TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Civil Engineering and Architecture

LIFE CYCLE ASSESSMENT OF MUNICIPAL SOLID WASTE TREATMENT OPTIONS IN ESTONIA

OLMEJÄÄTMETE KÄITLEMISVIISIDE OLELUSRINGI HINDAMINE EESTI NÄITEL

MASTER THESIS

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Tallinn 2021

(*On the reverse side of title page*)

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Department of Civil Engineering and Architecture

THESIS TASK

Student: Mahmoud Magdy Nouh, 194399EABM
Study program, EABM, Environmental Engineering and Management
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Thesis topic:
(in English) LIFE CYCLE ASSESSMENT OF MUNICIPAL SOLID WASTE TREATMENT OPTIONS IN ESTONIA

(in Estonian) OLMEJÄÄTMETE KÄITLEMISVIISIDE OLELUSRINGI HINDAMINE EESTI NÄITEL

Thesis main objectives:
1. To identify the most suitable municipal solid waste treatment options for Estonia based on the current practices.
2. To evaluate the environmental impact of municipal solid waste treatment options using the life cycle assessment technique
3. To recommend the most suitable municipal solid waste treatment from an environmental point of view

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Literature review and research introduction	14.06.2021
2.	Open LCA analysis of different case scenarios	05.07.2021
3.	Results, conclusion, and recommendations	15.07.2021

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1. INTRODUCTION

Municipal solid waste (MSW) and municipal solid waste management pose huge challenges in recent times. Most of the municipal solid waste generated (estimated around 190 million tons [1]) in Europe is still disposed of through unsustainable methods with over half going either for landfilling or incineration [2].

In Estonia in 2019 according to the waste reporting system, a total of 465.14 thousand tons of municipal solid waste (MSW) was generated (excluding a separately collected packaging waste), of which about 71% is still collected and treated as mixed waste. There are separately collected streams of paper and cardboard 8.7%, biodegradable waste from households and gardens 5.1%, bulky waste of 3%, and Glass, textiles, and metals of 1% combined [3].

The separately collected packaging waste streams were reported to reach a total of 217.17 thousand tons in 2018 with an increase in separate collection streams of 13% from the previous year and almost doubled in the last 10 years. The major fractions currently collected in packaging waste are Glass packaging 14.3%, plastic packaging 14.5%, Wooden packaging 26.1%, metallic packaging 5%, paper and cardboard packaging 22.4%, and 16.6% of mixed packaging materials [3].

The main concerns about the Municipal solid waste and waste management systems are the adverse environmental impacts on the ecosystem and human health, such impacts are connected to waste collection, treatment, and disposal.

With the ongoing growth in waste generation, the environmental impacts associated with the waste management system are expected to deteriorate even further without a proper strategy of legislation to maintain environmental sustainability and adapt the most environmentally efficient waste management option.

To comply with the European policy [4], national, regional, and local policymakers and stakeholders have important decisions to make in the next couple of years about the sustainable management of municipal solid waste and how to achieve set targets for recycling and move up the waste hierarchy

The research aim of the current thesis is to evaluate the MSW management treatment options in Estonia using the life cycle assessment The research is focused on identifying the most suitable MSW treatment options for Estonia based on the current practices, evaluation of the environmental impacts, and providing recommendations on the most suitable treatment options from the environmental point of view.

2. THEORETICAL BACKGROUND

2.1. EU legislation and circular economy targets

The council of the European Union was always a driving force toward environmental protection and sustainable development both on international and regional levels. The goals established to reach sustainable development were the guidance to the council and also the pushing force to make a legislative action helping the EU member states to make major changes in their environmental management systems economically and legally to ensure the protection and preservation of the environment.

Waste management generally and municipal solid waste management especially were a major challenge in the EU considering the large reliance on unsanitary landfilling in the past and the environmental impacts associated with it. The council of the European Union decided to take actions regarding waste management improvement by transforming it into a sustainable material management system by adapting the modern waste management hierarchy that emphasizes the importance of waste prevention to improve the quality of the environment, protecting human health and ecosystem while making sure an efficient and rational utilization of natural resources through the concept of a circular economy.

In order to achieve a sustainable economy, additional measures needed to be taken on sustainable production and consumption, by focusing on the whole life cycle of products [4]. Such a change of scope would reflect a better image of how production and waste management truly impact the environment and it helps to assess the different alternatives and potential improvements.

The Initial targets were laid down by the council of the European Union and stated in the Waste Framework Directive WFD (2008/98/EC) to implement a circular economy principle in all member states. The Initial targets were amended by a new Directive (2018/851) setting up a higher bar for the member states to ensure a true reflection of the European union's ambitions to move toward the circular economy [5].

To achieve goals set by the council all member states must adopt economic instruments and other measures such as landfill charges, pay-as-you-throw scheme, and extended producer responsibility scheme, along with any necessary additional measures to assure the application of the waste hierarchy and compliance with the set targets. [4]

The European Parliament and the council of the EU acknowledge the difference between member states in terms of environmental targets. In accordance, the council is to pressure all member states - which by 2013 had prepared for re-use and recycling rates below 20% or landfilling more than 60% of their MSW - to enforce stricter environmental policies and increase their recycling capacity to achieve their targets by 2025, 2030, and 2035 [4].

The targets for preparation for reuse and recycling of municipal waste were set to be at least 55% by weight at the end of 2025, 60% by 2030, and 65% by 2035 and in case of postponing not less than 5% from the original target should be achieved [4]. The reduction targets as per capita food waste amount reduction were set at 30% by 2025 and 50% by 2030.

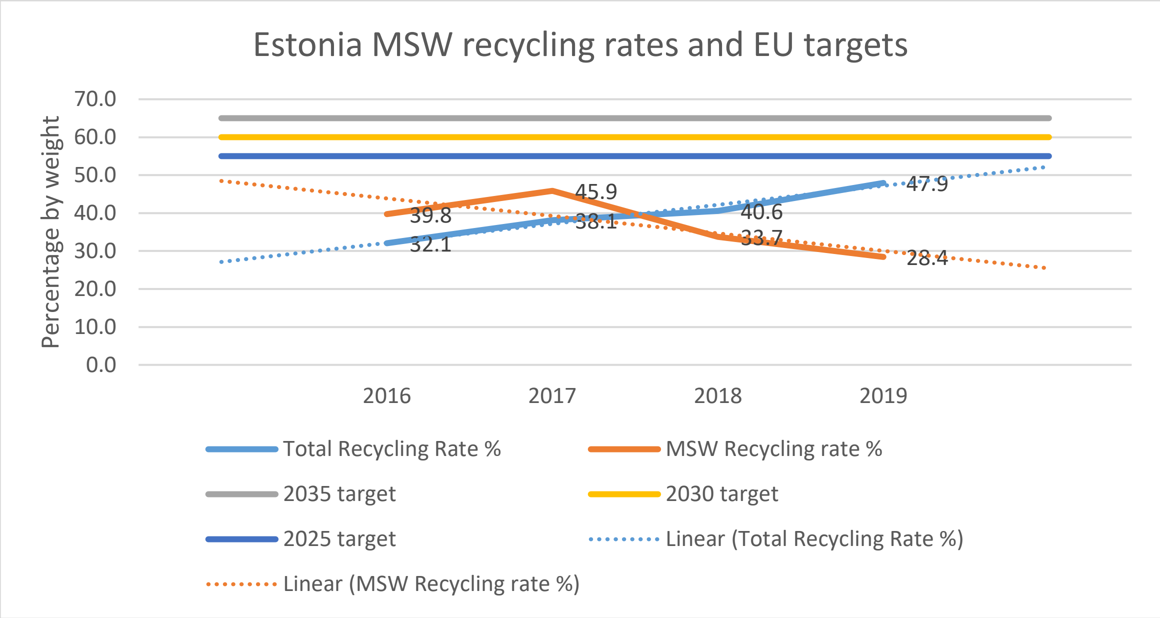


Fig (1)- Estonia recycling rates and EU Targets. [3] [4]

Despite the clear increase in waste recycling rates in recent years, MSW recycling rates have been declining due to some factors. The relatively lower costs of mixed MSW collection in comparison to the rent of separate collection pins [6], the lower costs to waste incineration process, and the low profits from the recycling process.

The targets were set in force that all member states shall set up a separate collection for paper, metal, plastic, glass, textiles, and municipal hazardous waste by the 1st of January 2025.

The European Commission decided that it shall re-evaluate the progress and set targets in accordance with member state compliance and set new targets by the end of 2024.

2.2. Municipal waste management in Estonia

The Estonian Waste Act established the legislative grounds on which waste management plans were developed in Estonia by enforcing important policies and setting the framework of the waste handling system to reflect the state ambition of achieving sustainable waste management and compliance with EU targets.

The waste management system in Estonia adopts the modern waste hierarchy by giving higher priority in waste management to waste prevention options followed by material recycling (Fig.2).

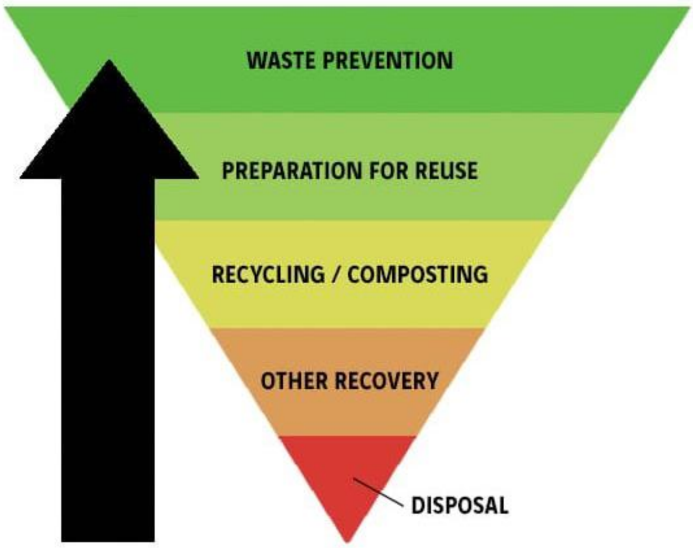


Fig (2) – Modern waste Hierarchy. [4] [6]

The Estonian waste management system was completely privatized in the last 2 decades and the management responsibilities lie with the local municipalities to organize and define the suitable waste treatment fitting each area.

Municipal solid waste is defined in this research according to the Estonian Waste act and in line with the European union waste framework directive (2008/98/EC) and its amendment Directive (2018/851) to be the waste generated by households and any other service that produce a waste of the same composition and nature to household waste [7].

As shown in Fig.3, the increasing trend in the recycling of materials combined with some of the main legislative actions taken by the Estonian government since joining the EU in 2004.

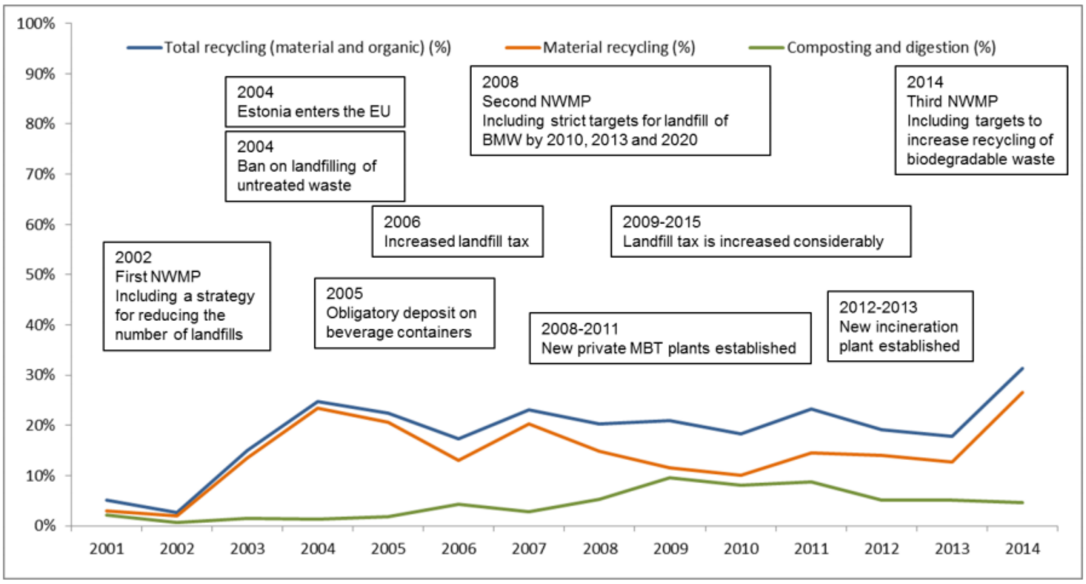


Fig (3) – Recycling of municipal waste and important policy initiatives [8]

The waste act adapted clear legislation to mandate the sorting of waste both at source and after collection, facilitating separate collection processes, and prohibited the landfilling of unsorted waste, such policies reflected the positive trend in Estonian waste management, recycling, and material recovery.

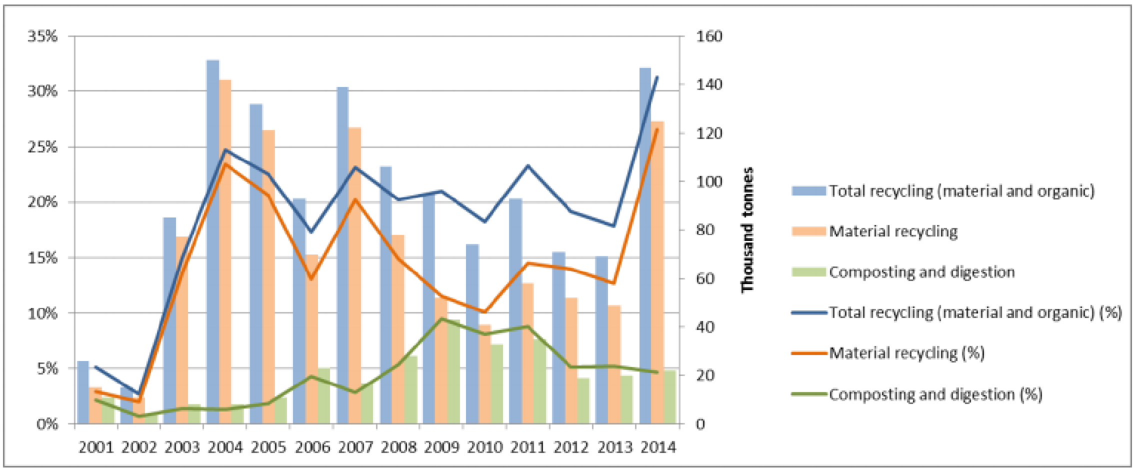


Fig (4) - Recycling of the municipal solid waste in Estonia, 2001–2014, percent and tons [8]

2.2.1. Recycling

Recycling is one of the key elements in mitigating the environmental impacts of waste management in the modern waste hierarchy by avoiding the emissions resulting from raw material extraction. The EU legislation [4] is getting stricter with enforcing policymakers to make a clear change in waste management systems to achieve higher recycling rates which will contribute to lower the carbon footprint and lower impact on the environment.

Estonia made a clear change by introducing the extended producer responsibility legislation in 2004 which initiated a deposit refund system for the packaging waste. [9] The packing waste is collected from companies and retailers, and for the household packaging waste, it is majorly collected through the collection point network and a deposit refund for the packaging of beverage containers (glass, aluminum, and plastic containers). Besides the packaging collection, a separate collection for glass, paper and cardboard, textile, and bio-waste is applied. [9] [10]

The package recovery system has been very effective and quite successful in retrieving packaging waste which reached over 85% of beverage packing return and with packing waste separately collecting reaching the third of all the municipal waste collection and it has quite potential to grow even more to reach the target of 50% of municipal waste being recycled through separate collection [10].

Along with the separate collection process the collected mixed waste goes under separation and material recovery process. In Estonia, there are many mechanical separations and material recovery facilities for the sorting and preparation of recycled material for market use.

Mechanical separation plants are responsible for waste sorting from the mixed waste stream, a recent study [11] showed the composition of recoverable materials from mixed waste to be:

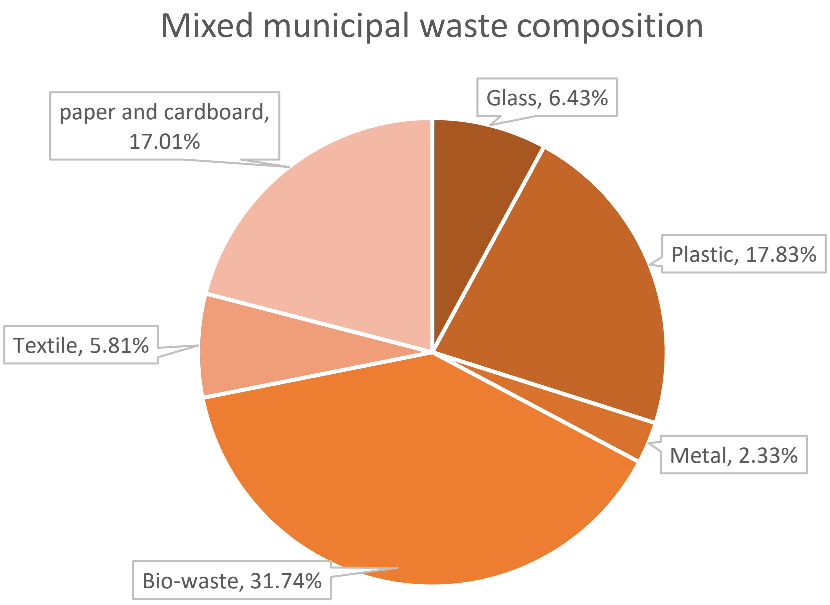


Fig (5) – Mixed MSW composition in Estonia. [11]

Bio-waste separately collected and obtained from the waste separation process is recycled with garden waste through anaerobic digestion processes to create compost material with the retrieval of bio-gas to be utilized in energy production.

Waste recycling is a key factor in the reduction of environmental impacts caused by raw material extraction which results in lower energy and natural resources consumption. Also, waste recycling limits the emissions resulting from waste disposal in landfilling and waste incineration.

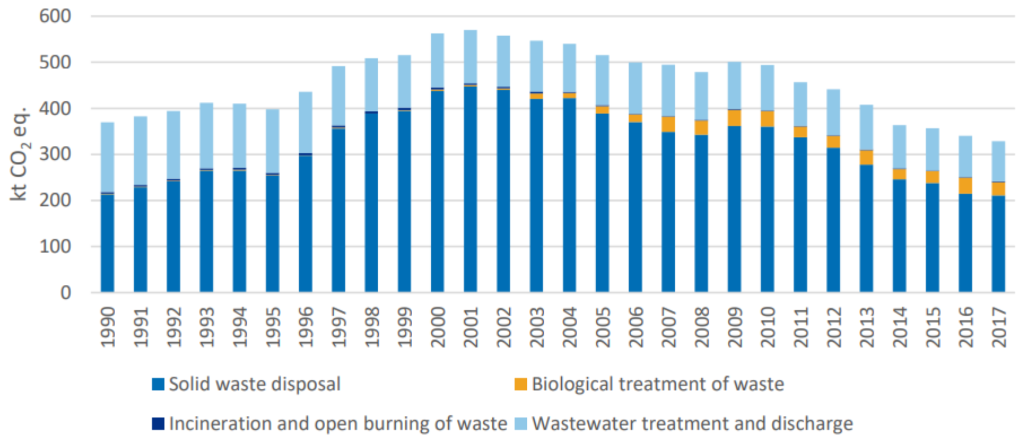


Fig (6) – Greenhouse gas emissions from the waste sector in Estonia. [12]

2.2.2. Incineration

Waste incineration is one of the "Waste to Energy" WtE transformation methods providing an economically efficient tool that can sustain better energy production and providing more advantaged scalable municipal waste treatment options.

Estonia made a clear transformation from landfilling to waste incineration with the construction and launching waste incineration at Iru power plant in 2013 and now it processes up to 260000 tons of municipal waste each year exceeding 50% of the municipal waste produced in Estonia and generating 50 MW of heat and 17 MW of electricity [13] and the plant is offering a more environmental replacement in heat and electricity generation than oil shale burning which is the dominating energy generating method used in Estonia.

Waste incineration is one of the most controversial waste management options for holding both strong advantages and disadvantages on many different aspects economic and environmental.

The waste incineration process is responsible for several environmental issues such as residual ash and flue gas which contains particulate matter, heavy metals like mercury, dioxins, furan, sulfur dioxide, carbon dioxide, and hydrochloric acid [14] [15].

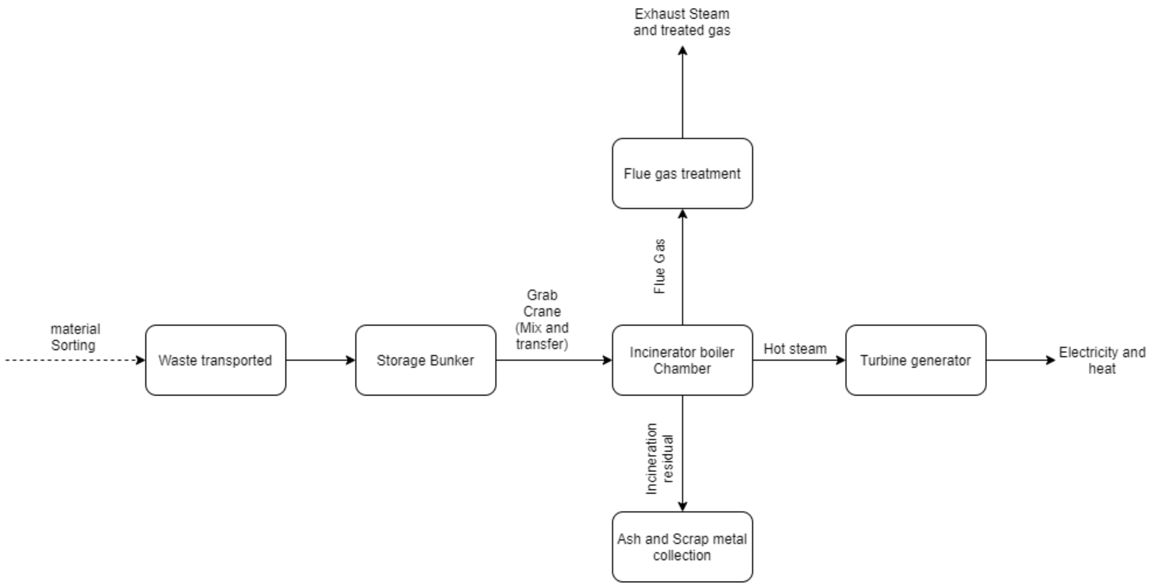


Fig (7) – Iru power plant Schematic diagram. [13]

The incinerators are designed to sufficiently break down all organic and some inorganic molecules allowing them to react with oxygen and nitrogen from the air and the waste stream calorific value varies based on the different waste composition and being monitored to sustain a steady energy production [16].

In the Iru power plant, the flue gas is treated through cycles of cleaning using lime to neutralize the toxins before filtration and releasing the flue gas with only steam and remaining carbon dioxide [13].

The lime scrubbing technique is used to neutralize and remove toxins such as sulfur oxides SOx, hydrogen chloride HCl, and hydrogen fluoride HF. Hydrated Lime is sprayed in the air and injected into the exhaust ducting the removal of SOx and HF can reach 95% and the removal of HCl can reach over 99% [15]. The neutralization reaction happens as follows.

$$Ca\,(OH)_2 + SO_2 \rightarrow CaSO_3 + H_2O$$

$$Ca\,(OH)_2 + SO_2 + 0.5O_2 \rightarrow CaSO_4 + H_2O$$

$$Ca\,(OH)_2 + 2HCl \rightarrow CaCl_2 + 2H_2O$$

$$Ca\,(OH)_2 + 2HF \rightarrow CaF_2 + 2H_2O$$

The waste is stored in the Iru power plant in a closed area so no odor will disturb neighboring areas. The plant incinerates around 720 tons [13] of mixed waste every day. Additionally, the scrap metal in the bottom ash after the incineration process is being fully recycled [13].

Management and recycling of produced fly ash and bottom ash from the combustion process is one of the key factors to determine the full environmental impact of an incineration plant. A lot of recycling pathways are being projected to make full use of incinerator ash to minimize the impacts of the incineration process.

Different studies [17] [18] [19] [20], evaluated the environmental impacts from the use of ash in different products as a replacement for raw materials such as cement production and ceramics, while different approaches evaluated the benefits of using fly ash in construction processes like pavement layer. Despite the lack of the full life cycle assessment studies on the different use cases of wastes incineration ash, the environmental impact assessment studies showed a good potential in its utilization [17]

With higher rates of recycling and energy recovery from incineration, there is an anticipated reduction in greenhouse gas emission as a net result [21]. The resulting carbon emission from the incineration process after the proper treatment is somewhat equivalent to the emission from 35 private house boilers [13].

One of the concerns about waste incineration is that it works disincentive to the principles of the waste hierarchy by offering an economical advantage in energy recovery from waste incineration and encouraging the generation of more unseparated waste [2]. While the impact of incineration is still debatable in comparison with other recycling and material recovery options, the incineration option offers less flexibility economically because it requires a huge fund ahead of it starting and it works as an obstacle in developing and adapting new emerging environmental solutions and strategies in time compared to other nations depending solely on recycling [22].

2.2.3. Landfilling

Landfilling is the most traditional and the oldest known waste management method used in waste management systems. Traditionally landfill sites used to be open dumpsites just for disposal of waste outside the city. The convenience of the solution and the rapid increase in population followed by the increase in waste generation caused the landfill site numbers to grow further and be the main method of waste management everywhere.

The main environmental impact connected to open dumpsites is the landfill gas emission which consisted mainly of methane one of the main contributors to greenhouse gases. Another environmental impact is associated with the leachate formation with most of the organic contaminants, pathogenic microorganisms and, the high concentration of ammonia slipping through landfill layers with rainwater to groundwater levels and reaching the drinking water cycle causing numerous health risks and environmental hazardous on the ecosystem.

The legislation imposed by the EU (landfill directive and waste directive) helped make a huge change in landfill policies around member states by making a change toward sanitary landfill sites with obligatory landfill gas management and leachate control to curb the environmental impacts from landfill sites.

Estonia had over 200 unsanitary landfill sites before 1990 before the imposing of the landfilling tax, the tax provided the needed incentive to divert waste from landfills to more sustainable options. Nowadays the unsanitary landfilling sites are closed and replaced by 5 sanitary non-hazardous landfill sites [9] In light of the new waste management plan adopted by the Estonian government and the impacts of the waste act legislation with less than 10% of the municipal waste going to landfill sites.

Estonia was able to achieve its targets for biodegradable waste sent to landfills for 2020 by 2012 and significantly decrease the amount of landfilled waste. [10].

The landfilling of waste has been on a steady reducing pace for the last 10 years and Fig.8 shows the fluctuations in the amount of waste ending in landfills with the lowest amount recorded in the last years

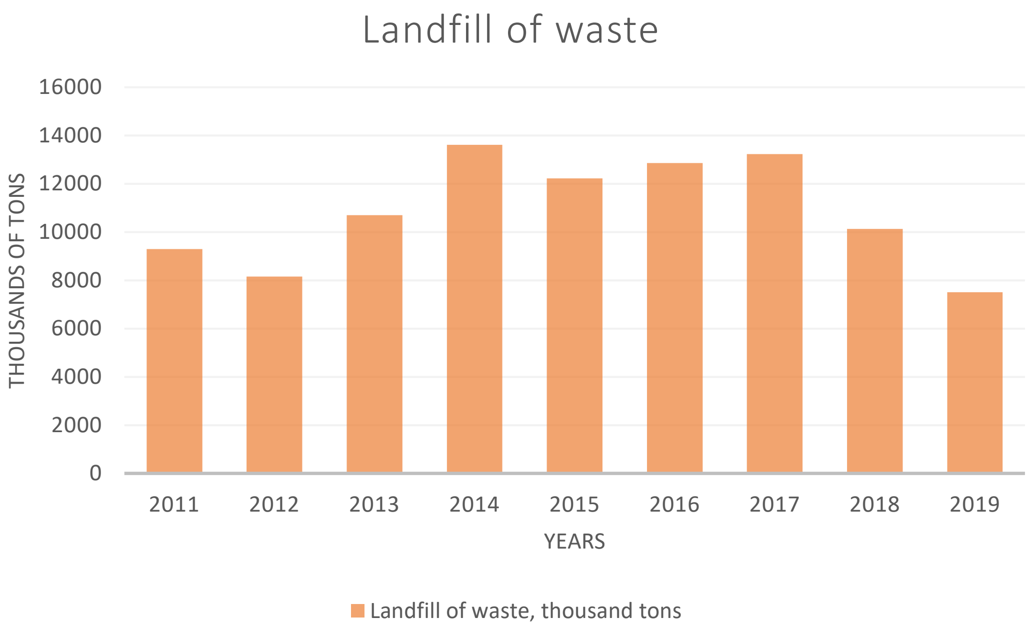


Fig (8) – Amount of waste goes to landfill per year in Estonia [23]

Waste ending in landfill sites will remain a cause of environmental impacts for a very long time and a landfill site needs proper assessment to choose the fitting options in landfill gas collection and utilization and leachate prevention and treatment.

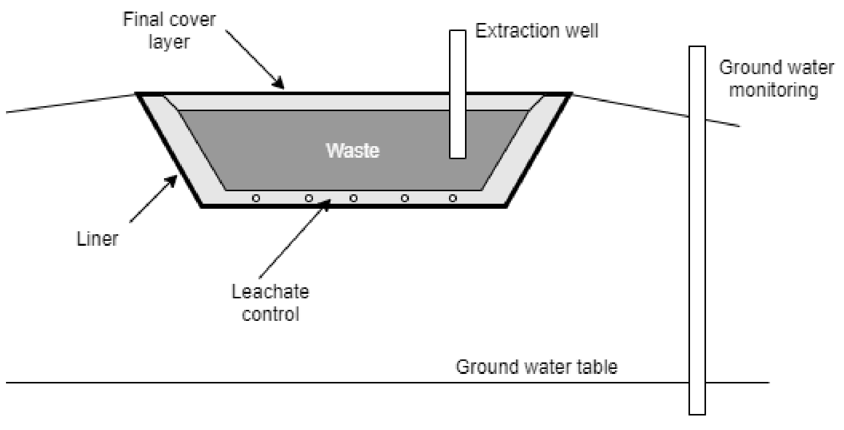


Fig (9) – Illustration of a typical Landfill site. [24]

Landfill leachate needs a proper pre-treatment process before discharging it and various treatment methods were assessed previously in different landfill sites around Estonia, the leachate composition and amount however is highly dependent on the age of the landfill site and the composition of waste reaching the landfill making it interconnected with the performance of waste sorting facilities [24].

Generally, leachate amount is assumed to be a certain percentage of rainfall within a season, and it contains organic and inorganic contaminants such as ammonia, humic acids, heavy metals, and inorganic salts [24].

The decomposition of organic waste under anaerobic conditions causes the formation of methane CH_4 and carbon dioxide CO_2 along with the formation of nitrogen oxides NOx and other volatile organic compounds which make the landfill gas management in the landfill site of great importance.

Operational landfill sites in Estonia have a gas collection and flaring system installed in all the landfill sites and the landfill gas is extracted through extractions wells the most common types used in Estonia are the vertical wells which are used in Jõelähtme landfill and horizontal pipe collection like in Väätsa and Uikala [24].

2.3. Summary of the environmental impacts for the MSW management

The waste management system in Estonia is highly relying on waste incineration as the main waste treatment method along with waste sorting facilities for the collected mixed waste. According to the recent collection data statistics [1] [23] more than half of mixed waste collected in Estonia end up in incineration and the rest is being recycled and landfilled.

The total amount reaching landfilling sites is decreasing and giving good indications on achieving Estonia targets for landfilling but proposing a different economical aspect about the over-investment in the landfilling [24] from past years and possible utilization of landfill sites in future with the anticipated reduction in landfill waste.

With proper landfill management, the environmental impacts are minimized, and by utilization of landfill gas in energy production, the environmental impacts of the landfill reduce even further but the long-term management of landfill site and site closure needs to be considered with more dedicated studies to evaluate each landfill site case and proper management suitable for its condition.

Incineration being the main MSW treatment method adopted in Estonia. The major challenge attributed to the waste incinerator unit is the greenhouse gas emissions from flue gas and the treatment and utilization of incinerator ash as a by-product similarly to the collected scrap metal after incineration.

In a previous study [21] to determine the greenhouse gas emission from different MSW treatment case scenarios in Estonia, it was found that even with proper landfill management and high landfill gas collection rates, there was a significant reduction in greenhouse gas emissions for higher rates of recycling and incineration rather landfilling.

Another environmental impact is addressed in the same study [21] about the collection and transportation of waste as most of the waste undergoes multiple trips between collection source, sorting facilities, import, export, and treatment, and transportation distance can play a key role in the amount of greenhouse gases emissions.

In a separate dedicated study [25] to determine the biomass content in the incinerated MSW at IRU power plant and as a result of the 1-year analysis it was found that biomass share of approximately half of the MSW weight sent to the incinerator and result in annual average CO_2 emission was approximately 429 kg.

A comparative study [26] between MSW recycling and incineration was done on MSW in Denmark, The study showed a clear advantage in most of the impact categories for almost all material fractions for recycling. However, the study suggested that the impact of incineration when combined with energy recovery instead of coal-based energy source and recycling of fly ash and scrap metal the results for cardboard and plastic fractions showed potential in environmental benefit from the incineration process.

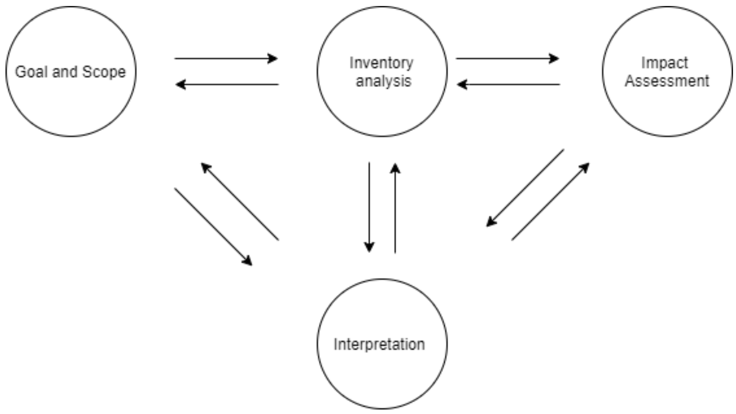
A lifecycle assessment model for recycling scrap metal from waste incineration in Switzerland [27] showed that even though direct recycling has greater benefits in some countries where most of the waste ends up being incinerated.

While assessing the impacts on air pollution from the incineration process a study [14] found that with proper energy recovery the incineration is considered a viable option for green energy production and with extensive air pollution control there will be no significant impacts from the waste incinerator in comparison of energy produced from fossil fuel.

3. METHODOLOGY

As a method of determination for the full environmental impacts for municipal waste at the end of life stage, the life cycle assessment approach was found to be the best approach that could categorize such impacts and assist in finding the optimal solutions and the assessment of different alternatives to achieve the set goals.

Life cycle assessment is one of the key tools for evaluation of environmental impacts and providing support to decision making by considering the full life cycle of products and targeting the key elements that can eliminate major environmental impacts. And it follows 4 main stages.



Fig(10) – Main stages of life cycle assessment [28]

The European Union aims to transform toward sustainability and circular economy and by the assistance of implementing life cycle thinking practices as a part of the environmental evaluation to include the end-of-life treatment within the product assessment.

The lifecycle assessment is based on the best practice according to ISO standards 14040 using the green delta openLCA software V1.10.3, Ecoinvent Database 3.7.1, and the Recipe impact methods for Mid-point and End-point impact categories.

The research is based on the case study of the municipal waste management system in Estonia by evaluating the current practices of municipal waste management treatment options to determine the environmental performance of the current practices through the life cycle assessment and to give recommendations on the best pathway of treatment options suitable for the local conditions.

3.1. Life cycle assessment

As a method of determination of environmental impacts of the waste treatment options for end-of-life management a gate-to-grave life cycle assessment model of the treatment options was made to present the environmental consequences of treatment options adopted in Estonia with the following consideration in studied scenarios:

- The major reliance in waste management in Estonia due to socio-economic factors is on the waste to energy through both waste incineration and mechanical and biological treatment.
- Potential increase in recycling to comply with the EU targets for recycling and material recovery.
- potential decrease in landfilling combined with higher recycling and material recovery rates.
- Recent permission by the government for expansion of incineration of bio-degradable waste
- Plans of expansion in separate collection of bio-waste and bio-waste digestion to produce compost.
- The Environmental impacts connected to the waste management treatment options are highly reliant on the composition and the volumes of waste produced.
- Consideration of the increasing trend in waste generation and the possible approaches to stabilize the consumption to achieve waste prevention.

3.1.1. Allocation

The ash and scrap metal collected from the incineration process are being recycled and will be considered in this research as by-products of the incineration process along with heat and electricity. The emissions from the collection and transportation of the by-products will be allocated by system expansion.

3.1.2. Functional Unit

The functional unit is calculated based on the MSW collection data for the year 2019 [3] which was reported to be 465141 thousand tons of which 333620 thousand tons are collected as mixed MSW with additional 216720 thousand tons of separately collected packaging waste and 68181 or separately collected recycled material. Based on waste treatment technology percentage, different case scenarios will be assessed.

3.1.3. Limitation and assumptions

The research goal to evaluate different case scenarios of MSW management was obstructed by certain limitations.

The study scope focused on the MSW primarily, hence other different types of Municipal waste were neglected during the calculations.

There was a lack of available data on the specific amounts of Refuse Drive Fuel used by Kunda Cement factory neither any available data about the amounts produced yearly by Tallinn Recycling Center or Ragen sell AS.

According to the waste reporting system [3], about 10% of MSW have unspecified handling and around 5% is being exported hence all the amounts to be calculated for evaluation scenarios will be modified to account for the difference.

There was no data available for the last year 2020 in the waste reporting system and statistics neither on any available database, most recent data were used as stated not older than 2017.

Preparation for reuse and recycled material preparation processes are considered to be at the Tallinn recycling center with a transportation distance of 21 Km per trip and the waste incineration is considered to happen at iru power planet solely with a distance of 12.5 Km per trip from Tallinn city center. All distances are estimated by measuring traditional truck routes.

All waste and recycled materials are transported by an ordinary garbage truck with a 21-ton capacity.

The data provided in the analysis and openLCA model is mainly based on Estonian data when available and substituted with European data (EU-27) then global data (GLO).

3.2. Waste Management Scenarios

For the evaluation of MSW management impact, three different case scenarios are assessed in this research.

The base scenario for waste management that is being evaluated is representing the current waste management methods and their current percentages as end-of-life options in Estonia according to the last statistical data available for 2019 [1] [3] [23].

The first evaluated case scenario is supported by the Estonian government's compliance with the EU legislation to reach at least a 60% recycling rate in the next decade [4]. The second scenario would be to evaluate the potential of increasing the recycling rate to the desired rates set by the EU targets Lower landfilling rates with more Mechanical and biological treatment and Refuse drive fuel generation

A Second hypothetical scenario would evaluate the increase in separate collection for bio-waste and MSW recycling rates not only to comply with the EU targets but exceeding it to majorly rely on waste recycling. This scenario would evaluate the benefits of solely relying on waste recycling instead of waste incineration and getting rid of waste disposal in landfills. MSW will be collected as separate recycled material streams with direct transportation to preparation for re-use and recycling facility, the refuse would be sent for incineration.

Table(1) – Research case scenarios

Method	Incineration with scrap metal recycling	Recycling and material recovery facility	Landfilling with landfill gas recovery
Base scenario	45%	28%	14%
Scenario 1	35%	60%	5%
Scenario 2	10%	90%	-

3.3. Process maps and system boundaries

The process map on which the life cycle assessment model will be based is focusing on the end-of-life treatment options. The system boundaries were drawn to clarify the stated scope by excluding the impacts originating from the waste collection step and focusing more on the treatment processes' impacts and transportation between different processes.

The following scheme elaborates the baseline of MSW treatment in Estonia.

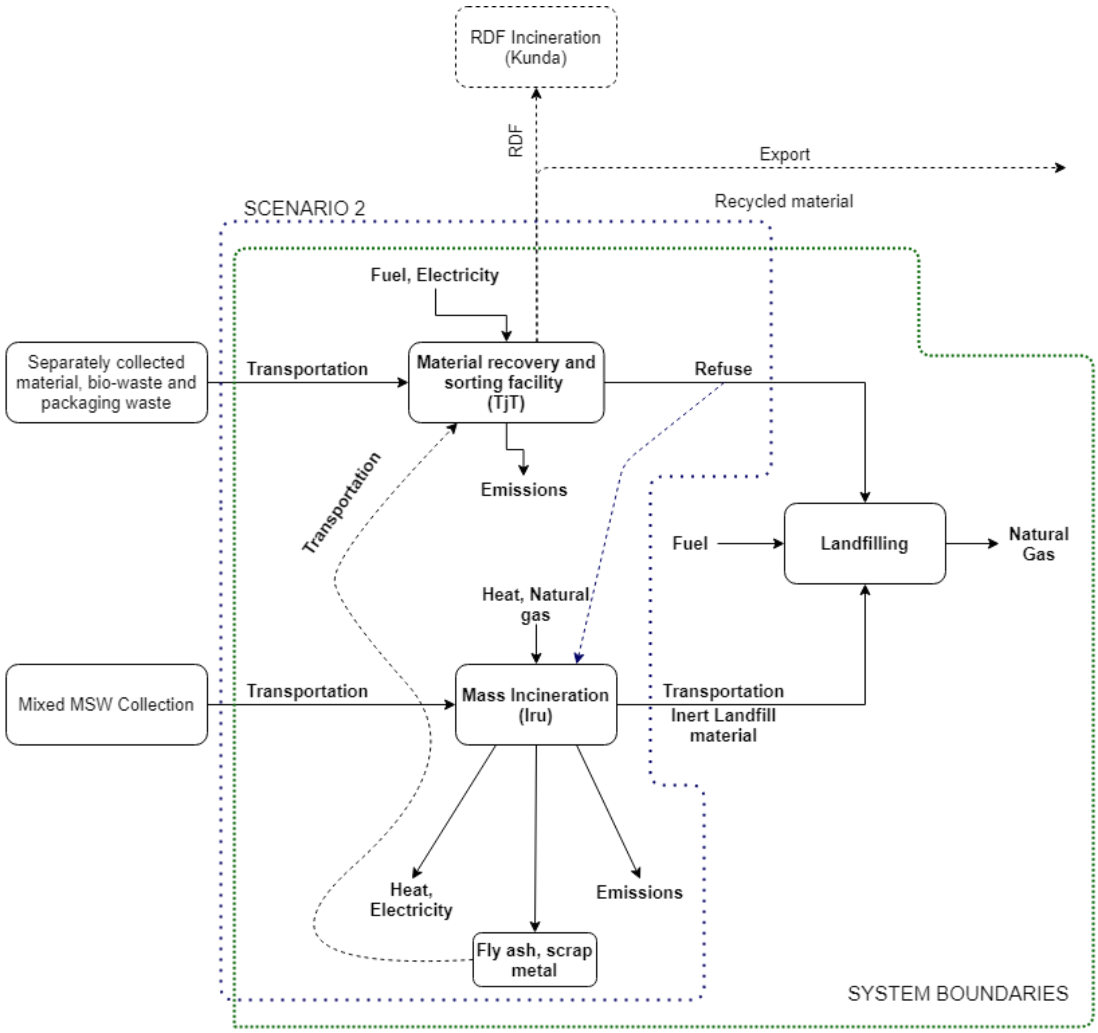


Fig (11) – Waste treatment process map and system boundaries

3.3.1. Waste incineration process

The waste collected from the sorting and storage facility after removing the recyclable materials fractions is being sent to the incinerator in a steady feed by trucks.

The waste incineration process starts with the transportation of waste to the plant storage facility, continuous mixing of waste patches ensures the consistent calorific value for the waste incinerated.

The waste storage bunker can take up to 4 to 5 days of waste loads – about 3500 tons- of waste and the waste delivered is mostly incinerated in the next few days and the storage bunker is sealed to limit the waste odor problem [13].

The waste is transported to the incinerator boiler chamber over grates and incinerated at a temperature ranging from 1100 to 1200 degrees the grate moves with the waste mass through the incinerator for at least 2 hours to ensure the full incineration of all the waste [13].

The ash falls from the moving grate sides and is being scrubbed with water and collected for further utilization. While the scrab metal remaining from the incineration process is being collected at the end of the incineration process.

The incinerator boiler chamber is connected to the turbines to generate electricity and a heating pipes network. The flue gas from the incineration process is transferred and treated by lime scrubbing before passing it through filtration to capture all particulate matter and release the remaining steam into the air.

3.3.2. Material recovery facility

After the collection process, separate collected waste and packaging waste is transported by trucks to a material recovery facility for preparation for market use. The material recovery facility process different waste streams and responsible for the further waste separation process.

Bio-waste fraction is separated, and it is moved for a biological digestion process to produce compost and the rest of the Refuse derive fuel (mainly consists of plastics and biodegradable waste like wood and paper, and cardboard) is transported to the incineration process.

The recycled material transported to the facility is stored and transferred to conveyor belts which go through a screening process to remove any unrecyclable and hazardous material that might ruin the patch or pose a safety risk for the processing.

Separation of different types of waste is done through different techniques: metals are removed by electromagnetic screening, plastics are separated using infrared screening to separate different grades of plastics, and paper and cardboard are sorted through mechanical processing. [29] [30]

After the separation process, different types of streams undergo different preparation processes: glass streams will be crushed into cullets and packed for transportation, plastic will be shredded into smaller granules and after the processing, the recycled material streams are packed and prepared for shipping. [29] [30]

Due to the nature of waste collection the material recovery facility is working with mainly clean streams which are separated at the source of collection and the further separation processes are provide a better economical value out of the recycled material streams.

3.3.3. Landfilling

The landfilling process starts with the transportation of the refuse from mechanical and biological treatment facilities and the unincinerated waste residuals from the incineration process.

The Waste is spread in layers and covered with dirt to contain odors from the site. The waste undergoes 5 phases of transformation in the landfill site starting from the aerobic digestion and the activity of the microbes followed by 4 stages of anaerobic digestion which results in the formation of decomposition gas which consists mainly of methane (CH_4) [24].

The decomposition gas is collected through extraction wells and flaring systems all the gas collected is being utilized in the energy sector for heating and electricity generation. The decomposition process with the precipitation in open landfills creates the leachate which is trapped by the lining layers however constant testing for the leachate leaking is important to make sure no seepage to groundwater levels [24].

Currently, in Estonia, the landfilling capacity far exceeds the waste generation needs, and the EU targets for landfilling biodegradable waste are realized however the Estonian targets of landfilling biodegradable material are still to be achieved.

4. RESULTS

4.1. Scenarios results

Figure 12 presents the LCA of the base scenario which represents the current waste management system in Estonia and also the first scenario which assesses the potential of complying with EU targets. Both were done based on the following model graph.

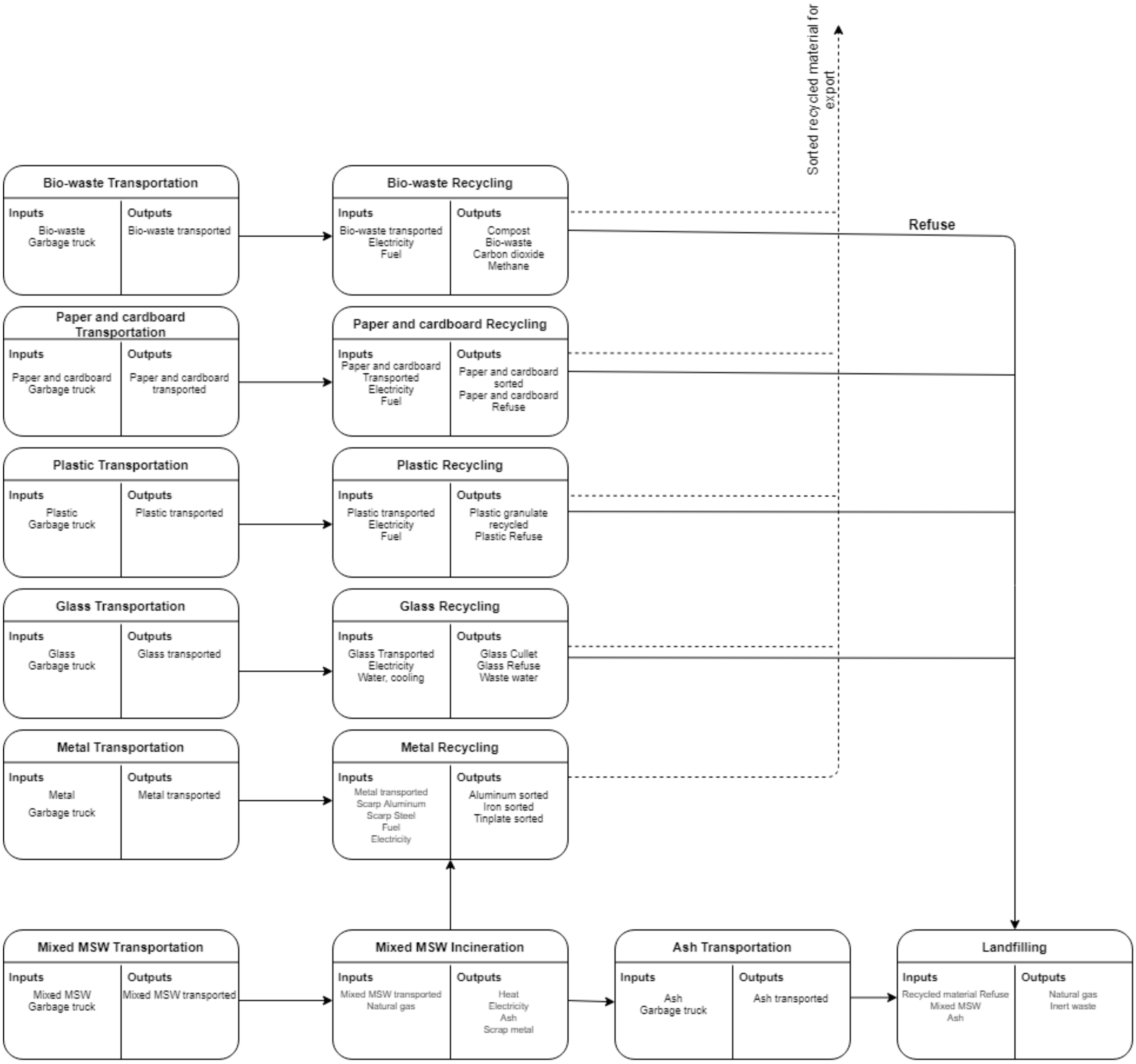
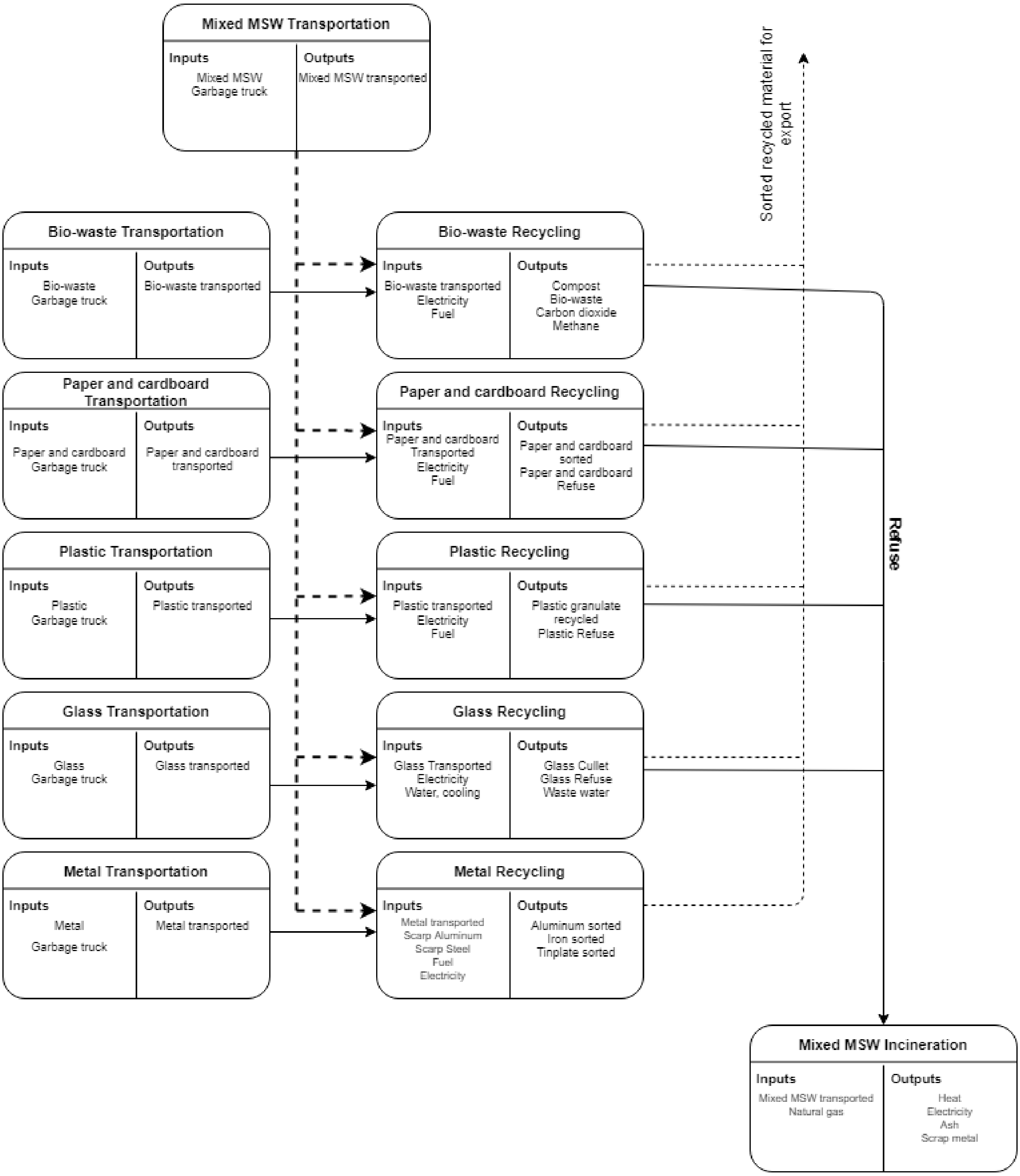


Fig (12) – Base Scenario and Scenario 1 model graph

The second scenario was prepared to evaluate the potential of relying mainly on recycling and to emphasize the importance of the role recycling can play in the future of waste management in Estonia. The Scenario was assessed based on the following model graph.



Fig(13) – Scenario 2 model graph

The life cycle assessment to the mid-point impact categories which represent the connection between key processes and the impact on the environment. Mid-point charachtrize environmental impacts in 18 impact category Prior to end point damage categories which measure the damage to human health, ecosystem qualtiy and resources to build a cause and effect chain.

Mid-point and End-point Impact category results for the MSW treatment scenarios were as follows in Table 2 and Table 3

Table (2) – Mid-point impact categories results for Base Scenario

Mid-point impact category	Reference unit	Base Scenario	Scenario 1	Scenario 2
Agricultural land occupation	m2a	1983.196084	651.0089749	466.0999
Climate change	kg CO2-Eq	837616.5247	276141.9425	139115.3
Fossil depletion	kg oil-Eq	38955.02378	11963.91709	67998.03
Freshwater ecotoxicity	kg 1,4-DCB-Eq	48596.66289	16191.91458	7248
Freshwater eutrophication	kg P-Eq	4.977852958	1.600975214	1.222607
Human toxicity	kg 1,4-DCB-Eq	319745.6996	106477.6881	48465.1
Ionising radiation	kg U235-Eq	7209.070128	2213.288261	3195.522
Marine ecotoxicity	kg 1,4-DB-Eq	42008.61162	13996.21179	6240.3
Marine eutrophication	kg N-Eq	3980.539588	1326.032418	14.70431
Metal depletion	kg Fe-Eq	1194.991608	380.5497872	1076.091
Natural land transformation	m2	-5.632594568	-1.83842905	-2.77128
Ozone depletion	kg CFC-11-Eq	0.019162082	0.005855447	0.019622
Particulate matter formation	kg PM10-Eq	889.1221545	289.1534752	124.5946
Photochemical oxidant formation	kg NMVOC-Eq	4773.551223	1560.78083	501.1321
Terrestrial acidification	kg SO2-Eq	805.4034466	253.6704569	271.1755
Terrestrial ecotoxicity	kg 1,4-DCB-Eq	649.0627164	216.1995159	3.005036
Urban land occupation	m2a	3413.424509	1120.168044	775.1049
Water depletion	m3 water-Eq	820.9302913	271.9450101	229.4312

From the charachtrized impacts in table 2, A clear impact for the base scenario of MSW treatment on toxicity, global warming and land occupation. However the Second scenario had higher impact in material depletion and performed less effeciently than first scenario in metal depletion, ionising radiation, and ozon depletion

The analysis is done on the End-point level is normalized and weighted within the modeling software to avarege European and results are presented as score points in each damage category.

In table 3 the final damage score of the different scnearios show a great environmental performance in the second scenario, however the impact on resources wasn't as well due to the limitaion in scope of the research and wasted potential of reusing the recycled material in manufactring instead of exporting it.

Table (3) – End-point impact categories results for Base Scenario

End-point impact category	Reference unit	Base Scenario	Scenario 1	Scenario 2
ecosystem quality	points	15115.77	4979.29	2617.246
human health	Points	32286.79	10637.86	9176.17
resources	Points	5282.992	1626.176	7463.952
total	Points	52685.56	17243.33	21257.37

4.2. Results interpretation

In this research, three case scenarios were assessed to evaluate the waste management system in Estonia and to assess the potential for future improvement. Several Mid-point impact categories had a huge environmental impact difference between scenarios.

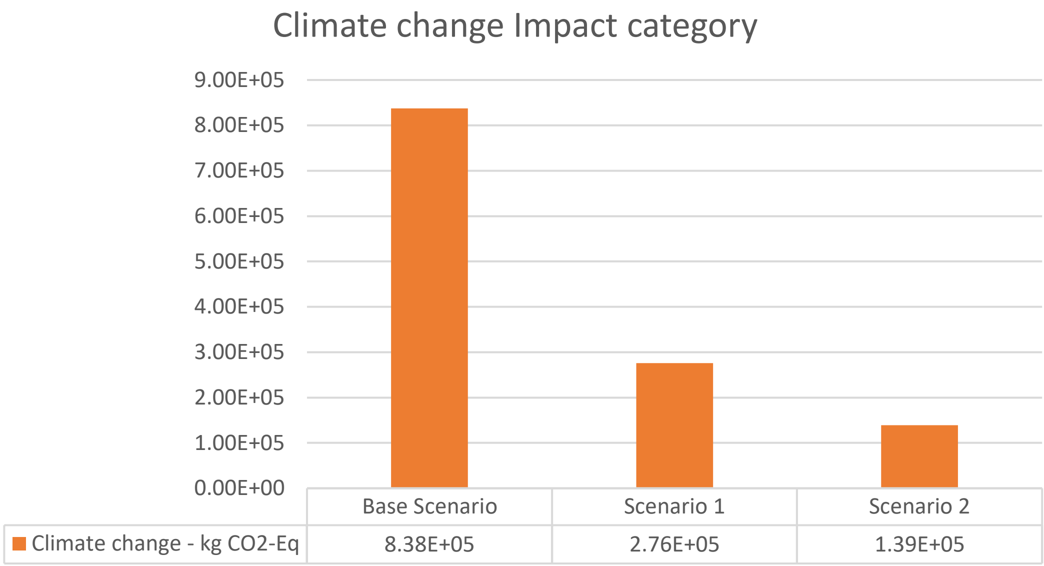


Fig (14) – Climate change Impact category of different MSW management scenarios

From Figure 14 Recycling shows great potential in reducing the carbon footprint both in short term and long term. The great reduction of carbon emission from waste incineration and landfilling plays a key factor in achieving the sustainability goals and mitigate the global warming impacts.

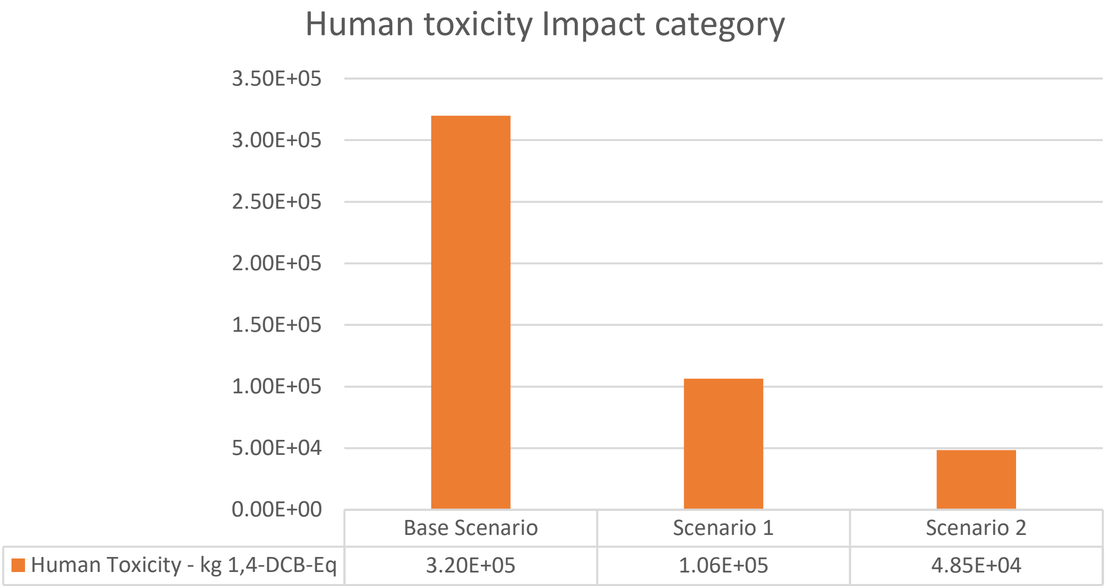


Fig (15) – Human toxicity Impact category of different MSW management scenarios

The second scenario -in figure 15- shows that by obtaining higher levels of recycling a massive reduction in impacts on human health as result, Such impacts originating from plastic treatment in landfills and incineration could be avoided.

The human toxicity impact category is the most affected category by the change in the recycling rates since the major contribution came from plastic and paper treatment.

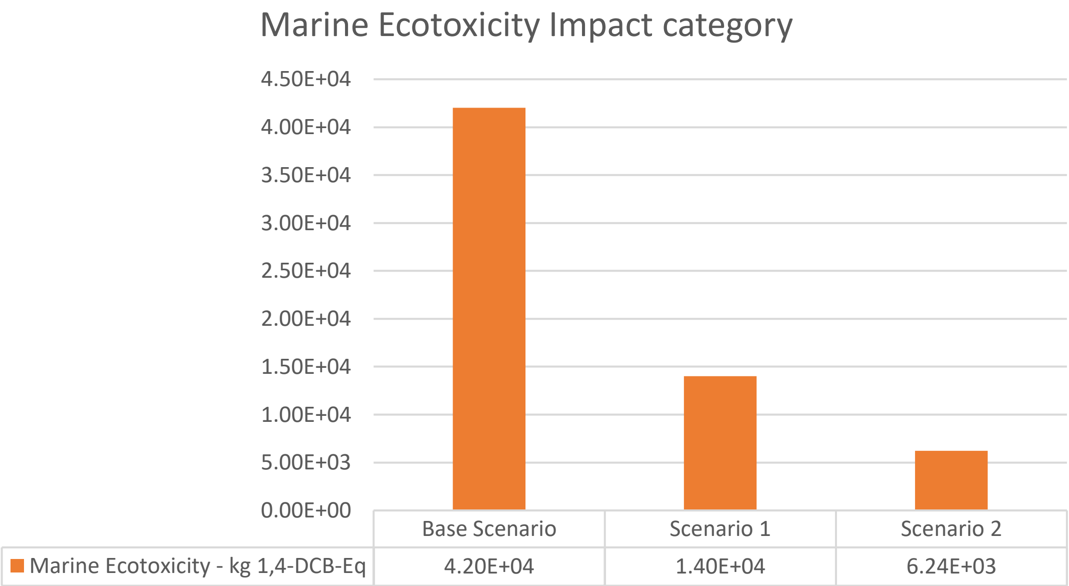


Fig (16) – Marine ecotoxicity Impact category of different MSW management scenarios

Lower levels of chemical residuals reaching the wastewater effluents from MSW treatment in the second scenario resulted in lower toxicity levels in marine, terrestrial and freshwater.

The save from MSW residual - from plastics and other toxins - resulting from the traditional MSW management system helped decrease the impact on marine ecotoxicity and marine life by reducing the potential to almost 5% of the original impact.

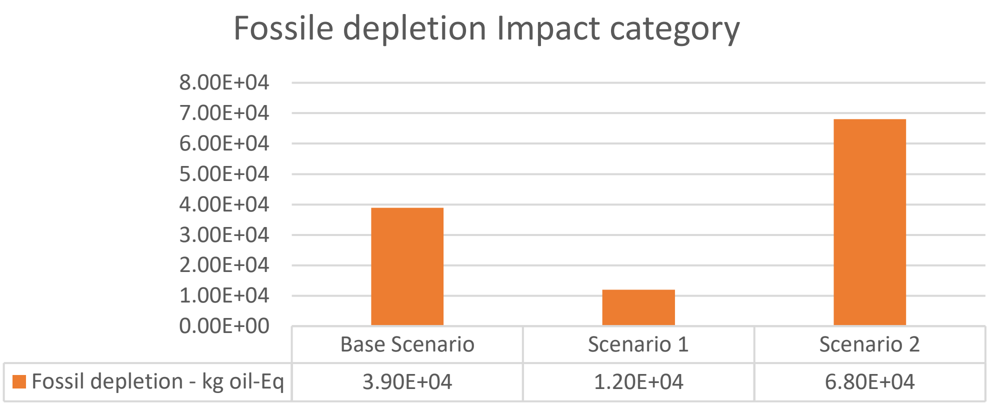


Fig (17) – Fossile depletion Impact category of different MSW management scenarios

The higher rates of recycling with low rates of energy recovery will result in higher levels of fossil depletion for the second case scenario. Despite the existence of the waste-to-energy option in the base scenario higher levels of fuel are consumed in waste transportation and treatment.

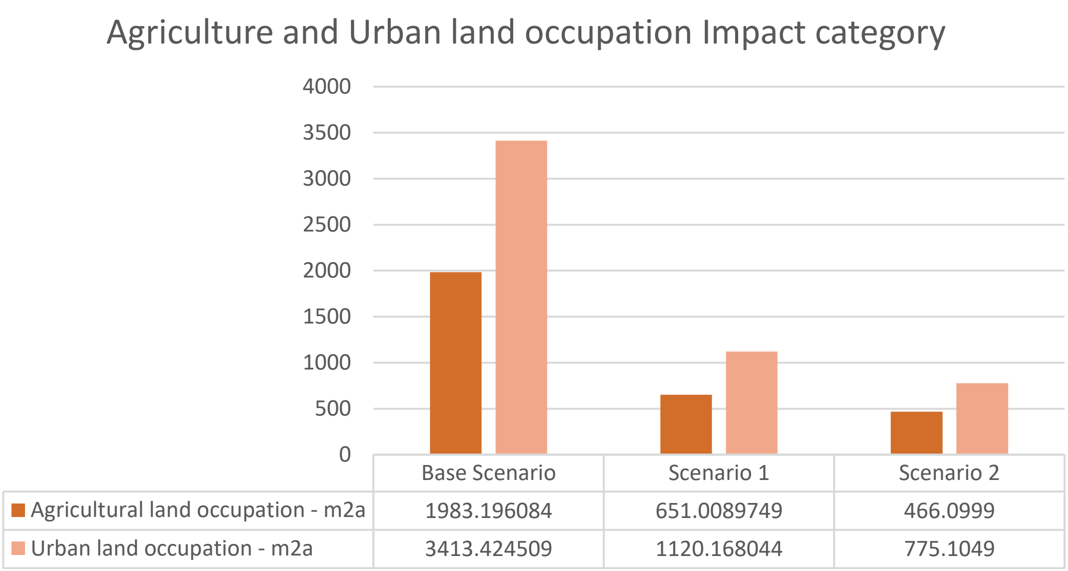


Fig (18) – Agriculture and Urban land occupation Impact category of different MSW management scenarios

Lower levels in Landfilling in both scenario 1 and scenario 2 cause a huge impact on land occupation in agriculture and urban land. Landfill dump areas require a long period of monitoring and rehabilitation after closure which makes land unusable for longer periods and leads to a more environmental impact.

By comparing the three case scenarios for the End-point impact categories to measure the damage on human health, ecosystem quality, and resources.

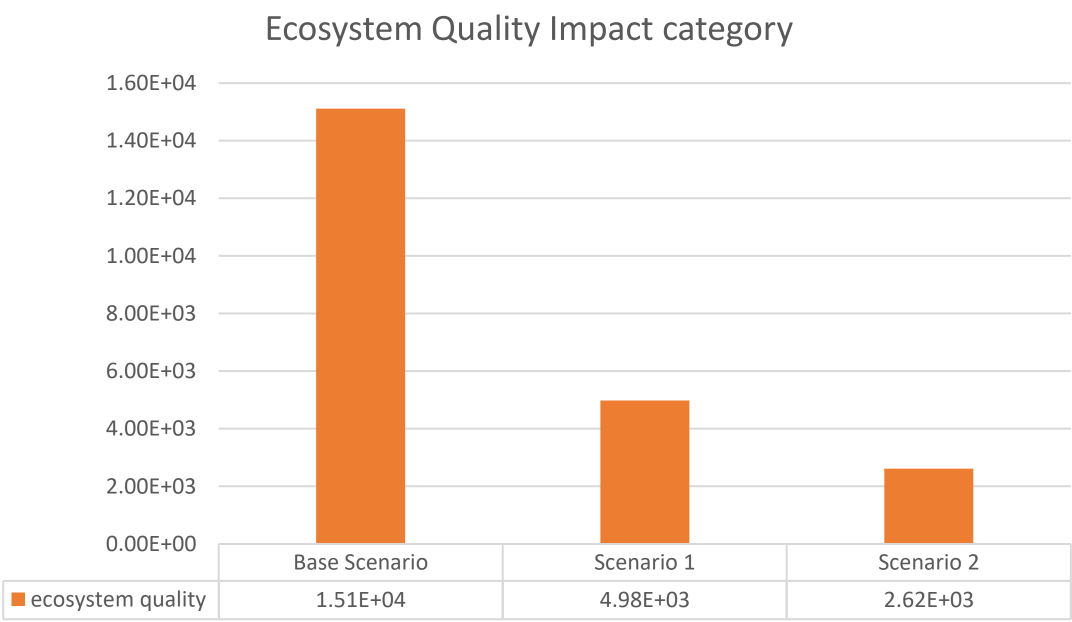


Fig (19) – Ecosystem quality impact category for MSW treatment scenarios

Scenario 2 in figure 19 had the lowest impact score on ecosystem quality with almost 80% improvement from the base scenario. The low impact on the ecosystem by recycling will help protect and maintain the biodiversity in the ecosystem which interconnects with the ecological stability of human life.

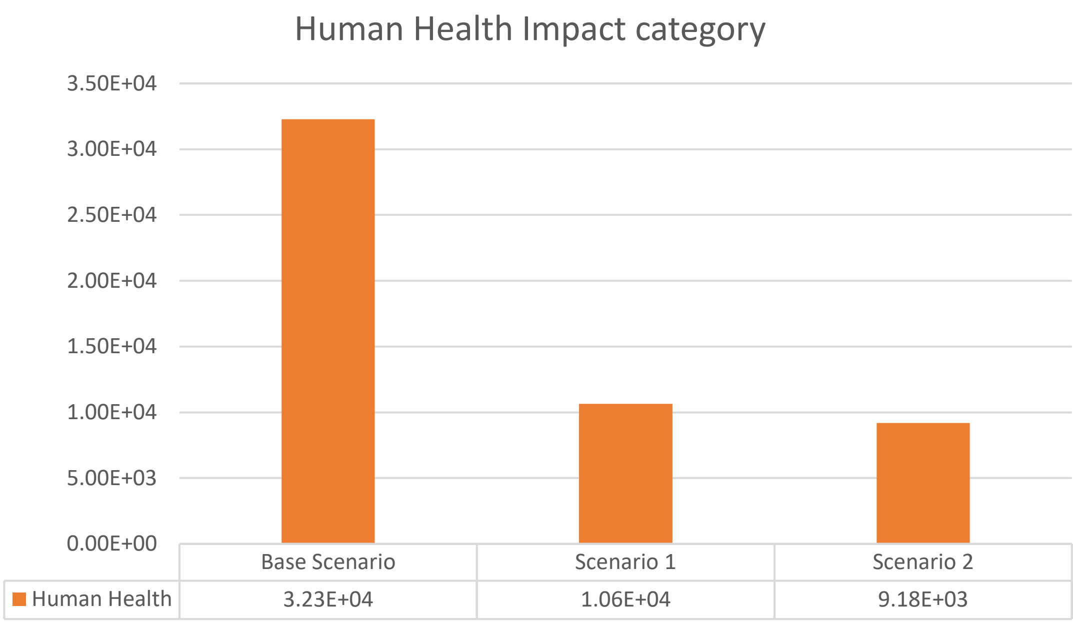


Fig (20) – Human health impact category for MSW treatment scenarios

Higher levels in MSW recycling in short term and long term have a lower impact on human health as shown in figure 20. Lower levels of landfilling and incineration create a lower impact on human health, with less residual and runoffs that reach freshwater sources and contribute to both marine and terrestrial toxicity.

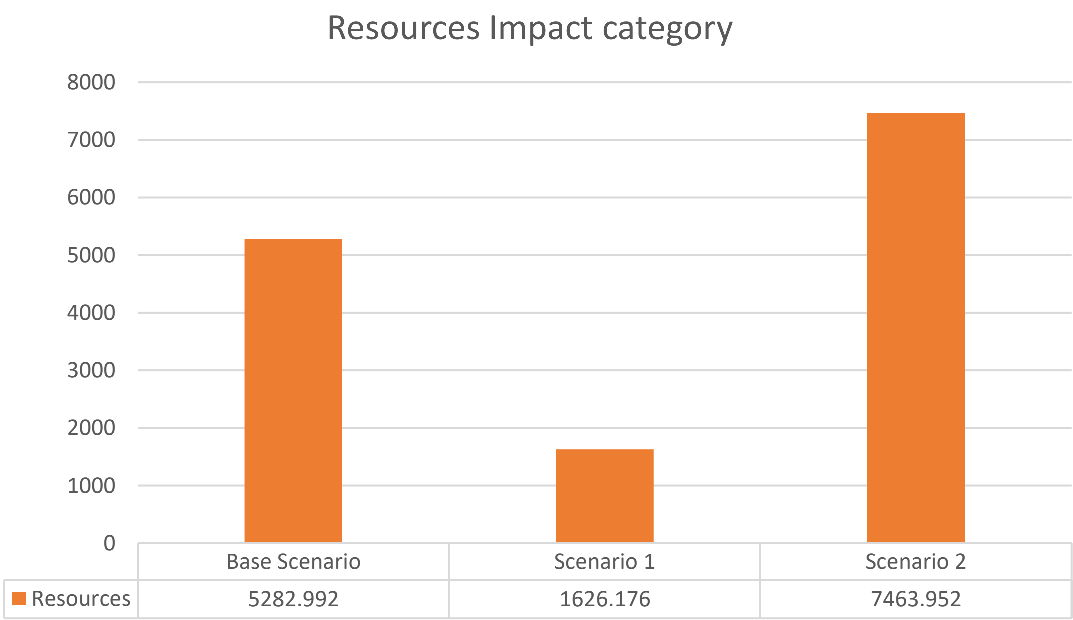


Fig (21) – Resources impact category for MSW treatment scenarios

Despite the clear improvement from treatment scenario 2, MSW recycling is an expensive process that requires higher amounts of fuel consumption, and energy generation which unlike scenario 1 can't be generated from the waste to energy option and landfill gas utilization.

The current MSW management system is posing a huge threat to human health and the ecosystem and the current recycling pace isn't enough to mitigate all the risks which are connected with environmental impacts. MSW residual and toxins from incineration and landfilling, which - even in small amounts - create a huge impact.

5. CONCLUSION AND RECOMMENDATIONS

In this research, 3 different case scenarios for MSW management were assessed using the Life Cycle Assessment methodology to evaluate the environmental performance of the current MSW handling system in Estonia and the potential improvements that can be achieved through increasing the rates of MSW separate collection and recycling.

The assessment was done on Mid-point and End-point impact categories to evaluate, compare and provide a more detailed view of the environmental impacts from each case scenario

Impacts on terrestrial ecotoxicity were the most improved with MSW recycling with impacts reduction over 90% while an increase in fossil depletion was the major drawback of the Second scenario.

The results showed the biggest impact posed by the current MSW handling system is in human toxicity with $3.19 * 10^5$ kg 1,4-DCB-Eq (Dichlorobenzene Equivalent) and impact on climate change with $8.44 * 10^5$ kg CO_2-Eq (Carbon-dioxide Equivalent) per year. Such impacts translate to a high damage score in End-point on human health and ecosystem quality.

By increasing the recycling rates to comply with the regional targets in the EU, a visible reduction in the environmental impacts exceeded 60% reduction in most of the impact categories. A major key to that improvement is the assumption that all MSW will be handled through a treatment system in the hypothetical scenarios which remove the unspecified handling for waste in the base scenario.

Despite the drastic reduction in impacts in the second scenario, it had the highest impact on resources due to high fossil depletion. To ensure the minimization for such scenario impacts assessment of using alternative green energy resources and fuels to reduce the rucksack of impacts.

Waste transportation is one of the key factors in all three scenarios which suggest the assessment of using alternative fuel types or renovating the waste collection system in Estonia.

Collected data from previous studies showed that despite the decrease in landfilling in Estonia, waste generation is still on an increasing trend and the amount of mixed MSW is also increasing for the reliance on waste incineration as the main waste treatment option. Initiatives to achieve waste prevention are a future necessity.

The key benefit of increasing the recycling rates is the lower impact on human health and the improvement in ecosystem quality. In future studies, the Gate-to-gate approach to account for the replacement of raw material with recycled material would help realize the full potential of the MSW recycling benefits.

Policymakers should start tackling the low recycling rates issue in a new light supported by the modern waste hierarchy and the regional pressure from the EU parliament, to increase the recycling rates and to lower the waste generation.

From the assessment results, future investment should be directed toward waste recycling and it should be supported by government initiatives to help speed up the transformation toward separate collection and material recycling systems.

Further studies to assess the possible benefits from having recycling streams utilized locally in Estonia instead of exporting sorted material.

The development of better tools for waste reporting and data collection would offer great support for any future studies regarding waste management in Estonia.

SUMMARY

Municipal Solid waste management as the main part of Municipal waste systems became the modern society challenge, Despite the great progress done in many environmental aspects most of the MSW is still disposed of through the traditional non-sustainable methods.

Estonia as a part of the European Union aspiration to achieve sustainability and circular economy needs to pick up the pace and develop its waste management system in a sustainable way to adapt to the modern waste hierarchy and to comply with the Latest EU recycling target.

Despite the huge success in the local MSW system for the waste deposit system and packaging collection rates, Estonia is yet to face a different challenge in the MSW collection and treatment. Estonia still has over 70% of MSW collected as Mixed waste with relatively low separate waste collection percentages.

The mixed MSW in Estonia contains for the bigger portion of it bio-degradable and kitchen waste, plastic, and paper and cardboard. The Mixed MSW still carries a huge potential for further recycling which could help the country achieve its sustainability goals.

This research focused on the life cycle assessment of MSW management to evaluate the current waste management system and to give recommendations about the potential pathway in recycling.

The legislative background for MSW management both locally and regionally was examined and a clear determination from the government to improve the MSW management system through a build of legislative acts, laws, and regulations to base the foundation for future development

Three separate case scenarios were assessed to compare the current situation with the near and far future targets. The first scenario was based on the EU targets to achieve at least 60% recycling rates in the next decade. The second scenario was based on a hypothetical scenario that relies mainly on waste recycling.

Life cycle assessment was chosen as the most appropriate methodology to approach the set task to assess the impacts for a year worth of MSW amount including transportation and end of life treatment

Limitation of data provided and the general assumption was addressed properly and process system was designed to reflect the needed research scoop.

The carried assessment showed great impacts and hazards from the current MSW treatment system with major impacts on climate change and human toxicity. The current MSW treatment system results in 8.44 * 10^5 kg CO_2-Eq per year and 3.19 * 10^5 kg 1,4-DCB-Eq on human toxicity.

The assessment showed great results for both scenarios and nearly 60% of impacts associated with MSW treatment by just complying with EU targets in the first scenario. While further environmental impacts improvements were realized in the second scenario.

By the major reliance on Recycling, more than 80% of impacts on climate change, human toxicity, and ecotoxicity are reduced. While other aspects such as fossil depletion showed worse results due to the limitation of the study scope.

Recycling is a key factor in improving the environmental performance of the current MSW treatment system in Estonia, However, the interconnected impacts from the energy sector should be considered as well to maximize the benefits from such a scenario.

Several recommendations for governmental initiatives and policy changes should go into force to better assess the potential and realize the set goals. Development of data collection tools and waste collection systems are initial steps toward a sustainable approach for MSW management.

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