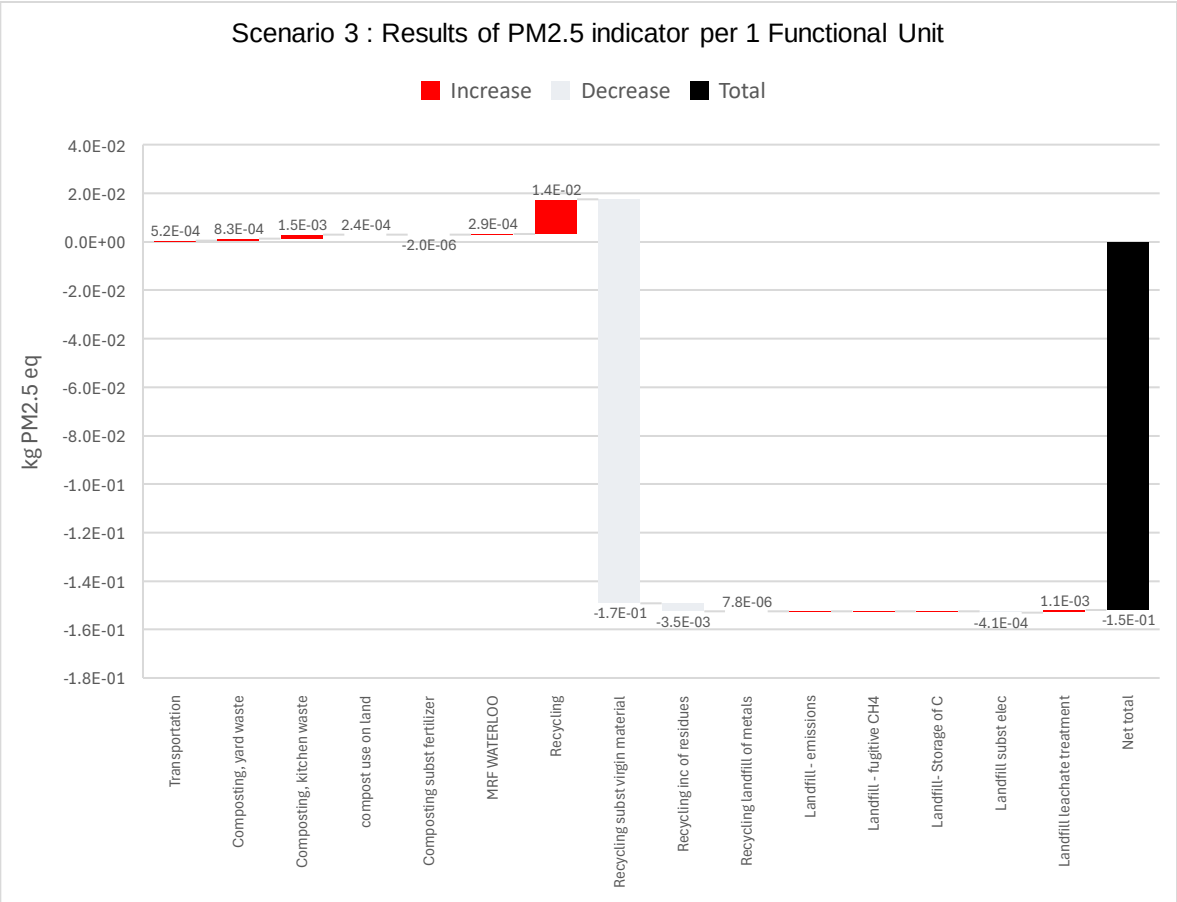

Figure 20: PM2.5 process contribution results of Scenario 3

5.2.2. Sensitivity analysis 1: High and Low Natural gas in the electricity mix of the Region of Waterloo

The first sensitivity analysis performed on the PM2.5 impact category is related to the change in the energy mix of the Region. The results of the PM2.5 (shown in Figure 21) are not affected by the change in the energy mix for all the scenarios. Thus, the PM2.5 is not sensitive to an increase and decrease in the percentage of natural gas available in the grid.

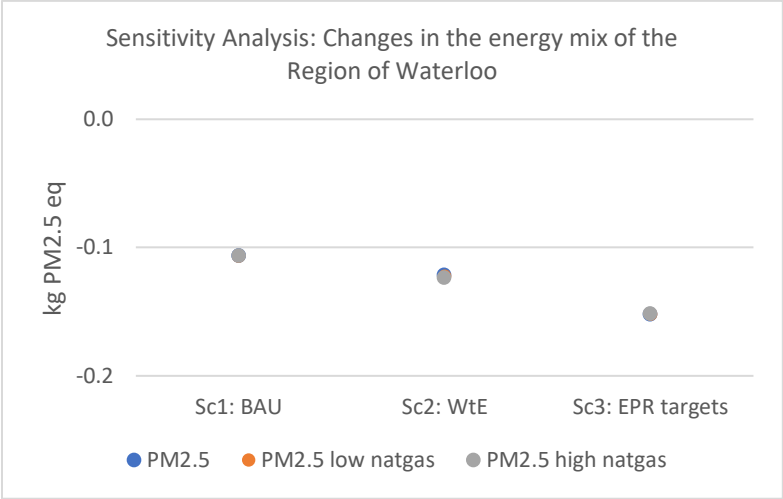

Figure 21: Results of sensitivity analysis 1: effect of change in energy mix of the Region (high and low natural gas percentages in the mix) on the PM2.5

5.2.3. Sensitivity analysis 2: Combined Heat and Power system

The second sensitivity analysis (Figure 22) performed on the PM2.5 impact category is related to the change to a CHP system in each of the landfill and the incinerator. The results indicate that the CHP outcomes in nearly 3 % lower impacts in the PM2.5 indicator than the electricity-based systems. The PM2.5 indicator is not sensitive to the energy system selected.

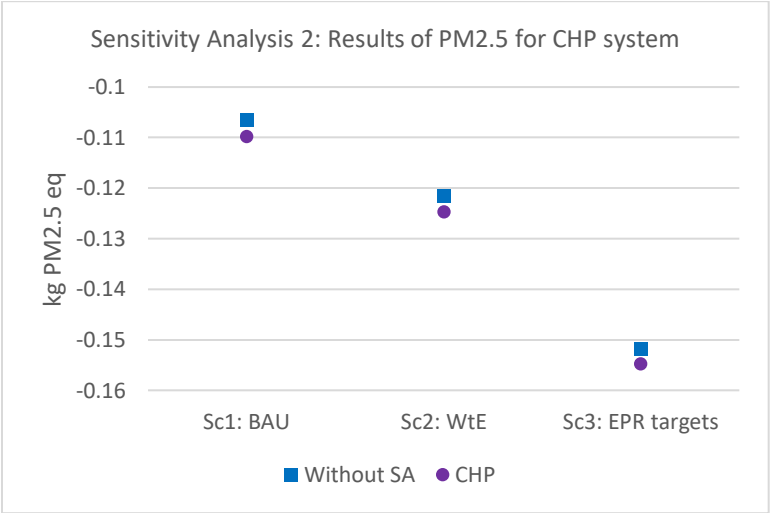

Figure 22: Sensitivity analysis 2 showing the results of CHP system on PM2.5

5.3. Impact category: Photochemical Ozone Formation

This section presents the results of photochemical ozone formation for the three scenarios. This impact category refers to the ground level ozone; it is a harmful air pollutant which constitutes the main chemical in smog formation. Photochemical ozone can harm the health of the population residing near the emissions

as well as the sensitive vegetation and ecosystems. The overall impact of this indicator is summarized in Figure 23. Except for Scenario 2, the other scenarios present avoided burdens in photochemical ozone formation. A thorough process contribution analysis is performed in order to better analyze the patterns observed.

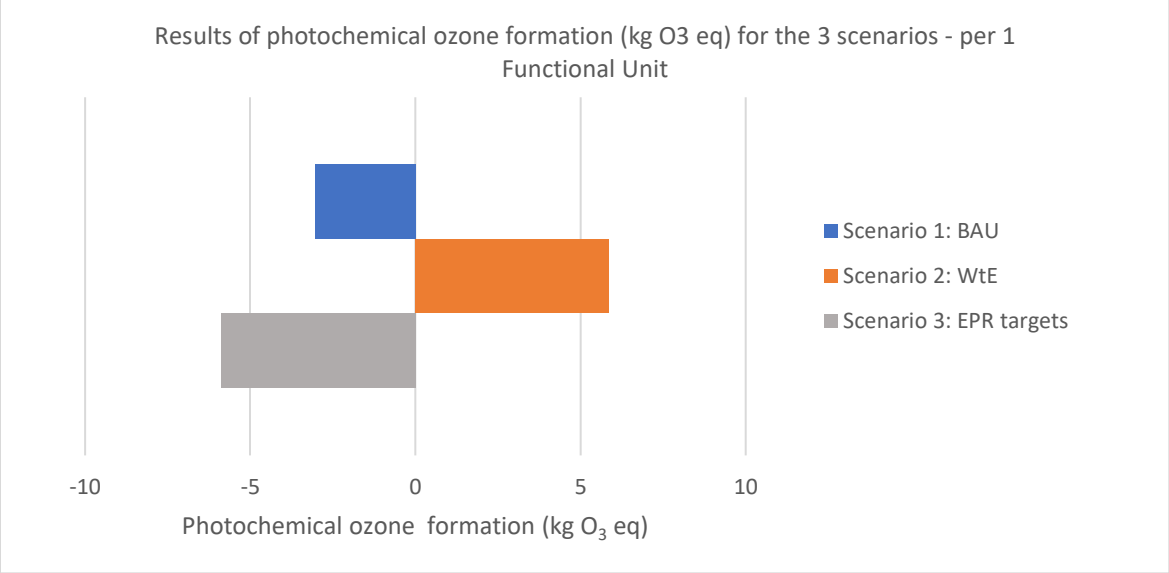

Figure 23: Results of photochemical ozone formation for the three scenarios

5.3.1. Process contribution analysis of the scenarios

In Scenario 1 (Figure 24), the process of electricity generation in the landfill contributes to nearly 46% of the overall burdens in this scenario, and the process of recycling of blue box materials accounts for 32% of the burdens. A thorough analysis of the processes shows that the generation of power through a turbine is responsible for nitrous oxide emissions. When this molecule interacts with sunlight, it is split into nitric oxide and an oxygen atom. Ozone is then produced when the oxygen atom is combined with an oxygen molecule in the atmosphere, leading to an aggravation in photochemical ozone formation. However, the avoided burdens achieved through the substitution of virgin material production due to the recycling of materials in Scenario 1 outweigh the impacts mentioned, which leads to avoided burdens in photochemical ozone formation.

In Scenario 2 (Figure 25), this impact category results in a harmful impact of 5.9 kg O_3 eq per FU. The incinerator and AD of waste contribute to 78 % of the total burdens in this scenario. The AD plant has a stationary engine combustion plant that generates biogas, which leads to nitrogen oxide emissions. The incinerator has a wet flue gas cleaning system and uses selective non catalytic reduction to reduce nitrogen oxides emissions. Nevertheless, the process still emits nitrogen oxides to the environment and results in an

impact of 11.1 kg O_3 eq/ton of MSW. In this scenario, the savings are not sufficient to outweigh the impacts mentioned.

In Scenario 3 (Fig 26), the EPR targets result in 95% lower impacts in the photochemical ozone formation indicator relative to the impacts of Scenario 1. This is attributable to 50% additional savings from the substitution of virgin material production due to the recycling process.

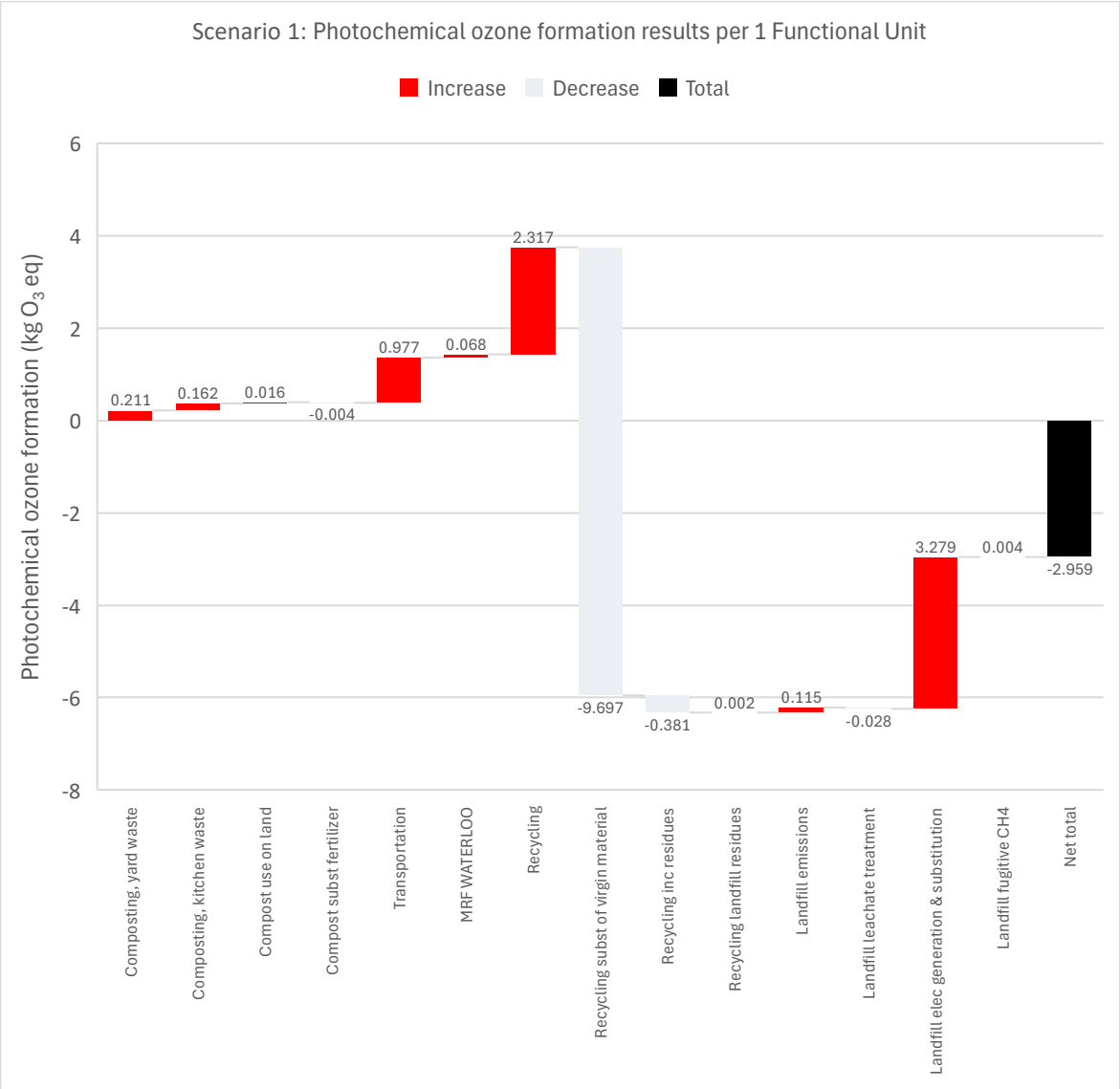

Figure 24: Process contribution analysis of photochemical ozone formation for Scenario 1

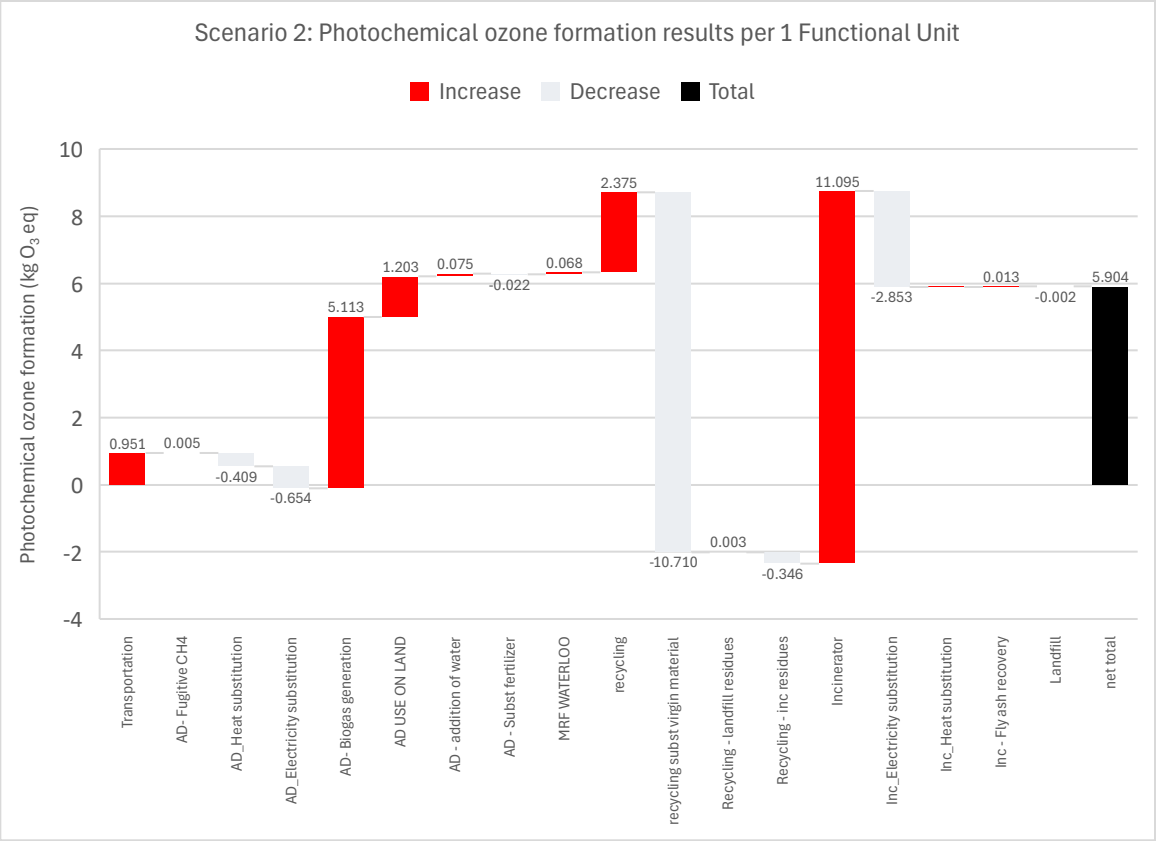

Figure 25: Process contribution analysis of photochemical ozone formation for Scenario 2

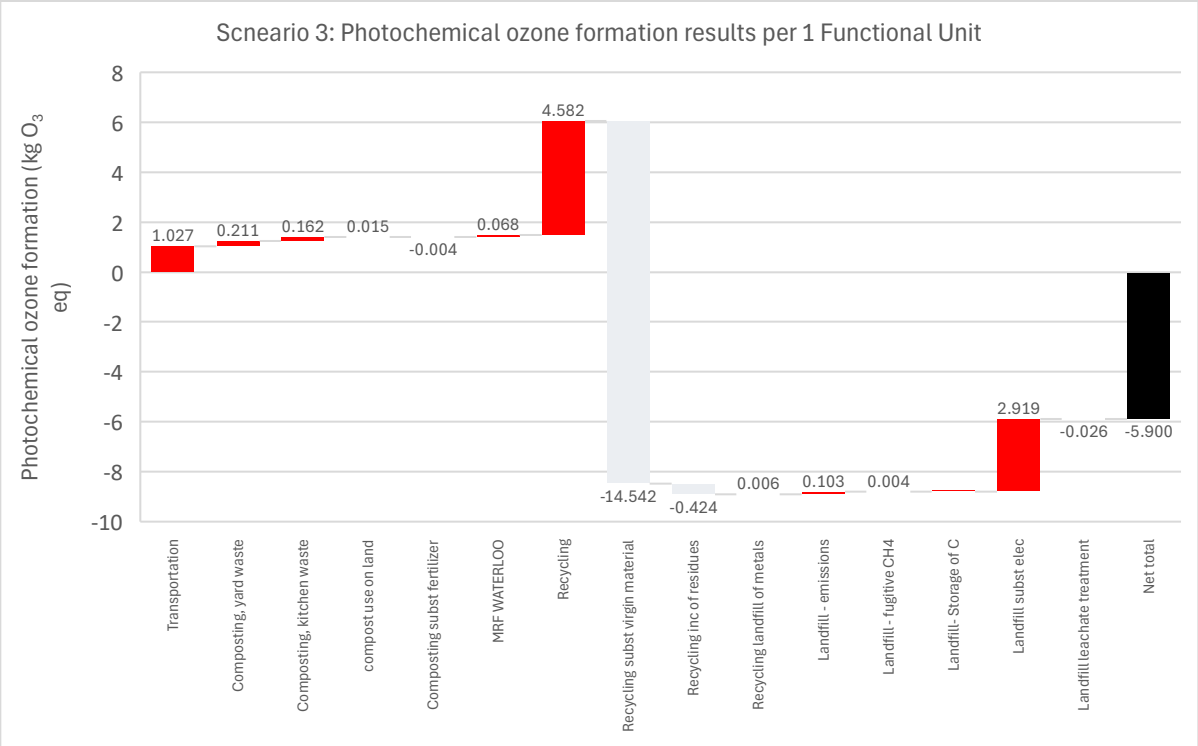

Figure 26: Process contribution analysis of photochemical ozone formation for Scenario 3

5.3.2. Sensitivity analysis 1: High and Low Natural gas in the electricity mix of the Region.

As previously described, a sensitivity analysis is performed on the energy mix of the Region of Waterloo. The results are presented in Figure 27. Scenario 2 considering WtE in the model shows sensitive results on the energy mix. On one hand, a high percentage of natural gas in the energy mix leads to 14% lower impacts from photochemical ozone formation in Scenario 2 (relative to the impact of the scenario without sensitivity). Natural gas, considered an unclean source of energy, aggravates the impact of photochemical ozone formation. On the other hand, a low percentage of natural gas in the energy mix leads to an additional impact of 8 % in Scenario 2. The processes that are the most affected by the sensitivity analysis within Scenario 2 are the following: substitution of electricity generated from the incinerator and substitution of electricity from the biogas of the AD.

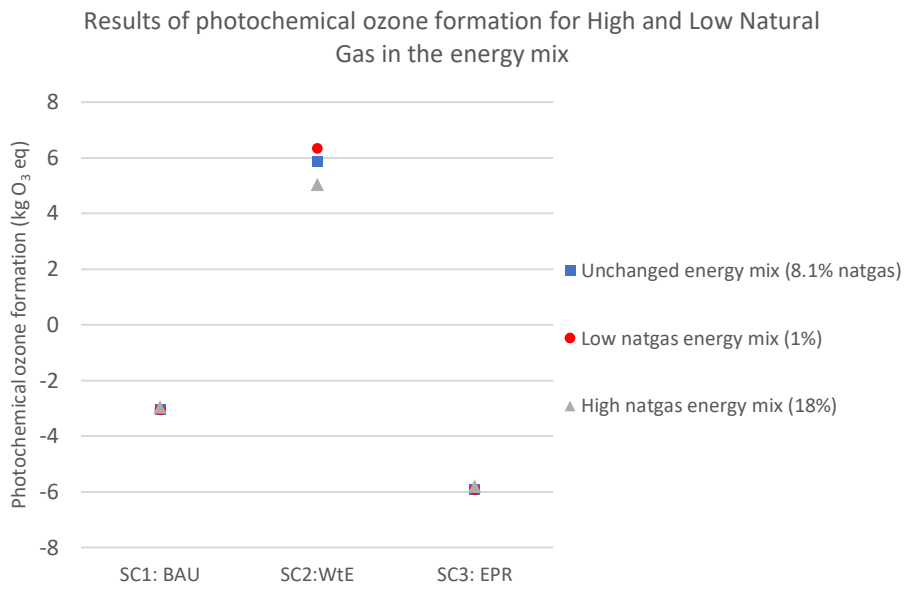

Figure 27: Effect of sensitivity analysis on the energy mix of the Region of Waterloo (high and low natural gas percentages) on photochemical ozone formation

5.3.3. Sensitivity analysis 2: Combined Heat and Power system

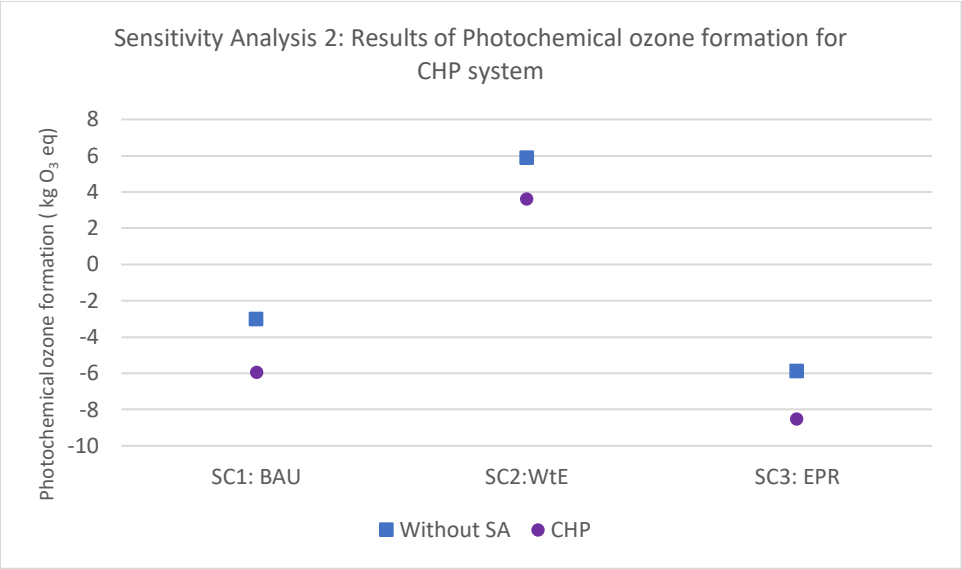

Figure 28: Sensitivity Analysis on the power system of the scenarios; results of photochemical ozone formation for a CHP system.

The results of the second sensitivity analysis conducted on the photochemical ozone formation impact category are shown in Figure 28. The pattern of results of scenarios, from least to most impactful on the environment, is still the same as the results without any sensitivity analysis. The generation of power through a turbine and the generation of heat through a boiler are responsible for nitrous oxide emissions, as seen in Figure 24. Recovering energy as electricity allows for the replacement of the average Ontario electricity mix, which is predominantly nuclear-based and thus has a relatively low GHG intensity. In contrast, recovering energy as heat in a CHP system primarily replaces fossil-fuel-based heat consumption, thereby providing a significant benefit.

5.4. Impact category: Eutrophication

The last impact category studied in this LCA is eutrophication, which is related to water quality. There are many sources of pollution leading to this phenomenon, and they are generally divided into two main groups: point and non-point pollution. The process contribution analysis performed in the following section will further touch upon the pollution source responsible for eutrophication in the respective scenarios. The results of eutrophication for the five scenarios are shown in Figure 29. While all scenarios contribute to an avoided burden in eutrophication, Scenario 2 results in an environmental burden. The process contribution analysis of each scenario is presented in the next section.

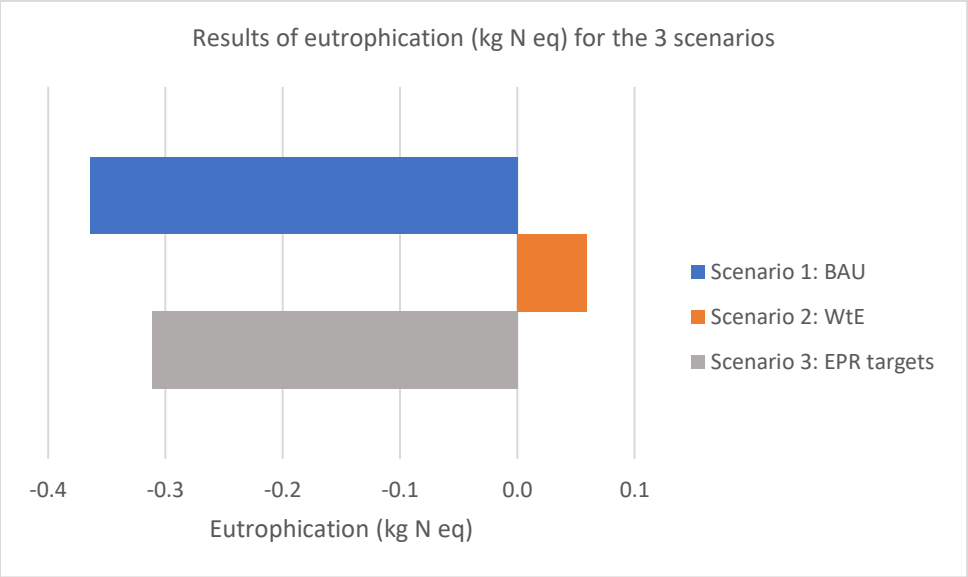

Figure 29: Results of eutrophication for the three scenarios

5.4.1. Process contribution analysis

Scenario 1 (Figure 30) results in avoided burdens of -0.362 kg N eq, primarily due to the substitution of virgin material production from the recycling of blue box materials.

In contrast, the major process resulting in eutrophication are the following:

- 36% of the burdens are the result of the use on land of compost: When used on crops, the compost can leach nitrate (NO_3) into the groundwater as well as runoff in surface water. These are considered categories of non-point pollution.
- 34% of the burdens are the result of recycling activities: Municipal wastewater discharge and industrial processes can create water high in chemical oxygen demand and biological oxygen demand, which requires preventive treatment prior to discharge.
- 21% of the burdens are the result of the treatment of landfill leachate: The leachate treatment has an impact on eutrophication due to process-specific emissions during treatment. The transfer coefficient of nitrogen to water is 23% in the modelling.

In Scenario 2 (Fig 31), the use of WtE technologies aggravates the results of the eutrophication indicator and leads to a burden of 0.06 kg N eq per ton of MSW. The impacts are primarily attributed to the use on land of the digestate of the AD. The eutrophication impact of digestate use on land is 14 times higher than that of compost. This is explained by the difference in nitrogen availability amongst the two products. In the digestate, the nitrogen phosphorus potassium (N:P:K) ratio is 6:1:2 whereas in the compost it is 2:1:6. The largest two avoided burdens in this scenario are the following:

- 53 % of the avoided burdens are the result of the substitution of virgin material due to the recycling of blue box waste.

- 37% of the avoided burdens are the result of the substation of fertilizer due to the use on land of the digestate. The nitrogen availability from digestate was assumed to be 85% of that from synthetic fertilizers in the first years of application, with the remainder being slowly released over subsequent years. The presence of organic forms of nutrients in digestate can slow nutrient release, potentially reducing the immediate risk of runoff compared to synthetic fertilizers.

In Scenario 3 (Fig 32), the net impact from eutrophication (-0.312 kg N eq) does not vary much from the eutrophication impact in Scenario 1 (-0.362 kg N eq). Thus, increasing recycling rates at the MRF do not heavily affect the eutrophication potential of the recycling activities.

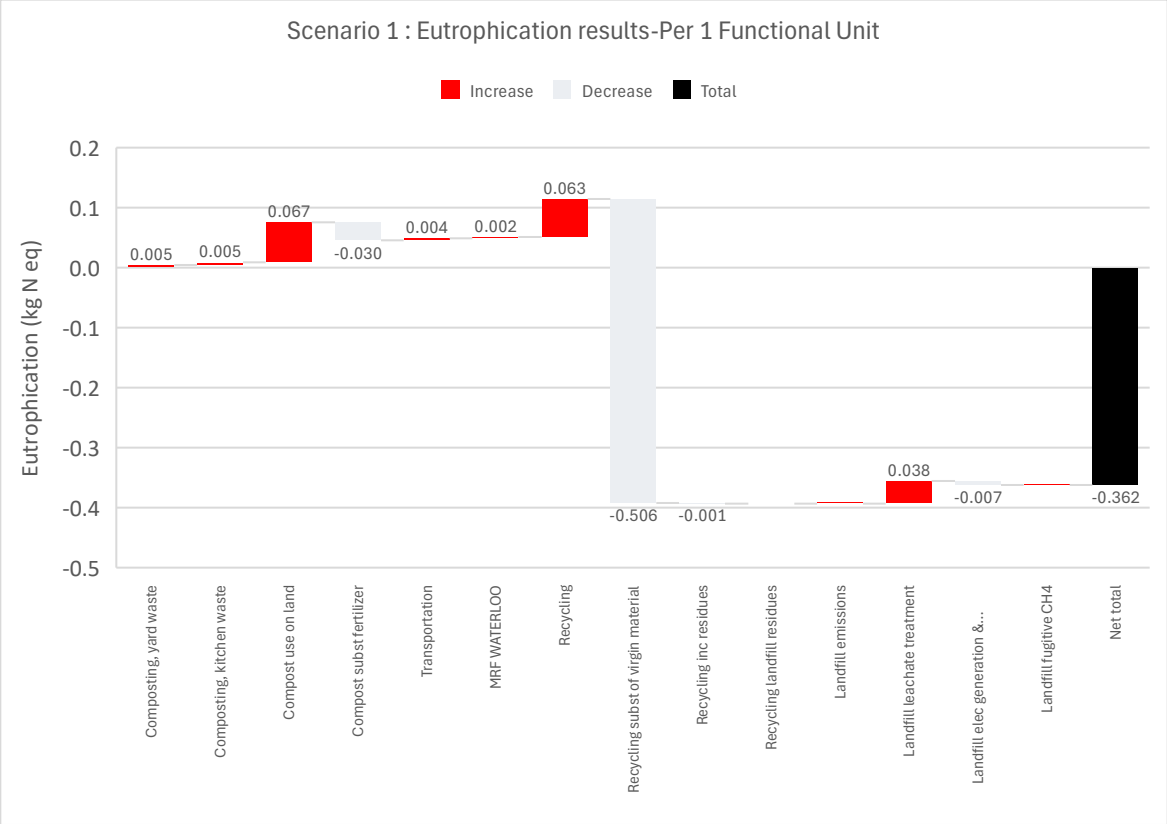

Figure 30: Process contribution analysis of scenario 1 - eutrophication (kg N eq)

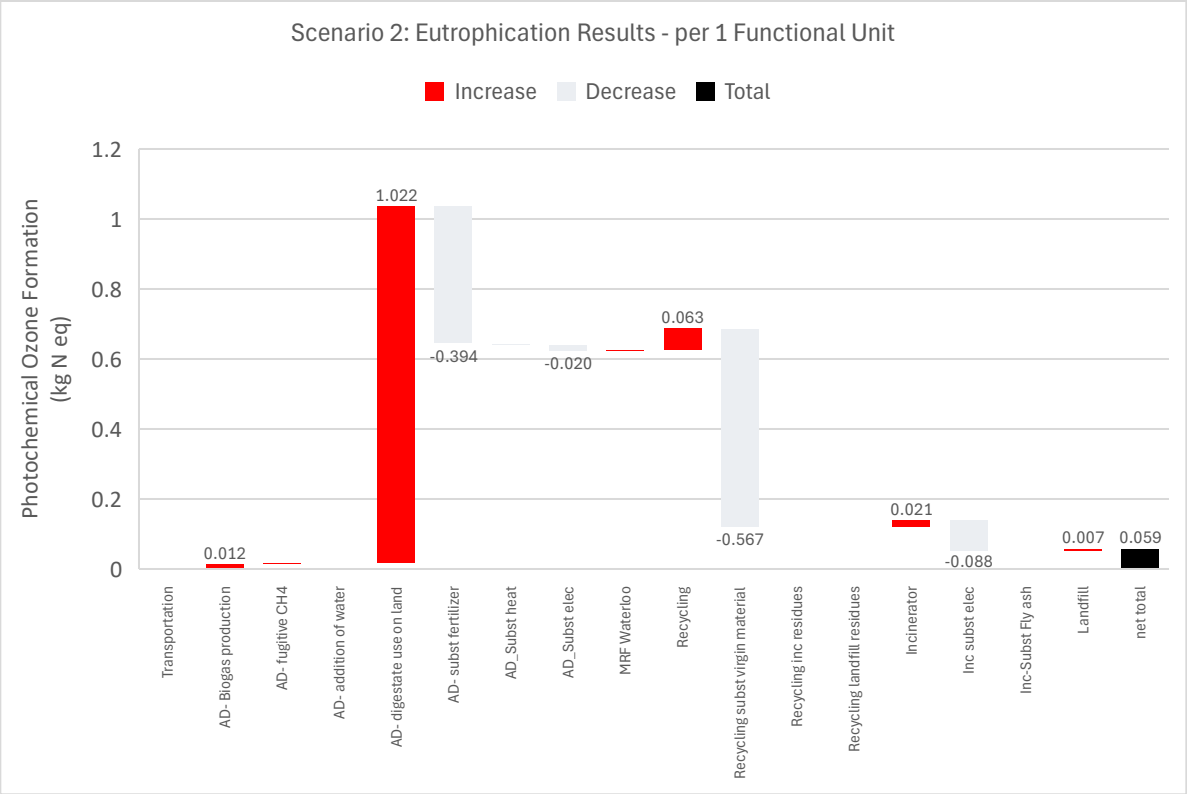

Figure 31: Process contribution analysis of scenario 2 - eutrophication (kg N eq)

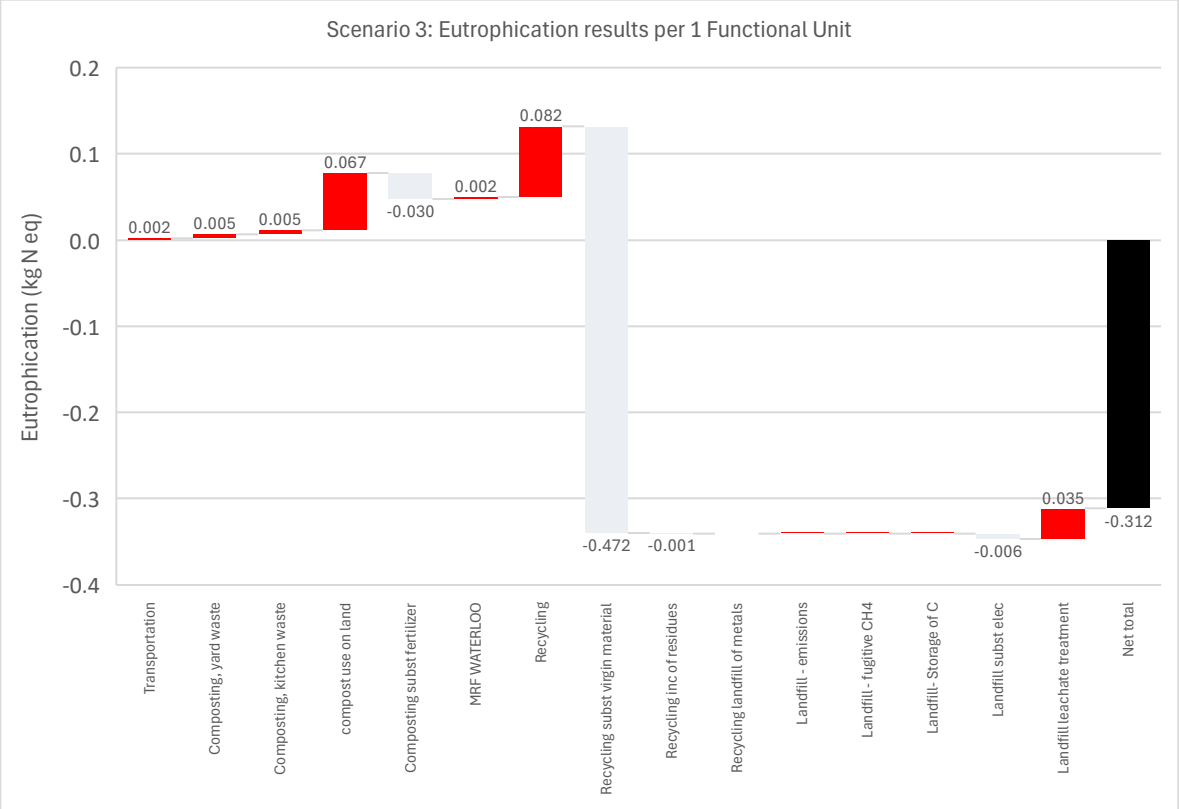

Figure 32:Process contribution analysis of scenario 3 - eutrophication (kg N eq)

5.4.2. Sensitivity analysis 1: Energy mix of the Region of Waterloo

The first sensitivity analysis performed on the eutrophication indicator is related to the electricity mix of the energy system in the Region of Waterloo. As explained in the previous sections, the energy grid is modified to have the following two sensitivity analyses: high and low natural gas percentage in the grid. The results are summarized in Figure 33 and Table 42. As per the results, only Scenario 2 is slightly sensitive to the changes in energy mix. On one hand, a low natural gas-based grid increases the impact from eutrophication by nearly 5.6% relative to its impact without sensitivity analysis. On the other hand, a high natural gas-based grid results in nearly 13.3 % savings in eutrophication relative to the results without sensitivity analysis.

A process contribution analysis of Scenario 2 shows that a low and high natural gas grid affects the eutrophication impact arising from the substitution of electricity in the AD as well as in the incinerator. Moreover, recycling increases the impact of eutrophication by 27% with a higher percentage of natural gas in the energy mix and decreases the impacts by 12% with a low natural gas percentage. By increasing the percentage of natural gas in the grid, an increase in the fossil-based resource leads to increased eutrophication. The combustion of fossil fuels releases nitrogen oxides into the atmosphere. These NOx compounds can be deposited onto water bodies through precipitation, increasing the nitrogen content in the water, and increasing the risk of eutrophication.

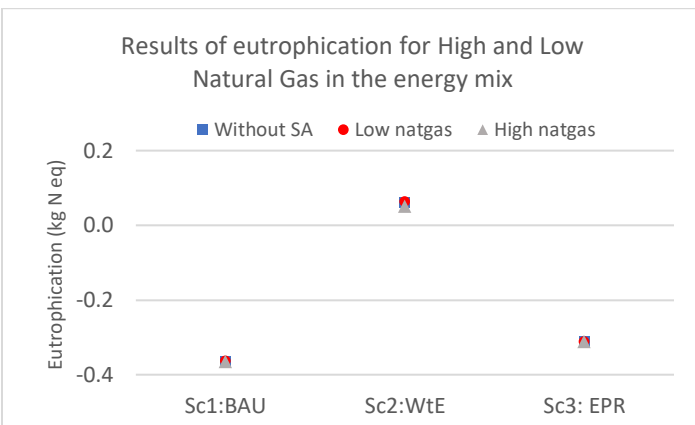

Figure 33:Eutrophication results of changes in the energy mix of the Region of Waterloo.

Table 42: Results of sensitivity analysis of energy mix on eutrophication (including percentage change)

	Without SA (kg N eq)	Low natgas (kg N eq)	Percentage change (low natgas) relative to results without SA	High natgas (kg N eq)	Percentage change (high natgas) relative to results without SA
Scenario 1:BAU	-0.364	-0.364	0.19%	-0.366	-0.36%
Scenario 2:WtE	0.059	0.063	**5.69%**	0.051	**-13.34%**
Scenario 3: EPR	-0.312	-0.312	-0.11%	-0.311	0.25%

5.4.3. Sensitivity analysis 2: CHP system

The second sensitivity analysis performed focuses on a change in the energy system used in the landfill in Scenarios 1 and 3, and the incinerator in Scenario 2. The results are summarized in Table 43. Scenario 2 is the most sensitive to the CHP system; the eutrophication indicator results in a 27% increase in impacts relative to the results achieved when an electricity system is used. As seen in Table 44, the CHP system impacts the following two processes:

- Incinerator substitution of heat: Now, Scenario 2 has avoided burdens due to the substitution of natural gas as a heating source.
- Incinerator substitution of electricity: The impact of eutrophication increases by 26% relative to its impact with an electricity system. The electricity efficiency in the CHP system is 20%, compared to 27% to an electrical-only system. Burning natural gas for heat in CHP systems produces NOx emissions. However, these operations might be smaller in scale compared to electricity generation power plants, potentially resulting in lower overall NOx emissions. Moreover, the heat generation from natural gas has a more localized impact, potentially leading to more direct but less widespread impacts on local water bodies. Hence, a decrease in electricity produced decreases the substitution of electricity from the grid, which decreases the avoided burdens achieved from substitution.

Table 43: Percentage change between eutrophication results of scenarios without sensitivity analysis (electrical system) and results considering a CHP system

	Electrical system (kg N_3 eq)	Combined Heat and Power (kg N_3 eq)	Percentage change (%)
Scenario 1: BAU	-0.3642	-0.3895	7%
Scenario 2:WtE	0.0592	0.0752	**27%**
Scenario 3: EPR	-0.3115	-0.3340	7%

Table 44: Two processes contributing to the difference in eutrophication impacts in Scenario 2

	Electrical system (kg N_3 eq)	Combined Heat and Power (kg N_3 eq)	Percentage change
Incineration – substitution of electricity	-0.088	-0.06518	26%
Incineration – substitution of heat	0	-0.00687	-

Chapter 6: Discussion

The study met the goal of assessing the environmental impacts of different MSWM pathways in the Region of Waterloo, Ontario. Findings show that Scenario 3 (EPR targets) leads to the lowest environmental impacts considering GWP100, photochemical ozone formation, PM2.5, and eutrophication, while Scenario 2 (WtE) results in the worst MSWM option in terms of GWP100, photochemical ozone formation, and eutrophication.

The outcomes of this study reveal some differences compared to similar research conducted. These disparities primarily stem from variations in the underlying assumptions and modeling techniques employed throughout the stages of goal and scope definition, LCI, and LCIA. Such differences highlight the importance of context-specific parameters (i.e. recycling processes and use on land modelling) and assumptions used (i.e. carbon storage in landfills) in shaping the results of life cycle assessments. By understanding these variations, the findings can be better interpreted, enhancing the applicability of LCA studies across different regions and waste management contexts.

The results of the study are intended to aid different stakeholders in management decisions around MSWM. The Region of Waterloo Waste Management Division will find the results of the study particularly interesting, as it provides the opportunity to pinpoint the processes that contribute the most to the different environmental impact categories assessed. As per this study, for the quantity of MSW landfilled in 2021, the CH_4 emissions result in a total of 32,370 t CO_2 eq when using the GWP100 indicator. This amount includes the emissions from the degradation of organic waste, the combustion of methane gas to produce electricity, and fugitive emissions occurring due to losses during gas collection. In contrast, the data from the Region of Waterloo reporting system reported a total of around 57,500 t CO_2 eq (Region of Waterloo, 2021). The difference between the result on EASETECH and the result from the Region's reporting can be explained by the difference in time period considered during the calculation. The Region of Waterloo's landfill was opened in 1972, and hence has been operating for 49 years by 2021. The emissions account for 49 years of waste disposal. In this study, the results account for the consider a 100-year landfill timeframe.

The choice between using a GWP20 versus a GWP100 in LCA studies on MSWM introduces a significant challenge. This decision requires the user to prioritize a specific timeframe, which can lead to considerable variations in the reported impacts, especially for CH_4. When the GWP20 is selected instead of the GWP100, Scenario 1 becomes the least favorable scenario for MSWM, whereby the result increases from -35 kg CO_2 eq per FU with a GWP100 to 119 kg CO_2 eq per FU with a GWP20. Choosing a short-term horizon like 20 years emphasizes the strong immediate impact of CH_4 but neglects the enduring effects of CO_2. Given the urgent need to stabilize greenhouse gas concentrations and limit long-term climate

change to below 2 °C, adopting a dual-horizon approach, evaluating both GWP20 and GWP100, can provide a more comprehensive understanding of the environmental impacts and aid in developing more balanced and effective waste management policies (Balcombe et al., 2018). Nevertheless, most of the environmental impact at landfill sites is the result of CH_4 emissions, choosing a GWP20 is more beneficial when prioritizing such gases with short timeframes.

In this study, the emission of methane from degradation of organic waste is the driving process leading to the largest GWP100 impacts in Scenarios 1 and 3. This is also the case in a study performed on Danish landfills using EASETECH, where the GWP impacts coming from methane emissions far exceeded the savings achieved through substitution of fossil-based energy. The avoided burdens arising from electricity substitution were more significant than those achieved from the substitution of heat produced by natural gas in a CHP scenario (Scheutz et al., 2023). However, this was not the case in this study, as seen in the sensitivity analysis considering CHP systems for landfill gas. The savings from the substitution of heat are much more significant than those associated with electricity. The reason for the difference among the two studies is the energy mix selected in each of the studies. In the study by Scheutz et al., (2023), the energy mix was assumed to change throughout the lifetime of the landfill, with the first five years being 100% coal, the next 15 years being half coal half wind, and the last 80 years being wind. Thus, the gas resulting from the organic degradation that happens mostly in the first 20 years was mostly substituting the non-renewable energy mix, leading to high avoided burdens. In this study, the energy mix of Canada is largely nuclear and hydro- based, which leads to very little saving from electricity substitution and higher savings from heat substitution from natural gas. When the sensitivity analysis on the energy mix is performed, and the natural gas share in the energymix increases from 8% to 18%, the GWP100 results decrease by 40%, as a result of higher substitution of fossil-based energy source.

Among all scenarios modelled in this study, Scenario 2 results in the highest impacts in the following impact categories: GWP100, photochemical ozone formation, and eutrophication. In contrast, two other studies found the opposite pattern. First, an LCA study conducted using WARM tool on the MSWM of the city of Guelph in Ontario has found that 1 ton of MSW led to 63% higher GWP100 impact when the residual portion of MSW is landfilled rather than incinerated (Abbassi & Abdel Mohsen, 2019). The incineration modelling in the study by Abbassi & Abdel Mohsen, (2019) led to overall GHG emissions offsets, which connotes that the negative impacts of the combustion process are offset by the substitution of electricity. Second, an LCA study performed solely on the residual waste of the city of Toronto resulted in higher GWP100 and nutrient enrichment potential impacts from the landfilling of the residuals compared to another scenario where half of the MSW was incinerated while the other half was landfilled. The authors assumed that the electricity generated from the landfill and incineration offsets only emissions from thermal

power plants of which four were fueled by coal and the fifth by oil and natural gas (Assamoi & Lawryshyn, 2012). In this study, a sensitivity analysis on the energy mix results in high savings in the incinerator scenario, in which the GWP100 decreases from 89kg CO_2 eq in a typical energy mix in Ontario to 53 kg CO_2 eq in the case of a high natural gas percentage in the energy mix.

In Scenario 3 modelling the EPR targets, all of the materials' recycling rates at the sorting facilities are increased to meet those targets. The results of the study show that Scenario 3 outperforms Scenario 1 in nearly all impact categories. Most notably, the GWP100 results decrease from -35 kg CO_2 eq in Scenario 1 to -81 kg CO_2 eq in Scenario 3, signifying an additional 134% saving from the increased substitution of virgin material production. A study by Manfredi et al. (2011) found that the paper, plastic, and aluminum fractions of MSW had the best environmental performance for the recycling option, providing the highest savings in GWP100 and nutrient enrichment potential. Although the results are not directly comparable due to the use of normalized results in the study, they still highlight that recycling is the most preferred management option for paper, plastic, aluminum, and glass fractions. The negative GWP100 impacts of the combustion process in Scenario 2 (302.6 kg CO_2 eq per FU) are also presented in the study, where the incineration of recyclable plastic and paper contributes to GWP100 due to emissions of fossil CO_2 (Manfredi et al., 2011).

Most studies in the literature focusing on EPR targets primarily address the plastic stream of MSW. However, the results of these studies are not directly comparable to this research, which also considers other recyclables such as paper and metals. In a study performed by the consulting firm Deloitte considering an ambitious 2030 zero plastic waste scenario for Canada, a 90% diversion rate of the Canadian resin flow is modelled. It is assumed that mechanical recycling quadrupled, chemical recycling scaled up, and WtE technologies were used to deal with the remaining volumes and hard-to-recycle plastics. The study projected a decrease in the GWP10 impact from 1200 to -600 kg CO_2 eq, which represents a 150% decrease in impact. This decrease was the result of the replacement of virgin material production with recycled plastics as well as the substitution of energy due to chemical recycling and WtE technologies (Deloitte & Cheminfo services, 2019).

Concerning the two different organic waste management alternatives, the composting process in Scenario 1 results in a GWP100 impact of around 16 kg CO_2 eq per ton of MSW while the AD process in Scenario 2 results in an offset of -21 kg CO_2 eq per ton MSW. Another study performed in Saguenay in the province of Quebec used IWM2 tool to compare different MSWM scenarios by changing the organic management pathway. The scenario assuming landfill of residuals, composting of organics, and recycling of recyclables resulted in 74 kg CO_2 eq per ton of MSW, while this amount is of -35 kg CO_2 eq per ton of MSW in Scenario 1 of this study. The other scenario assuming incineration of residuals and AD of organics

resulted in 152 kg CO_2 eq per ton of MSW in the study by Malmir et al., (2020), while the impact is of 89 kg CO_2 eq per ton of MSW in this study. The study using IWM model did not take into account the savings from offsetting the combustion of fossil fuels rather than biogas, which could be the reason for the higher impacts observed (Malmir et al., 2020).

6.1. Study limitations

The study presents some limitations that can affect the results of the LCA. The assumptions and boundary conditions set by the study can significantly impact its outcomes, necessitating careful consideration and transparency in the methodology. The following limitations are discussed:

- Methodology to calculate EPR targets: Achieving the EPR targets involves not just improving recycling processes but also reducing and reusing waste. This LCA study just considered a change in sorting efficiencies of the MRF.
- Methodology to calculate sorting efficiencies in MRF: the sorting efficiencies are calculated based on a mass balance of materials leaving the MRF and materials entering the MRF post collection, but this does not accurately represent the actual sorting efficiencies since the source of data is different among the two variable mentioned. The materials entering the MRF is based on CIF audits (not specific to Waterloo) while the materials leaving the MRF are based on reports from the Region of Wateroo. Moreover, it is assumed that the materials sorted at a household level (from CIF audits) represent the materials going into the facility. This can be erroneous due to losses that occur during collection of the blue box materials at a household level and during the drop off step at the MRF facility.
- Waste composition: The waste composition is an average composition from CIF audits performed on multiple urban regional cities in Ontario. The average composition from different cities can present some uncertainty as it does not fully represent the actual composition of the Region of Waterloo.
- The omission of collection of waste and its impact on PM2.5: The waste collection from households to the final disposal or treatment destinations is not included in this study. It is assumed that the collection is similar among the three scenarios, and that this process is outside the goal and scope of this study. Nevertheless, if computed, it is expected that the collection of waste will have an impact on the PM2.5 impact category.
- LCA type considered: The LCA assumed a consequential approach whereby the focus is on understanding the environmental impacts of changes in the MSWM systems by examining the consequences of decisions or actions such as the implementation of WtE and EPR. Nevertheless, the processes required for such LCA should be based on marginal data, which was not always

readily available. Hence, for some processes, such as the electricity mix, an average mix of Ontario is used instead. Average data may mask the true impacts of these changes by failing to account for the dynamic responses of the system, such as market shifts, behavioral changes, or technological adjustments.

6.2. Recommendations

The goal of the LCA is to assess the environmental impacts of different MSWM treatment pathways to treat MSW in the Region of Waterloo. The findings of this study hold significant implications for policymakers working on diversion and EPR initiatives, as well as stakeholders involved in exploring landfill alternatives (i.e. incinerator and AD). It is recommended that policymakers, including the Region of Waterloo, prioritize the GWP20 results due to the immediate impacts of gases with shorter lifetimes, such as methane. This prioritization is crucial as activities emitting methane (i.e. landfills) have a more pronounced effect in the short term. By emphasizing GWP20, policies can be designed to mitigate near-term climate change effects, which can help prevent reaching critical climate tipping points and provide more time to address long-term climate challenges.

The study's results indicate that achieving the EPR targets leads to the most favorable outcomes across all impact categories, highlighting the effectiveness of EPR strategies. In this study, it is assumed that the EPR targets can be met by only changing the sorting efficiencies, which sets unrealistic recycling efficiencies targets, particularly in the context of paper recycling sorting efficiency of 100%. However, this is a narrow view as the calculation of the EPR targets outlined in the regulation is derived not only from the materials sorted and sent to recycling facilities but also from the materials generated by producers within a given year. This necessitates changes in the composition of MSW through several strategies; innovations in product materials, increased public awareness about sorting, and implementing a more comprehensive sorting scheme categorized by material types can significantly contribute to this goal. Additionally, the willingness of households to sort waste efficiently plays a crucial role. Unfortunately, convenience often dictates household sorting behaviors, posing a significant challenge. It is recommended that future studies account for these variables when modeling new EPR targets to create more realistic and achievable goals.

To achieve higher recycling efficiencies, it is recommended to consider different recycling pathways. Mechanical recycling alone may not suffice, especially for hard-to-recycle and contaminated materials like those composed of various resins, such as flexible films. Here, chemical recycling becomes crucial. By breaking down plastics into their original monomers or other valuable chemicals, chemical recycling can produce secondary materials with properties akin to virgin materials. This, in turn, can broaden the market for secondary materials, providing a more sustainable solution.

Conversely, Scenario 2, which involves incineration, resulted in the least favorable outcomes, suggesting that incineration is not a viable alternative to landfilling due to the impacts arising from the combustion process. However, it is essential to conduct a comprehensive weighting step among various stakeholders to determine the relative significance of each impact category before making decisions and potentially omitting incineration as an option. This step ensures that the chosen waste management strategies align with broader sustainability goals and stakeholder interests.

Regarding the applicability of this study's results to other contexts, it is recommended that researchers conducting LCA of MSWM in different regions with similar waste management contexts should tailor their models to region-specific data. The detailed process contribution analysis of various impact categories and the sensitivity analysis modeling provided in this study offer valuable insights. These can aid researchers in identifying the key drivers of the results, thereby enhancing their understanding and facilitating the application of findings to other contexts effectively. By considering regional specificities and detailed process contributions, future studies can achieve more accurate and contextually relevant results. This approach not only improves the reliability of LCAs but also supports the development of targeted and effective waste management strategies across different regions.

6.3. Data quality

It should be noted that data quality poses a key limitation in this study, particularly in relation to MSMW within the Canadian context. For assessing the limitations of the study, a Pedigree matrix, detailed in Appendix B, is employed. This matrix evaluates five categories of Data Quality Indicators (reliability, completeness, temporal, geographical, and technological) and assigns numerical scores (ranging from 1 to 5) for each process in the Life Cycle Inventory. The matrix is presented in Table 45. It is divided by process, and the scores given are based on the information needed to create the processes. It is important to recognize that completing the matrix is based on the qualitative judgment of the author rather than on quantitative expert knowledge.

First, the uncertainty of the foreground data is discussed. In relation to the MSW composition, the uncertainty can alter the results of the study, especially that the Region includes other rural sub-regions that have differences in the MSW composition than the bigger cities such as Waterloo and Kitchener. The transportation data is representative of the combustion of 1 liter diesel oil in a medium-size truck according to euro 3 standards. Nevertheless, when sensitivity analysis was done on some of the studies, the results that excluded the transportation of waste to the incinerator facility did not significantly change the impacts (Ramos et al., 2018; Turconi et al., 2011). As a result, this process' data quality does not affect the results.

Second, the uncertainty of background data is discussed. The scores given to the composting are low for the temporal and geographic correlation. The composting of food waste is from Italy while the composting of yard waste process is representative of the US. The geographical location and local climate conditions (temperature, humidity, rainfall) affect the composting process and, consequently, the emission profiles. For example, composting in colder climates might slow down microbial activity, altering the emission rates. Nutrient uptake from compost varies widely based on soil texture, pH, organic matter content, and climate conditions. The results of the study might differ if data from the Region of Waterloo was used for the model. Moreover, the recycling and substitution of virgin material of different materials are mostly modelled according to European databases. However, when available, some of the processes represent the Canadian context in the province of Quebec (i.e. paper, aluminum, and steel) and are imported from Ecoinvent 3.9.1 (consequential modelling). It is important to acknowledge the differences in recycling impacts between a North American context and a European context. The variability was studied in an LCA of mixed wastepaper, whereby the authors compared the LCA results of a recycling of mixed wastepaper exported from sorting centers in Quebec, Canada with those of a non-regionalized recycling process for mixed wastepaper from the Ecoinvent database. The results of Quebec processes showed that nine impact categories remained more environmentally beneficial than producing virgin paper, whereas the results of Ecoinvent processes resulted in sixteen categories being more environmentally favorable than producing virgin paper. This comparison highlighted the significant impact that regionalization can have on LCA outcomes (Provost-Savard et al., 2023). The landfill background data is based on data from the US EPA Life Cycle Inventory of Landfill Process Model, whereas the foreground data is based on measurements and representative of the process of landfilling over different periods of time. The substituted electricity is specific to Ontario in 2021 and the different processes needed to create the mix are imported from Ecoinvent.

Table 45: Scoring Pedigree matrix indicators for different processes used in the study (Note: 1 to 5; 1 being the best data quality and 5 the most uncertain data quality).

	Reliability	Completeness	Temporal	Geographic	Technical
MSW composition	1	1	1	2	1
Transportation	1	2	5	2	4
Organics					
Composting	1	2	5	5	3
Compost Use on Land	2	1	2	4	4
Fertilizer Substitution	3	1	1	5	4
Recycling					
Paper recycling	1	2	5	4	2
Paper substitution	1	1	2	3	2
Cardboard recycling	1	2	5	4	2

Cardboard substitution	1	2	5	5	2
Aluminum recycling	1	2	3	5	2
Aluminum substitution	2	2	2	2	2
Steel recycling	1	2	3	5	2
Steel substitution	1	4	3	2	2
PP recycling	1	1	5	5	2
PP substitution	2	2	3	5	2
PET recycling	1	2	4	3	2
PET substitution	1	2	5	5	2
HDPE recycling	1	2	4	3	2
HDPE substitution	1	2	5	5	2
Mixed plastics recycling	1	4	4	5	4
Landfill					
Landfill gas composition	1	1	4	3	2
Landfill gas decay rate	1	1	3	3	2
Landfill gas collection	2	1	2	2	2
Treatment efficiency and emission of landfill gas treatment	1	1	4	3	4
Electricity generation	1	1	1	1	1
Landfill oxidation rate	3	1	3	3	4
Leachate concentration of materials throughout years	2	1	4	5	4
Leachate treatment	1	2	3	5	4

Chapter 7: Conclusion

This thesis assessed the environmental impacts of MSWM system in the Region of Waterloo, Ontario, Canada, by using LCA as a tool. The two main research questions addressed in this thesis are: "How does waste-to-energy system impact the environmental profile of MSWM in the Region of Waterloo?" and "How do the new recovery targets set by the province of Ontario affect the results of the LCA study?". Three scenarios for the MSWM in the Region of Waterloo are modelled. Scenario 1 depicts the current state of MSWM in the Region in 2021; Scenario 2 models an incinerator instead of a landfill and an AD instead of composting; Scenario 3 models similar processes as Scenario 1 but with the consideration of new EPR targets set by the province. The results show that the Scenario 2 with incinerator is the least favorable MSWM alternative in terms of GWP100, photochemical ozone formation, and eutrophication. The combustion process of incinerator is the main contributor towards the GWP100 and photochemical ozone formation impact categories, while using digestate on land contributes to eutrophication. When considering a GWP20, Scenario 1 becomes the least favorable MSWM alternative, which is explained by the significant impact of methane emissions from landfilling municipal solid waste over a 20 years' timeframe. Scenario 3 contributes to the highest savings among all MSWM pathways in all impact categories which is primarily due to the increased recycling rates that lead to higher avoided impacts due to the substitution of virgin material production. For instance, in Scenario 3, the GWP100 decreases by 130% relative to Scenario 1 where the only difference is increased recycling rates in Scenario 3.

This study adds to the growing literature on the LCA of MSWM. The use of EASETECH in North American studies has been particularly scarce, so this study uses a waste-specific LCA tool which allows material flow modelling whereby energy and mass of different material fractions are computed throughout the system. In addition, this research looks at an integrated MSWM in more detail than existing studies and includes a comprehensive process contribution analysis of results obtained for the different environmental impact categories condidereded. Future work could benefit from better data quality for some of the key parameters of this study, such as waste composition and background data (i.e. recycling and incineration) used for the modelling of the diverse technologies. Concerning Scenario 3, the EPR targets are only calculated based on a change in the marketed tons of waste leaving the MRF. However, it is important to also consider changes in waste composition of the MSW collected at a household level, which represents the total amount of waste supplied to the marketplace within a given year. More precise data on the waste supplied by producers is essential for such a study, and modeling additional chemical recycling technologies would expand the range of options available for managing the increased volume of recovered materials. It would also be interesting to model a scenario concerning the single use plastics ban set by the Federal Government of Canada in 2023, which is expected to alter the composition of the waste generated as well

as the reference flow used. Further, uncertainty analysis can be conducted to analyze the impact of uncertain data such as the landfill gas collection rate, the substitution of NPK fertilizers, and the use of compost and digestate on land.

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Appendices

Appendix A: Landfill Power Generation Capacity- Waterloo

Table 46: 2021 Data from Region of Waterloo used to calculate the average power generation capacity of the landfill

Month	Day	Gas Flow	TEL Flow	CH4	Avg power output	Gas flow	Average daily power output per m^3 of methane	Average yearly power output per m^3 of methane
Unit		(cfm)	(cfm)	(%)	(kWh)	m3/hr	kWh/m3 CH4	kWh/m3 CH4
January	1	1118	1118	55	3877	1900	3.74	3.816
	2	1119	1120	54	3878	1902	3.76	
	3	1119	1119	54	3877	1901	3.76	
	4	1117	1116	54	3852	1895	3.77	
	5	1133	1131	54	3894	1922	3.78	
	6	1133	1132	53	3838	1923	3.76	
	7	1133	1134	53	3818	1926	3.76	
	8	1116	1117	53	3765	1898	3.76	
	9	1136	1137	52	3818	1931	3.77	
	10	1144	1144	52	3793	1944	3.76	
	11	1064	1066	53	3551	1811	3.72	
	12	1140	1142	52	3796	1940	3.75	
	13	1129	1129	52	3762	1919	3.76	
	14	1102	1102	52	3732	1873	3.83	
	15	1084	1086	52	3747	1845	3.88	
	16	1086	1087	53	3786	1847	3.88	
	17	1084	1086	53	3786	1846	3.88	
	18	1075	1076	53	3736	1828	3.89	
	19	1111	1110	52	3847	1886	3.93	
	20	1100	1099	52	3772	1868	3.92	
	21	1048	1054	52	3710	1791	3.97	
	22	1066	1065	52	3727	1810	3.98	
	23	1108	1104	51	3733	1876	3.94	
	24	1100	1094	51	3708	1859	3.94	
	25	1096	1090	51	3690	1851	3.92	
	26	1086	1082	51	3693	1839	3.91	
	27	1111	1110	50	3690	1886	3.90	
	28	1116	1116	50	3670	1895	3.90	
	29	1095	1095	50	3631	1860	3.89	
	30	1101	1100	50	3664	1869	3.89	
	31	1096	1096	51	3659	1861	3.89	
February	1	1094	1094	50.53	3659	1859	3.89	
	2	1083	1084	50.54	3624	1842	3.89	
	3	1094	1094	50.37	3656	1859	3.91	
	4	1090	1088	50.28	3640	1848	3.92	
	5	1075	1073	50.53	3629	1824	3.94	
	6	1104	1104	49.78	3677	1876	3.94	
	7	1102	1103	49.32	3626	1874	3.92	

	8	1106	1105	48.91	3596	1878	3.91	
	9	1098	1097	49.14	3575	1864	3.90	
	10	1094	1094	49.32	3515	1858	3.84	
	11	1067	1068	49.60	3466	1814	3.85	
	12	1081	1081	50.00	3559	1837	3.88	
	13	1074	1077	50.10	3564	1829	3.89	
	14	1075	1076	50.02	3563	1829	3.90	
	15	1071	1072	50.05	3560	1822	3.90	
	16	1070	1072	50.04	3561	1821	3.91	
	17	1094	1094	49.14	3549	1858	3.89	
	18	1066	1063	49.48	3459	1806	3.87	
	19	1082	1079	49.53	3550	1832	3.91	
	20	1092	1092	49.17	3550	1856	3.89	
	21	1094	1093	48.94	3529	1858	3.88	
	22	1067	1068	49.59	3512	1814	3.90	
	23	1029	1031	48.41	3467	1751	4.09	
	24	1082	1080	50.69	3617	1836	3.89	
	25	1093	1092	50.04	3597	1856	3.87	
	26	1085	1085	50.59	3590	1843	3.85	
	27	1073	1071	51.59	3614	1820	3.85	
	28	1072	1071	52.70	3683	1819	3.84	
March	1	1076	1076	52.49	3709	1827	3.87	
	2	1070	1070	52.53	3644	1817	3.82	
	3	1066	1066	52.53	3621	1812	3.81	
	4	1073	1075	52.24	3656	1826	3.83	
	5	1062	1062	52.52	3645	1804	3.85	
	6	1066	1066	51.92	3626	1811	3.86	
	7	1077	1077	51.30	3620	1829	3.86	
	8	1068	1057	51.68	3570	1796	3.85	
	9	1076	1059	51.54	3564	1799	3.84	
	10	1071	1071	52.26	3634	1819	3.82	
	11	1060	1061	53.23	3646	1803	3.80	
	12	1077	1076	52.53	3686	1829	3.84	
	13	1084	1084	51.81	3668	1842	3.84	
	14	1093	1095	51.13	3670	1860	3.86	
	15	1069	1067	50.58	3505	1813	3.82	
	16	1044	1040	51.98	3500	1766	3.81	
	17	1035	1035	51.86	3466	1758	3.80	
	18	1062	1064	51.25	3542	1807	3.82	
	19	1064	1065	49.42	3414	1809	3.82	
	20	1063	1063	49.65	3407	1806	3.80	
	21	1055	1053	50.23	3415	1790	3.80	
	22	1034	1032	50.73	3366	1753	3.79	
	23	1046	1047	50.50	3407	1779	3.79	
	24	1044	1044	51.09	3413	1773	3.77	
	25	1032	1032	50.80	3352	1753	3.76	
	26	1032	1034	51.32	3398	1757	3.77	
	27	1017	1017	52.47	3384	1728	3.73	

	28	1011	1013	53.25	3439	1722	3.75	
	29	1030	1030	52.35	3441	1750	3.75	
	30	1029	1027	52.98	3473	1745	3.76	
	31	1027	1029	34.64	3436	1748	5.67	
April	1	1032	1034	51.83	3425	1757	3.76	
	2	1050	1050	51.33	3453	1784	3.77	
	3	1047	1045	51.45	3449	1776	3.77	
	4	1044	1042	51.64	3442	1770	3.77	
	5	985	390	52.12	1277	662	3.70	
	6	974	0	52.60	0	0	0.00	
	7	974	0	52.61	0	0	0.00	
	8	905	201	53.33	648	341	3.56	
	9	1041	1044	52.83	3481	1773	3.72	
	10	1051	1052	52.39	3493	1787	3.73	
	11	1043	1043	52.67	3478	1773	3.73	
	12	1025	1026	53.35	3454	1744	3.71	
	13	1031	1032	53.73	3497	1753	3.71	
	14	1029	1029	45.82	3502	1749	4.37	
	15	1025	1025	53.65	3497	1742	3.74	
	16	1019	1020	53.44	3455	1733	3.73	
	17	1039	1038	53.10	3502	1764	3.74	
	18	1040	1039	52.93	3496	1765	3.74	
	19	1035	1033	53.05	3468	1755	3.72	
	20	1051	1051	52.15	3474	1785	3.73	
	21	1041	1041	52.71	3468	1768	3.72	
	22	1026	1024	51.80	3349	1740	3.72	
	23	1055	1055	51.34	3427	1793	3.72	
	24	1056	1055	51.57	3435	1792	3.72	
	25	1059	1060	51.27	3416	1800	3.70	
	26	1010	1010	51.19	3305	1716	3.76	
	27	1009	1008	51.93	3451	1712	3.88	
	28	999	997	51.93	3378	1694	3.84	
	29	1008	1008	52.22	3437	1713	3.84	
	30	1017	1015	51.17	3433	1725	3.89	
May	1	1015	1016	51.46	3445	1726	3.88	
	2	1025	1022	51.55	3485	1736	3.89	
	3	1032	1029	51.36	3481	1748	3.88	
	4	1009	1008	51.72	3413	1712	3.85	
	5	1032	1031	50.55	3415	1752	3.86	
	6	1024	1024	50.98	3397	1740	3.83	
	7	1023	1024	51.86	3425	1741	3.79	
	8	1039	1040	51.59	3439	1767	3.77	
	9	1035	1036	52.26	3448	1761	3.75	
	10	1042	1043	51.92	3442	1771	3.74	
	11	1055	1056	51.45	3434	1794	3.72	
	12	1044	1043	51.47	3375	1772	3.70	

	13	1057	1055	51.58	3443	1793	3.72	
	14	1040	1040	51.82	3404	1767	3.72	
	15	1053	1053	51.71	3450	1788	3.73	
	16	1034	1034	51.80	3370	1756	3.70	
	17	1019	1017	50.81	3329	1727	3.79	
	18	839	839	50.00	2736	1426	3.84	
	19	804	804	51.77	2751	1366	3.89	
	20	854	857	52.27	2954	1456	3.88	
	21	862	863	52.37	2937	1467	3.82	
	22	878	878	52.81	3036	1492	3.85	
	23	881	883	52.78	3075	1500	3.89	
	24	880	883	52.57	3085	1500	3.91	
	25	875	837	52.32	2916	1423	3.92	
	26	948	947	52.74	3112	1609	3.67	
	27	949	949	52.06	3110	1613	3.70	
	28	939	941	52.52	3095	1599	3.68	
	29	948	948	51.97	3092	1611	3.69	
	30	962	961	51.51	3117	1633	3.71	
	31	956	957	51.53	3071	1627	3.66	
June	1	898	898	52.09	2860	1526	3.60	
	2	943	943	52.43	3060	1602	3.64	
	3	946	946	52.58	3052	1608	3.61	
	4	955	953	51.85	3042	1619	3.62	
	5	960	960	51.51	3032	1631	3.61	
	6	961	961	51.30	3019	1633	3.60	
	7	956	956	51.47	2988	1624	3.57	
	8	960	961	51.52	2950	1633	3.51	
	9	936	937	51.50	2899	1593	3.53	
	10	940	939	51.28	2981	1595	3.64	
	11	945	945	51.67	3021	1605	3.64	
	12	945	946	51.60	3042	1607	3.67	
	13	929	928	51.74	3000	1577	3.68	
	14	943	945	51.35	3047	1605	3.70	
	15	949	950	49.91	2984	1614	3.70	
	16	897	898	47.97	2778	1526	3.80	
	17	911	909	49.02	2841	1545	3.75	
	18	897	896	50.01	2861	1523	3.76	
	19	904	902	49.52	2875	1533	3.79	
	20	896	895	49.41	2833	1521	3.77	
	21	870	868	49.76	2757	1475	3.76	
	22	882	883	48.03	2741	1501	3.80	
	23	897	896	47.50	2748	1523	3.80	
	24	896	896	47.91	2746	1523	3.76	
	25	891	891	48.94	2749	1513	3.71	
	26	876	876	50.18	2748	1488	3.68	

	27	877	877	49.97	2749	1490	3.69	
	28	874	877	49.33	2701	1490	3.67	
	29	832	831	50.89	2644	1412	3.68	
	30	854	854	51.76	2779	1451	3.70	
July	1	856	855	51.92	2830	1452	3.75	
	2	865	865	51.81	2871	1469	3.77	
	3	876	876	51.65	2921	1489	3.80	
	4	886	884	51.17	2929	1502	3.81	
	5	849	849	51.17	2911	1443	3.94	
	6	840	839	50.76	2943	1425	4.07	
	7	841	841	50.70	2943	1428	4.06	
	8	837	838	50.94	2943	1424	4.06	
	9	822	821	50.52	2826	1394	4.01	
	10	809	808	50.60	2768	1373	3.98	
	11	833	833	50.75	2878	1416	4.01	
	12	835	835	50.14	2806	1419	3.94	
	13	794	764	51.15	2626	1299	3.95	
	14	842	842	50.54	2886	1431	3.99	
	15	843	843	51.28	2937	1433	4.00	
	16	840	840	50.85	2916	1428	4.02	
	17	853	855	50.66	2963	1453	4.02	
	18	856	857	50.29	2960	1456	4.04	
	19	857	858	50.52	2964	1458	4.02	
	20	835	834	50.85	2871	1418	3.98	
	21	839	842	50.47	2905	1430	4.03	
	22	852	856	50.08	2943	1454	4.04	
	23	830	832	50.49	2874	1413	4.03	
	24	851	854	51.23	2972	1450	4.00	
	25	840	841	50.59	2899	1429	4.01	
	26	836	837	50.28	2880	1422	4.03	
	27	843	845	50.48	2923	1436	4.03	
	28	849	852	50.40	2942	1447	4.04	
	29	842	839	51.11	2925	1426	4.01	
	30	834	830	50.35	2867	1411	4.04	
	31	841	841	50.85	2940	1429	4.05	
August	1	845	845	50.64	2961	1435	4.07	
	2	854	853	49.88	2957	1450	4.09	
	3	855	854	49.95	2957	1452	4.08	
	4	861	862	49.67	2965	1465	4.08	
	5	887	887	48.24	2834	1507	3.90	
	6	858	859	47.61	2576	1459	3.71	
	7	841	841	50.00	2618	1429	3.66	
	8	845	845	49.83	2624	1436	3.67	
	9	872	872	50.47	2746	1481	3.67	
	10	909	910	51.32	2936	1545	3.70	
	11	908	908	50.99	2923	1543	3.72	
	12	929	929	50.30	2969	1578	3.74	
	13	935	935	49.92	2973	1589	3.75	

	14	939	939	48.88	2961	1595	3.80	
	15	934	933	49.00	2936	1585	3.78	
	16	917	917	49.54	2888	1558	3.74	
	17	932	931	49.57	2950	1581	3.76	
	18	932	931	49.49	2944	1581	3.76	
	19	925	923	49.66	2933	1568	3.77	
	20	925	924	49.77	2942	1570	3.76	
	21	925	924	50.03	2941	1569	3.75	
	22	848	835	50.74	2678	1419	3.72	
	23	915	917	51.25	2968	1557	3.72	
	24	908	907	50.91	2909	1541	3.71	
	25	915	916	50.75	2932	1556	3.71	
	26	931	931	50.43	2982	1582	3.74	
	27	926	927	50.33	2890	1574	3.65	
	28	937	936	50.28	2835	1591	3.54	
	29	887	886	50.80	2684	1505	3.51	
	30	907	908	51.40	2840	1542	3.58	
	31	921	921	51.01	2894	1564	3.63	
September	1	926	927	50.79	2908	1576	3.63	
	2	907	908	50.49	2819	1543	3.62	
	3	929	930	50.53	2881	1580	3.61	
	4	919	917	51.06	2853	1558	3.59	
	5	926	926	51.28	2876	1573	3.57	
	6	920	919	50.73	2851	1562	3.60	
	7	812	800	51.20	2483	1359	3.57	
	8	936	346	51.92	1106	588	3.62	
	9	936	935	51.11	2936	1589	3.62	
	10	938	937	50.86	2927	1592	3.62	
	11	946	945	51.11	2953	1605	3.60	
	12	956	955	50.68	2953	1622	3.59	
	13	949	949	50.73	2932	1612	3.58	
	14	951	950	51.83	2962	1614	3.54	
	15	957	957	50.53	2948	1625	3.59	
	16	904	902	50.39	2859	1533	3.70	
	17	918	914	51.07	2941	1554	3.71	
	18	930	927	50.18	2970	1574	3.76	
	19	931	930	50.03	2973	1581	3.76	
	20	925	925	50.90	2983	1572	3.73	
	21	914	911	51.75	2968	1548	3.70	
	22	894	894	53.58	3011	1519	3.70	
	23	869	868	55.35	3003	1475	3.68	
	24	834	832	55.77	2997	1413	3.80	
	25	820	821	55.77	3008	1394	3.87	
	26	823	824	55.37	3013	1399	3.89	
	27	860	859	54.98	3083	1460	3.84	
	28	834	675	54.03	2365	1147	3.82	
	29	915	914	52.56	3167	1553	3.88	
	30	934	931	51.30	3149	1583	3.88	

October	1	954	955	46.76	3177	1622	4.19	
	2	957	955	50.13	3178	1622	3.91	
	3	972	972	49.76	3182	1652	3.87	
	4	939	938	49.61	3082	1593	3.90	
	5	893	891	49.51	2976	1514	3.97	
	6	851	852	51.81	2988	1447	3.98	
	7	833	832	53.01	2945	1413	3.93	
	8	841	840	53.50	2996	1427	3.92	
	9	830	830	54.27	2991	1410	3.91	
	10	823	823	54.75	2987	1399	3.90	
	11	822	821	54.92	2988	1395	3.90	
	12	828	826	54.66	2997	1403	3.91	
	13	823	822	54.60	2979	1396	3.91	
	14	855	854	54.45	3068	1451	3.89	
	15	884	887	53.97	3171	1507	3.90	
	16	887	889	54.27	3231	1510	3.94	
	17	899	900	53.67	3247	1529	3.96	
	18	912	911	52.74	3248	1548	3.98	
	19	849	629	53.49	2305	1069	4.03	
	20	947	950	53.58	3244	1614	3.75	
	21	983	982	54.25	3332	1669	3.68	
	22	993	994	52.79	3335	1689	3.74	
	23	1012	1012	51.93	3357	1720	3.76	
	24	1027	1027	51.09	3357	1746	3.76	
	25	1012	1013	52.16	3350	1722	3.73	
	26	999	1002	52.80	3354	1702	3.73	
	27	1018	1017	52.15	3350	1729	3.72	
	28	1016	1017	52.26	3346	1727	3.71	
	29	1000	1000	52.83	3294	1699	3.67	
	30	991	994	53.59	3355	1688	3.71	
	31	994	996	53.21	3348	1692	3.72	
November	1	1019	1018	51.28	3353	1730	3.78	
	2	1010	1009	51.18	3307	1714	3.77	
	3	1028	1027	50.81	3347	1745	3.78	
	4	1019	1019	50.89	3323	1732	3.77	
	5	924	841	51.81	2737	1429	3.70	
	6	1006	1007	52.30	3368	1710	3.77	
	7	1015	1013	52.24	3399	1722	3.78	
	8	965	964	52.19	3215	1637	3.76	
	9	1006	1005	51.90	3368	1708	3.80	
	10	1025	1026	51.17	3406	1744	3.82	
	11	1026	1025	51.51	3425	1742	3.82	
	12	1020	1022	51.88	3426	1736	3.80	
	13	1024	1024	51.51	3425	1740	3.82	
	14	1028	1029	51.37	3431	1748	3.82	
	15	1012	1012	50.67	3321	1719	3.81	
	16	1029	1029	50.42	3282	1748	3.72	
	17	1008	1006	51.60	3261	1710	3.70	

	18	1011	1011	51.98	3404	1718	3.81	
	19	1019	1017	50.74	3352	1729	3.82	
	20	1030	1030	50.97	3411	1750	3.82	
	21	1013	1014	52.17	3425	1723	3.81	
	22	1022	1024	51.93	3472	1740	3.84	
	23	1024	1026	51.14	3423	1743	3.84	
	24	1030	1030	50.59	3404	1749	3.85	
	25	983	980	51.78	3421	1665	3.97	
	26	992	992	51.32	3532	1686	4.08	
	27	994	993	50.61	3484	1687	4.08	
	28	987	987	50.97	3478	1677	4.07	
	29	1008	1006	49.98	3484	1709	4.08	
	30	1000	1000	50.01	3461	1698	4.07	
December	1	1012	1011	49.39	3464	1718	4.08	
	2	984	989	50.53	3455	1680	4.07	
	3	992	992	49.69	3420	1685	4.08	
	4	1011	1010	49.12	3459	1716	4.10	
	5	1012	1011	49.03	3455	1717	4.10	
	6	970	977	51.08	3445	1659	4.07	
	7	998	999	49.84	3457	1697	4.09	
	8	971	973	50.30	3382	1654	4.07	
	9	999	999	49.99	3462	1697	4.08	
	10	996	994	50.29	3464	1690	4.08	
	11	757	675	46.45	2413	1147	4.53	
	12	830	523	54.25	1928	889	4.00	
	13	1009	1009	52.14	3646	1714	4.08	
	14	1046	1037	49.13	3554	1762	4.11	
	15	1027	1021	49.43	3513	1734	4.10	
	16	1001	998	50.33	3500	1695	4.10	
	17	1032	1029	48.54	3497	1748	4.12	
	18	1019	1018	48.77	3436	1729	4.08	
	19	1037	1033	47.85	3433	1756	4.09	
	20	1016	1012	48.37	3386	1720	4.07	
	21	1011	1011	49.08	3435	1718	4.07	
	22	1013	1014	48.68	3434	1722	4.10	
	23	1047	1047	47.78	3378	1778	3.98	
	24	1068	1064	48.39	3435	1807	3.93	
	25	1048	1044	49.30	3433	1774	3.93	
	26	1071	1065	47.93	3414	1810	3.94	
	27	1048	1043	48.84	3385	1773	3.91	
	28	1048	1044	49.20	3404	1773	3.90	
	29	1054	1050	48.92	3405	1784	3.90	
	30	1046	1041	48.71	3367	1769	3.91	
	31	1053	1048	49.03	3415	1781	3.91	

Appendix B: Data quality Pedigree matrix

Indicator score	1	2	3	4	5 (default)
Reliability	Verified data based on measurements	Verified data partly based on assumptions ***or*** non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g. by industrial expert)	Non-qualified estimate
Completeness	The data is representative for the process considered, over an adequate period to even out normal fluctuations	The data is representative for >50% of the process considered, over an adequate period to even out normal fluctuations	The data is representative for only part of the process (<<50%), ***or*** >50% but for shorter time periods	The data is representative for only one part of the process considered, ***or*** for small part of the process but for shorter time periods	It is not known which part of the process the data represents
Temporal correlation	Less than 3 years of difference to the time period of the dataset	Less than 6 years of difference to the time period of the dataset	Less than 10 years of difference to the time period of the dataset	Less than 15 years of difference to the time period of the dataset	Age of data unknown or more than 15 years of difference to the time period of the dataset
Geographic correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions.	Data from area with slightly similar production conditions	Data from unknown ***or*** distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia)
Further technical correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study (i.e. identical technology) but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials	Data on related processes on laboratory scale ***or*** from different technology

Figure 34: Data quality pedigree matrix as adopted from Ecoinvent