TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Materials and Environmental Technology

OPTIMISING THE IRU WASTE TO ENERGY PLANT THROUGH PERIODIC PLASTIC CO-PYROLYSIS FOR RENEWABLE ENERGY GENERATION IN TALLINN

IRU JÄÄTMETE ENERGIAJAAMA OPTIMEERIMINE PERIOODILISSE PLASTILISE KO-PÜROLÜÜSI ABIL TAASTUVENERGIA TOOTMISEKS TALLINNAS

MASTER THESIS

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Tallinn 2020

AUTHOR'S DECLARATION

Hereby I declare, that I have written this thesis independently.

No academic degree has been applied for based on this material. All works, major viewpoints and data of the other authors used in this thesis have been referenced.

25th May, 2020.

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supervised by Eduard Latosov.

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Department of Materials and Environmental Technology

THESIS TASK

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Thesis topic:

Optimising The Iru Waste to energy plant through periodic plastic co-pyrolysis for renewable energy generation in Tallinn
Iru jäätmete energiajaama optimeerimine perioodilisse plastilise ko-pürolüüsi abil taastuvenergia tootmiseks tallinnas

Thesis main objectives:

1. Compare mass combustion Waste to Energy and pyrolysis plant profitability and environmental impacts.
2. To determine the optimum pyrolysis route for the use of Solid waste for renewable energy generation.
3. To improve the efficiency of the Iru Waste to Energy plant through improved energy use.

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Evaluation of the potential for Plastic Pyrolysis in Estonia	25/03/2020
2.	Calculations for the economic feasibility of a pyrolysis plant	25/04/2020
3.	Recommendations for the implementation of the technology in Tallinn	25/05/2020

Language: English **Deadline for submission of thesis:** 25th May, 2020

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CONTENTS

PREFACE

Sustainable energy in the light of recent efforts to fight climate change is an important attempt to keep carbon footprints low, change to a more environment-friendly type of fuel, or improve the efficiency of contemporary working engines. It is my passion to optimize energy so that waste is reduced to the barest minimum. But in the case that waste is unavoidable, it is necessary to consider waste as a material for energy generation. The Pyrolysis route appears to be a useful technology to tackle plastic waste, tap into their high energy content and improve energy supply simultaneously.

I wish to thank Dr. Eduard Latosov for his immense guidance without which the ideas here would not have been fully developed. Special thanks also to Andrei Vuhk and Dmitri Širokov of the Iru Waste to Energy plant for sharing more insight to the material used for writing this. To Frances Otor for her support throughout the writing of this paper, Eve Arm and my colleagues who have contributed in one or another.

Also, to the Njokus, Asajus, Aties and the family at Vineyard Tallinn; peace of mind is required to achieve anything. Thank you!

This thesis explores waste pyrolysis as a more efficient route to sustainable energy generation, through improving the process efficiency already used to burn waste energy.

Keywords

Materials, Municipal solid waste, Pyrolysis, Sustainable energy, Waste to energy incineration, Master thesis.

List of abbreviations and symbols

a	annum (year)
BMO	Biomass Oil
CAPEX	Capital Expenditure
CCUS	Carbon Capture Utilisation and Sequestration
CFB	Circulating Fluidized Bed
d	Day
DH	District heating
ENWRS	Estonian National Waste Reporting System
El	Electrical energy consumption (kWh)
EOS	Estonian Oil Shale
EC	European Commission
Et al	And all
HDPE	High Density Poly Ethylenes
HHV	Higher Heating Value
Gas	Pyrolysis gas
GPD	Gross Domestic Product
H	hour
IRR	Internal rate of return
ktoe	Kilo tons of Energy
ktpd	Kilo ton per day
kWh	Kilowatt hour
LDPE	Low Density Poly Ethylenes
LHV	Lower Heating Value
M	Mega/Million
MSW	Municipal Solid Waste
WtE	Waste to Energy
Mj	Mega Joules
MW	Mega Watts
N	Nitrogen
NOx	Nitrogen Oxides
NPV	Net Present Value
NZ	Natural Zeolite
Oil	Pyrolysis Oil
PBDE	Polybrominated diphenylethers
PCDD	Polychlorinated dibenzo-p-dioxins and dibenzofurans

PPO	Plastic Pyrolysis Oil
PPP	Plastic Pyrolysis Plant
OPEX	Operating Expenditure
OCM	Other combustible material
ONCM	Other non-combustible material
OSO	Oil shale Oil
ROI	Return on Investment
RDF	Refuse Derived Fuels
SNCR	Selective Non-Catalytic Reduction
SPR	Sapporo Plastic Recycling
t	Tons
T	Temperature [^{o}C]
TGA	Thermo Gravimetric Analysis
Th	Thermal Energy
tpd	Tons per day
TTP	Thermal Treatment Plant
UHW	Unidentifiable Household Wastes
WEEE	Waste Electrical and Electronic Equipment
WPP	Waste Pyrolysis Plant
WTEMI	Waste to energy mass incineration

Other

Ou	Osaühing Limited (Ltd)

INTRODUCTION

Many inhabitants of cities in developing countries are faced with problems about the disposal, management and use of Municipal Solid Waste (MSW) thus environmental pollution is one of the leading causes of illnesses around the world [1]. Around the world, waste generation rates keep rising. In 2016, the worlds' cities generated 2.01 billion tons of solid waste, amounting to a footprint of 0.74 kilograms per person per day. Following rapid population growth and urbanization, annual waste generation is expected to increase by 70% from 2016 levels to 3.40 billion tons in 2050 [2].

In Tallinn alone, approximately 200,000 tons[3], [4] of municipal waste is generated every year. With the biggest shares being paper, cardboard packaging, bio waste and plastic and glass which accounts for 53% municipal waste out of which more than half was paper (55%), cardboard packaging and biowaste [5].

Traditional methods in which wastes have conventionally been used as land refill are unsustainable and do not benefit the environment nor people. However, wastes have been used for energy generation and waste management is being harnessed to improve living conditions, a cleaner environment and a cheap source of energy for the growing demands of a more energy dependent population [6]–[8].

On the other hand, in Estonia electricity consumption has grown to 621 ktoe, and heat demand to 476 ktoe, which is satisfied mainly by oil and oil products, biofuels and waste, natural gas and oil shale [9].

The method for reaching this energy requirement has been predominantly through using the oil shale resource despite its low calorific value and high carbon signature. As Estonia ranks first in the carbon intensity for energy production and would like to meet its target of decarbonising the energy sector, alternatives to the pyrolysis of oil shale must be tried.

The current technology for waste to energy (WtE) in Estonia is mass combustion, which is cost effective process friendly and somewhat renewable as it saves ton of oil equivalent which would have been derived from fossil fuel sources. On the other hand, emissions from combustion are not eliminated. As we shall see in more detail, the main plant responsible for implementing this technology is the Iru Waste to Energy plant; while considerations may be taken to other methods of waste management if they show feasibility.

However, pyrolysis is the preferred technology for oil shale oil extraction because of high efficiency and flexibility; by modifying the process parameters, it is possible to modify the products to some extent. Also, the Estonian oil shale sector is well developed and garners top notch specialist knowledge with innovative research backed by wealth of experience; establishing the Estonian Oil Shale (EOS) sector as one of the most competitive in world.

The main goal of this thesis is to investigate possibilities of plastic waste pyrolysis for Estonian waste to energy solutions in comparison with mass burning technology currently implemented for waste treatment. Following inherent characteristics of plastics; high energy content, large percentage in the waste stream, the problem of waste plastics destroying aquatic lifeforms, and the long life cycle required to neutralize plastic wastes, it is necessary to investigate better management for plastic waste in addition to incineration methods which have already been established, as we might discover a more valuable resource than oil shale in term of efficiency, and a cheaper cost of producing pyrolysis oil in comparison to oil shale oil.

I posit that plastic pyrolysis will prove to be a dependable, cost effective and environmentally friendly alternative with less cost compared to other situations since competencies for oil shale extraction have already been established especially in contrast to WtE mass burning.

This paper attempts to answer the questions: if pyrolysis technology is used for plastic wastes, would the energy generation from municipal wastes significantly increase, would it become greener and more sustainable? What would happen to the total revenue of the plant that implements co-pyrolysis of plastic waste and can this method have advantages over the classical methods of waste treatment?

To reach the main goal of optimizing the Iru waste to energy plant through periodic plastic co-pyrolysis for renewable energy generation in Estonia, the following sub goals are planned for investigation and evaluation:

- To estimate the amounts of produced municipal waste suitable for energy production
- Analyze the content of municipal waste for production of energy;
- Describe main difference and technical data for pyrolysis plants and mass combustion plants;
- Select best practice solutions for pyrolysis of solid waste;

- Calculate energy production technical and economic figures for pyrolysis plant in Estonian conditions;
- Compare mass combustion WtE and pyrolysis plant profitability, sustainability and environmental impacts;
- Suggest an optimized periodic co pyrolysis plant model;
- Provide sensitivity analysis for main pyrolysis plant parameters.

1. THE BASICS OF WASTE MANAGEMENT

1.1 Definition and Classification of Wastes

Though wastes exist within the three phases of matter; solid, liquid and gaseous phases, this paper will focus primarily on the solid component, namely; municipal solid waste (MSW). As mentioned above, municipal wastes include solid waste from towns, districts and urban settlements and generally refers to materials that remain from domestic or industrial consumption [10]; byproducts of manufacture; materials discarded by the agriculture industry; materials discarded from homes, and materials that are not originally intended for a particular purpose [19].

Municipal waste is defined as waste collected and treated by or for municipalities. It covers waste from households, including bulky waste, similar waste from commerce and trade, office buildings, institutions and small businesses, as well as yard and garden waste, street sweepings, the contents of litter containers, and market cleansing waste if managed as household waste [11] . "A material becomes waste when it is discarded without expecting to be compensated for its inherent value. These wastes may pose a potential hazard to the human health, or the environment (soil, air and water) when improperly treated, stored, transported or disposed of or managed" [12]. MSW thus may be rich biodegradable matter from household waste, cellulosic material, electronic components and plastics. Excluded from this definition are construction and demolition materials, as well as sewage networks and treatment wastes.

1.2 Municipal Solid Waste as a Source of Renewable Energy

The European Commission defines municipal waste as "(a)mixed waste and separately collected waste from households including : paper and cardboard, glass, metals, plastics, bio waste, wood, textiles, waste electrical and electronic equipment, waste batteries and accumulators; bulky waste including mattresses and furniture; garden waste, including leaves, grass clipping; (b) mixed waste and separately collected waste from other sources that is comparable to house hold waste in nature, composition and quantity; (c) market cleansing waste and waste from street cleaning services, including street sweepings, the content of litter containers, waste from park and garden maintenance" [11].

Based upon the interaction of such wastes with the environment, we can classify these further into biodegradable and non-biodegradable wastes. Biodegradable materials are high in organic matter and are easily incorporated back into the ecosystem. Biodegradable wastes can further be utilized for biomass-based energy sources, feed for gasification or digestion to produce high calorific value gases. Non-biodegradable sources on the other hand are characterized by a long time to break down into their constituent components. Components include dry matters glass, metal, leather, textile, paper packaging material, (and some) household wastes [13]. These constitute some of the big problems of environmental pollution.

In a strict sense, MSW as a fuel for energy generation is sustainable as it contains food wastes, biodegradable wastes, and organic material that form part of the carbon and nitrogen cycles, as combusting them for energy production is Carbon and Nitrogen neutral in theory. Research carried out using plastics for pyrolysis show that plastic pyrolysis can reduce the dependence on biofuels, reduce consumption of fossil fuels and utilize a pollutant that would otherwise harm aquatic life and take 600 years to be decomposed [14]. In the real scenario however, varying compositions of MSW with components including textiles, packaging materials, plastics food wastes etc are more common.

1.3 Composition of Wastes

Compositional analysis of MSW vary from region, season, economic welfare among other variables. In a study by Chabhra et al , random sampling of different wastes were analyzed using Thermogravimetric analysis (TGA) [15]. MSW with a composition of ten valorizable components was studied. These components rubber, polystyrene, farm waste, metal, inert compounds, unidentifiable household wastes (UHW), textile, plastics, paper, soil and yard wastes were measured and studied. Typical waste compositions are included in the chart below. Their study concluded that waste compositions affect the reaction kinetics and the char composition after waste to energy processing.

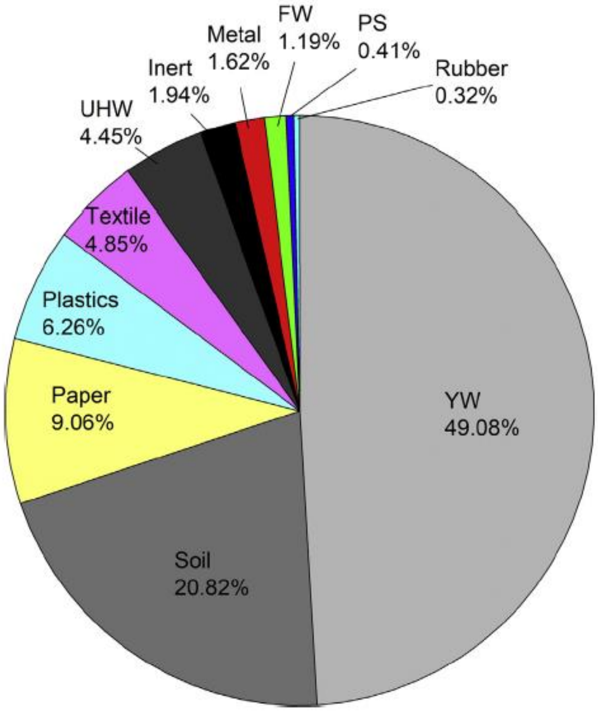


Figure 1.1 Composition of MSW Sample.

1.4 Variation of Waste

1.4.1 Waste Variation and Seasonality and Geographical Region

Edjabou et al sampled 101 residential houses in Denmark for seasonal variation in their waste generation. Using statistical and experimental methods, they discovered that waste composition does not significantly vary with season. They also show that similarities can be found for countries with similar climates, comparative income and purchasing culture as Denmark [16].

1.4.2 Waste Variation and Geographical Region

In a study conducted by Denafas, seasonal variations in waste generation in four (4) Eastern European cities; Lithuania (Kaunas), Russia (St Petersburg), Georgia (Kutaisi) and Ukraine (Boryspil) was studied. They found that the seasonal variations were similar; with more waste generated in the September/Autumn (mostly due to food waste fraction as a result of harvest, and bio wastes that follow this process), and less generated in February with a spike in the volume of waste per capita in the spring; which they attribute to spring cleaning activities. They show that the patterns in waste generation depend more strongly on the economic development and geographic location of the country. Their results are included in the Appendix section.

1.4.3 Waste and Socio-Economic standing

From prior research, we know that reasons for variations in the composition of MSW are caused by various social factors including; economic welfare, holiday activities, influx of students during academic sessions, summer events and festivities, and the influx variations of tourists, especially in economies with strong dependencies on tourism. [17][18] [19].

In another study by Ali et al (2015), researchers studied the effects of socio-economic status and seasonal variation on municipal solid waste composition in Shalimar Town, Punjab district Pakistan [20]. They discovered that waste generation per capita per month shows strong correlation with the socio-economic groups; with the lowest income groups producing the lowest waste category by mass, and the highest income group having the highest amount of household waste by mass. This result can be extrapolated to wealthier economies producing more waste than economies with less resources. With this understanding, it follows that areas of privileged economic prosperity will produce more waste per capita per month, than under privileged or low-income earning communities.

Their analysis of the domestic waste product shows

Organic waste	81%
Paper	5%
Plastic	6%
Glass	2%
And Others	5%

The increasing population and waste disposal concerns in developing nations necessitate a different approach to waste generation, including the use of mathematical models to predict the waste generation profile and plan for it accordingly.

Waste compositions vary by country, season, these constituents are similar, and account for different kinetic reactions.

1.4.4 Waste and Economic wellbeing

J. Malinauskaite et al (2017) established that waste generation has increased in (Eastern) European countries as the economy has improved. They explain that as purchasing power has improved, consumers have access to more products. These products have a short market span and become part of household wastes within a short time [21].

In their paper, they noted that Estonia produces waste below the E.U average and has improved in recycling over the years. The waste to energy recovery capacity has also increased, and over capacity has been reported. Excess energy generation presupposes that an improvement in the WtE process is due for energy efficiency and deployment of energy to better serving sectors. The reason behind the improvement in WtE rather than landfilling has been attributed to high tax and landfilling fees.

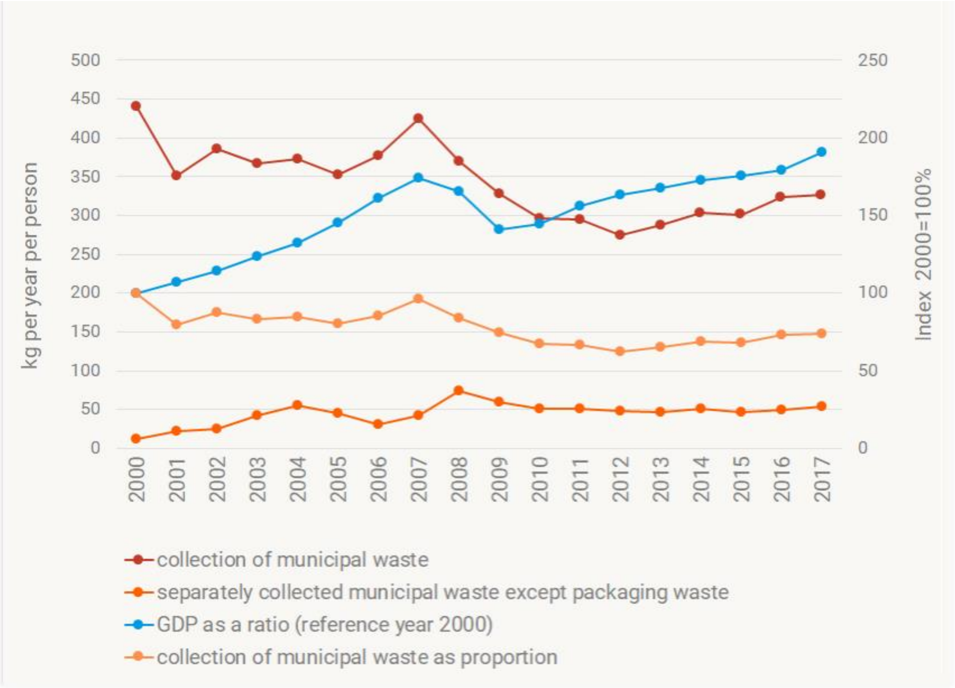


Figure 1.2 The variation of Municipal waste generated and collected on GDP year on year in Estonia [3]

1.4.5 Waste Variation and Cultures

Summarily, several studies show waste quantities to change as a result of economic welfare, increase in population, as well as by municipalities. These results can help energy planners decide the optimum waste handling method to employ depending on the quantity of waste available, the composition of the waste as well as the energy demand required in the season. For the absence of similar data, these results can be extrapolated to the Estonian MSW scenario as the patterns are similar across similar cultures, consumption patterns, populations, seasons and regions.

Mintz et al show that waste production can be linked with cultural behaviours. This indicated that in the absence of further data we can conclude that the Estonian waste production pattern follows a similar can be likened to some degree with Denmark's pattern [22], and Eastern Europe.

1.5 Current waste treatment and uses in Estonia

In 2015, more than 200,000 tons of municipal waste was generated in Estonia [11]. The Iru waste to energy plant runs on a capacity of about 250,000 tons yearly, out of about 300,000tons generated in Estonian homes each year [23]. The composition this waste is given below. Previously, these MSWs were taken to landfills. But concern for contamination of the ground water and the environment and standards of the EU to reduce land filled waste necessitated a more efficient way to handle wastes.

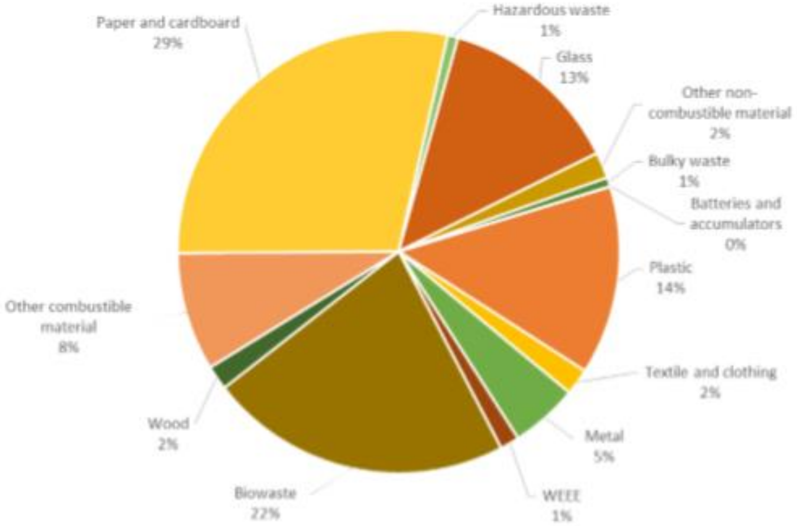


Figure 1.3 Composition of Municipal Waste in Tallinn in 2012 [4]

Fischer C. highlights that Estonia's waste collection system is two tiered; National and Local. Emphasis on home composting in rural areas in the Second National Waste Management Plan reduces the amount of biodegradable waste that is sent to the landfills. The problem of waste sorting is reduced using bins designated for different classes of waste. This approach is commended as little effort will be required in waste treatment plants to separate waste into different valorizable components.

The Estonian system of waste handling is very efficient, currently in Tallinn, the waste handling system achieves more than 22% of waste collection for thermal treatment, 7.44% of organic waste collected separately, and 49% of recyclable MSW. In recent years, the amount of wastes sent to landfills has reduced to less than 10%. [24], as shown below

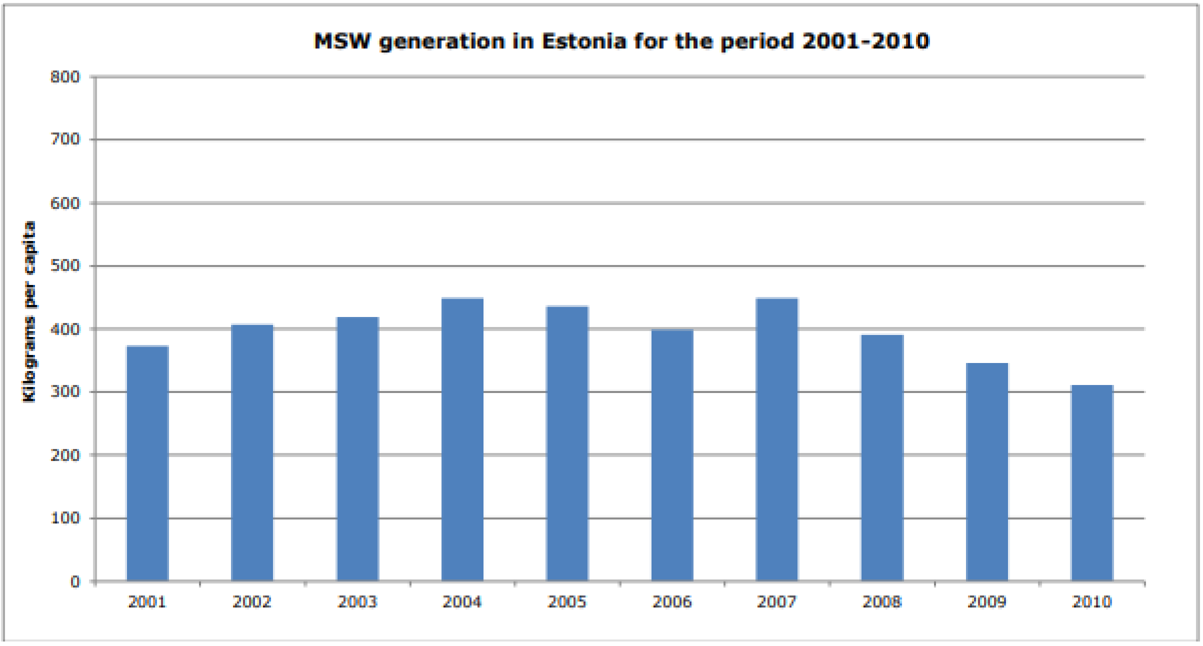


Figure 1.4 Municipal Solid Waste Generation in Estonia [24]

Estonia waste handling is efficient and has grown significantly from 80% of total disposal and only 5% recycling in 2002 to less than 10% disposal rate and recycling as high as 28% in 2015 [25]. Within the Tallinn municipality, the trend in the volume of municipal waste collected has shown decline due to a modest rate of consumption, and collection of waste is forecast to stabilize by the year 2020.

From The Estonian National Waste Reporting system (ENWRS), approximately 5,290 tons of food waste alone was generated in 2013 [26]. As the economy improves in Estonia, the trend in municipal waste generated has also been on the increase as seen above. This waste is expected to be more in Tallinn; being the main city. Energy demands are also expected to grow in the coming years as well as increased municipal wastes.

1.6 Utilizing Waste as a sustainable source of Energy

With the European Union (EU) framework of keeping the global temperature below 1.5°C [27], several novel models of transitioning from fossil fuel dependence to clean and green energy sources are being investigated. Central to the EU's objective to decarbonize the energy sector is the target to increase renewables into the heating and cooling mix. So far, the methods used for increasing the shares of renewables in the heating and cooling network are the use of torrified wood, pellets and biomass sources as shown in the figure below. Municipal solid waste is also an important energy source to be considered in achieving this goal, though the use is increasing.

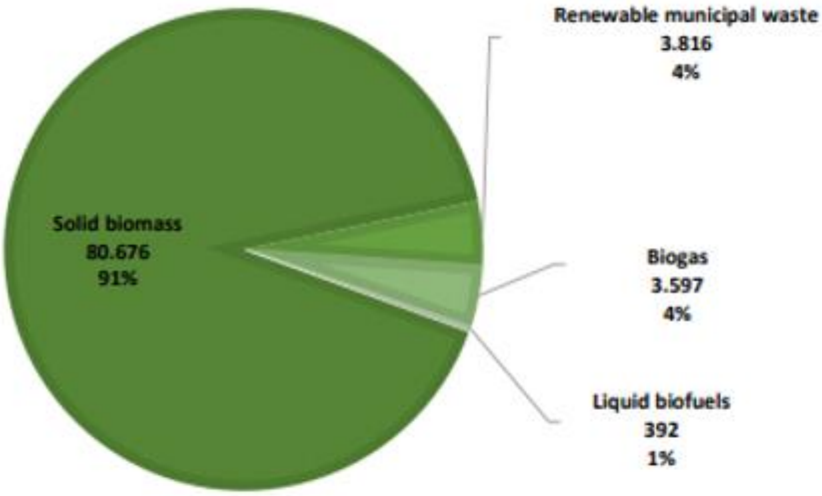
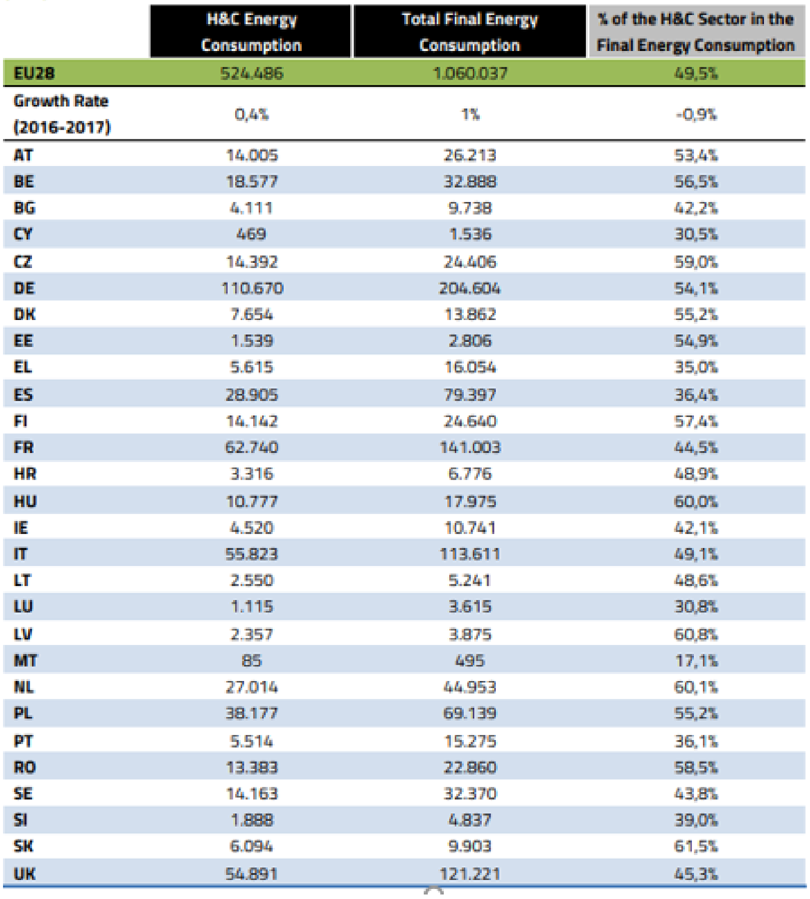


Figure 1.5 Municipal Solid Waste in Energy Generation Contribution [28]

Energy consumption in Estonia is chiefly categorized into uses for transportation, electricity generation and use in heating and cooling systems although other uses also exist. Heating and cooling account for over 50% of the energy consumption in Estonia, amounting to 1.539ktoe between the years 2016-2017 as shown by the table below [28].

Table 1.1 Heat and cooling consumption with total final energy consumption in EU28 and to member states in 2017 [28].



	H&C Energy Consumption	Total Final Energy Consumption	% of the H&C Sector in the Final Energy Consumption
EU28	524.486	1.060.037	49,5%
Growth Rate (2016-2017)	0,4%	1%	-0,9%
AT	14.005	26.213	53,4%
BE	18.577	32.888	56,5%
BG	4.111	9.738	42,2%
CY	469	1.536	30,5%
CZ	14.392	24.406	59,0%
DE	110.670	204.604	54,1%
DK	7.654	13.862	55,2%
EE	1.539	2.806	54,9%
EL	5.615	16.054	35,0%
ES	28.905	79.397	36,4%
FI	14.142	24.640	57,4%
FR	62.740	141.003	44,5%
HR	3.316	6.776	48,9%
HU	10.777	17.975	60,0%
IE	4.520	10.741	42,1%
IT	55.823	113.611	49,1%
LT	2.550	5.241	48,6%
LU	1.115	3.615	30,8%
LV	2.357	3.875	60,8%
MT	85	495	17,1%
NL	27.014	44.953	60,1%
PL	38.177	69.139	55,2%
PT	5.514	15.275	36,1%
RO	13.383	22.860	58,5%
SE	14.163	32.370	43,8%
SI	1.888	4.837	39,0%
SK	6.094	9.903	61,5%
UK	54.891	121.221	45,3%

2. OVERVIEW OF WASTE MANAGEMENT TECHNOLOGIES

A.U Zaman (2010) classified the waste management technologies into:

- Sanitary landfill,
- Incineration,
- Gasification – pyrolysis of the waste treatment technologies [29].

Sanitary landfills act by breaking down and stabilizing disposed wastes over time. It is extensively used for MSW management. There are five (5) stages of landfills gas formation; initial adjustment, transition phase, acid phase, methane fermentation and maturation phases [29]. Landfill treatment of waste is the least expensive, but also the least effective. Concerns over environmental pollution, contamination and loss of land value all accompany landfill waste treatment. With respect to plastic waste, landfill waste treatment takes the longest time to neutralize plastic waste and is unsuitable for energy recovery.

Incineration processes use MSW as feedstock for combustion. Open air combustion requires enough amounts of oxygen for complete oxidation process. The products of combustion include water vapor, carbon dioxide (CO_2), some carbon monoxide (CO), ash and some amounts of carbon [30].

Pyrolysis- gasification is an endothermic process which occurs in the absence of oxygen or in the presence of other non-reactive gases at temperatures between 400^{o}C and 600^{o}C. During pyrolysis, organic materials are thermochemically decomposed at high temperatures and in the absence of oxygen [31]. Larger polymer molecules are broken into smaller molecules and recombined into useful products, mainly high energy density fuel.

Incineration and pyrolysis are described in more details below to aid comparison.

2.1 Mass incineration

Incineration is a waste treatment option that oxidizes waste at elevated temperatures of 1200^{o}C and 1600^{o}C [32], with the purpose of reducing the volume of waste and nullifying its hazard. The technology has developed to include enhanced energy recovery and simultaneous reduced greenhouse gas emission [33]. The main advantages of this waste treatment method are the simplicity of the process and little need for additional fuels as the waste combustion is a self-supporting process for municipal wastes of mixed compositional calorific value. In a controlled environment, waste combustion effluents can also be minimized, and the products can be monitored. Sources of revenue for energy recovery from incineration include; the gate fee charged for waste treatment (which is discounted from the cost of dumping in a landfill), and from the sales of heat and electricity.

During incineration, as temperature is increased, the material incinerated undergoes drying and degassing, followed by pyrolysis/ gasification and finally oxidation. In the drying and degassing stage volatiles are evolved, followed by the decomposition of organic substances in the absence of an oxidizing agent at elevated temperatures during the pyrolysis and gasification stage and finally, the combustion of the gases at elevated temperatures [34].

The flue gas of incineration include water vapour, nitrogen, carbon dioxide and oxygen with smaller amounts of CO, HCL, HF, HBR, HI, NOx, NH3, SO2, VOCs, PCDD/F, and heavy metal compounds, and solids; fly ash (dust) and solid ash (bottom ash). The composition of the waste streams vary from plant design to another [34] [7] [35]. At the time of this writing, 27% of the total waste in Europe is incinerated, with the rest being recycled, composted, or sent to the landfills [7] [14]. Estonia also has one mass incineration plant; Iru Waste to Energy plant which incinerates more than 65% of the mixed MSW produced in the country [36].

2.2 Pyrolysis

Instead of burning waste, pyrolysis technologies change the structure to more combustible hydrocarbons which have comparable properties with diesel, and natural gas, thus creating a value-added source of revenue from waste streams asides the gate fee charged to waste disposing companies. Comparatively, pyrolysis processes require lower temperature than incineration, and produce lower emissions of air pollutants such as polybrominated diphenyl ethers (PBDEs) [37][38][39]. Current applications of PP are utilized in improving the energy content of biomass to make charcoal in house heating. It has the potential to create a new value-added product, and depending on the feedstock, metal may be produced as well.

2.2.1 Equation of pyrolysis

Calorific Requirement of the pyrolysis process

$CxHyOz + Q \dashrightarrow Char + Liquid + Gas + H_2O$ [40]

Q is the reaction heat supplied and includes the heat

$Q1 = W \times 2260$, $kJ\ kg^{-1}$ [40]

$Q2 = Cp,M \int mM + Cp,ch \int mchdT + Cp,v \int mchdT + Qp,$ $kJ\ kg^{-1}$ [41]

where W is the feedstock water content
Cp,m and mM are the specific heat capacity J kg-1 °C^{-1} and the mass ratio of the dry material
Cp,ch and mch are the specific heat capacity J kg-1 °C^{-1} and the mass ratio of the char
Cp,v and mv are the specific heat capacity J kg-1 °C^{-1} and the mass ratio of the volatile

2.2.2 Factors affecting yield of pyrolysis processes

Pyrolysis processes can be modified to give different outputs; depending on the required yield, the process parameters can be designed. The composition of the products from a PP depend chiefly on the reaction temperature; the use of catalysts, the residence time, reaction kinetics and the type of reactor used. These results are included in the appendix section.

Slow pyrolysis occurs at elevated temperatures of 400°C to 800°C and longer residence times ranging from minutes to hours and increases the charcoal yield. Fast pyrolysis occurs between 650°C and 700°C with short residence time which can occur in milliseconds and yields up to 65% liquids. It is preferred if industrial focus is on more oil. At higher temperatures, the gas content is increased, but at lower temperatures, more oil is produced [41] [42] [44].

PP may be heated by burning with limited amounts of air, heating in an inert atmosphere of mainly unreactive gas or heating a solid energy carrier as a heat transfer medium. The third case is used in CFB boilers and has been applied to EOS with good results.

D. Czajczyńska et al explore the technical details for the selection of the reactor type based on the reaction specifics. Reactors are selected to improve the heat transfer. Reactor types applied the fixed bed reactors, batch or semi- batch reactors, rotary kilns, fluidized bed reactors, microwave assisted reactors and the process is conducted under atmospheric pressure [24].

Advantages of pyrolysis includes the ability to convert low energy density into high energy density fuels with the recovery of high value chemicals [45] [46], a more flexible scale than incineration plants [40]. The feedstock can be flexible utilizing domestic and industrial residues with input from paper, cloth, plastics, food waste and yard waste. The products as well can be flexibly changed by varying the operating parameters.

2.3 Cases from existing pyrolysis plants

2.3.1 Case 1: Waste Pyrolysis Plant, Burgau, Germany

Located in Gunzburg county, the WPP Burgau built in 1985 sits on 762 m^2 and serves 100, 000 inhabitants, and operates on 28,000-35000 tons per annum of municipal waste, industrial waste and sewage sludge in a ratio of 20:3:5 with an average calorific value of 9,000 kJ/kg. It uses two (2) rotary kilns for operation, and a condensation type turbine to maximize pyrolysis products and recover heat and electrical energy from the waste [37]. The process description is included schematically below, and summarized;

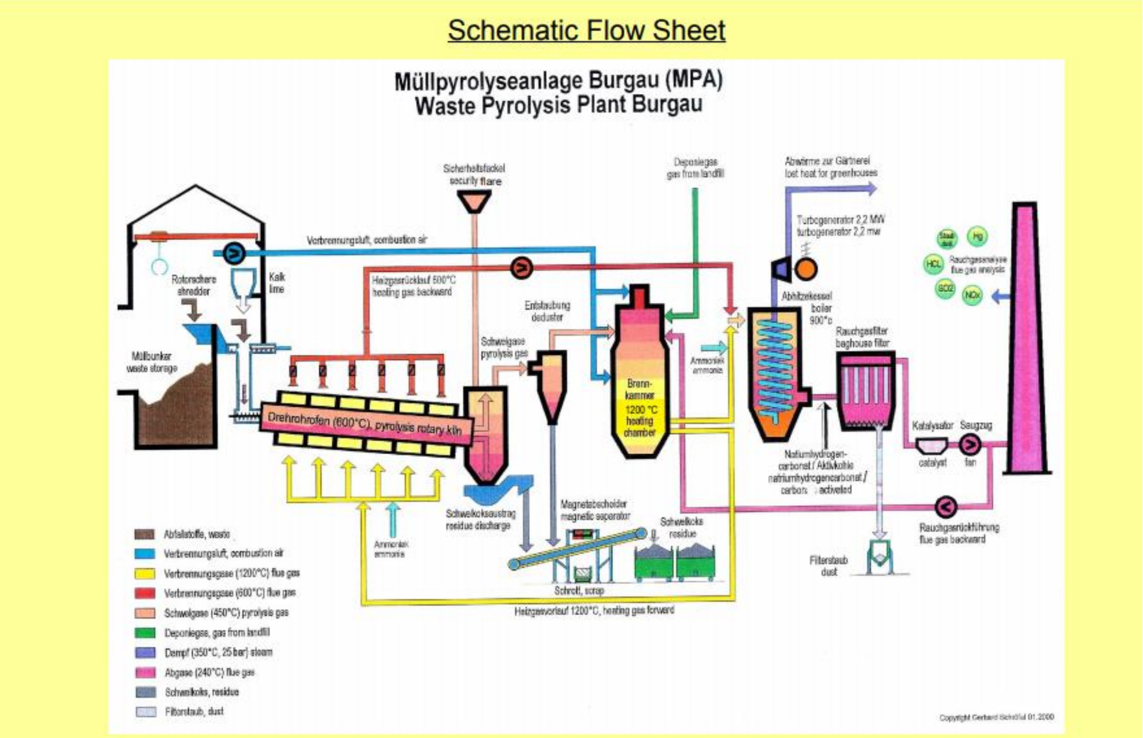


Fig. 2.1 Schematic Flow Sheet of the Waste Pyrolysis Plant Burgau [47]

Mixed Municipal wastes are first collected in the storage from whence they are picked and discharged onto rotor cutters and cut to reduce their sizes and improve reactivity. The sewage sludge as well is mixed with the wastes and fed into the pyrolysis kiln together with quicklime.

This mixture is heated indirectly with the flue gas from the pyrolysis gas incinerator at 120°C where it is dried, degasified and further raised to the process temperature of 500°C. At this temperature, organic matter is decomposed, and a solid residue is formed. The design of the rotary kiln process maximizes the amount of hydrocarbon produced, using the residence time, and pyrolysis temperature.

The addition of the quicklime also reduces the evolution of gaseous pollutants and consequently the need for cleaning the flue gases. The solid residue is further treated to separate metallic components from the residual coke; while the pre dedusted pyrolysis gas is combusted to fire a boiler to 1200°C and produce 350°C and 25bar steam to generate 2.2MW. The dedusted pyrolysis gas is collected for upstream condensation and the flue gas is reused to heat the boiler and the rotary kiln and requires minimal cleaning before being released. The waste heat is further fed to nearby greenhouses [47].

2.3.2 Case 2: Waste to Energy Pyrolysis Plant in Japan.

Sapporo Plastic Recycling (SPR) through Industry partners Klean Technologies Inc. established a 50 ton/day commercial plastic liquefaction facility in Hokkaido. SPR processes plastics into 70% oil; light oil, medium fuel oil, and heavy oil. Additionally, the process is optimized to produce 4 MW of electricity to the grid, and 4 MW of thermal energy for district heating, 3,000 tons per year of solid recovered fuel, 150 tons per year of hydrochloric acid, 100-125 tons per year of Aluminum as well as an offset of 15,000 tons per year of carbon dioxide emissions.

The unique technology enables SPR to also reduce the chlorine content of PVC and handle Benzoic acid without affecting the pH of the oil product. The outcome of this plant is exemplary in recycling over 100,000 tons of plastic and produce high grade marketable products. It is noteworthy though that though the plant was self-sufficient, and highly efficient, it withdrew from business in 2010 due to "extreme low profitability" [44] [48].

As the process is like that provided above, less explanation is included to avoid repetition. The process schematic is included below;

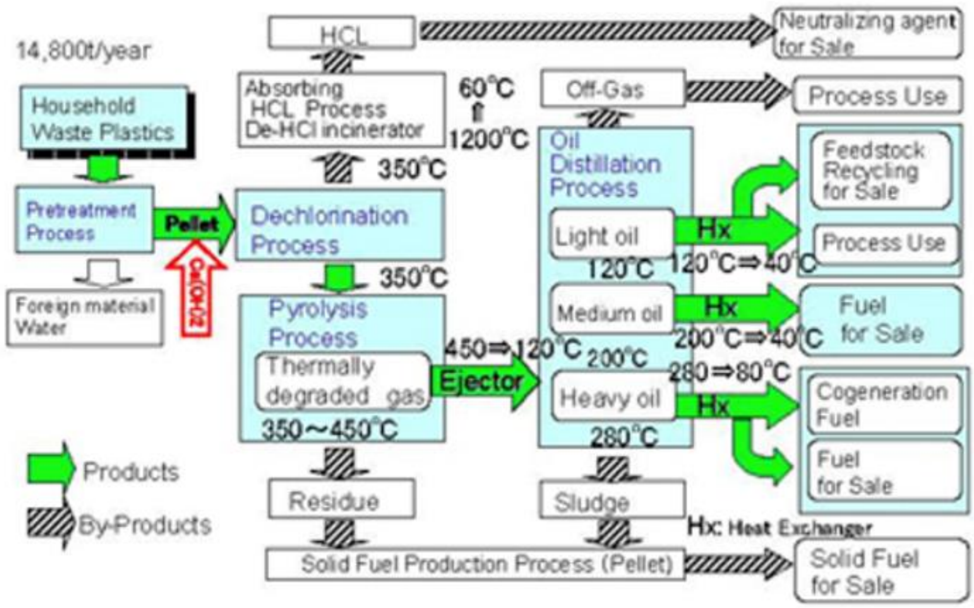


Figure 2.2 Flow chart of a Plastic pyrolysis Plant in Japan [49]

2.3.3 Case 3: Henan Doing.

Henan Doing China's fully continuous WPP converts waste plastics, tires, industrial solid waste and household waste to produce fuel oil using continuous liquefaction and catalytic breakdown reaction. The output capacity is 10tpd to 100tpd. The process uses indirect heating, and a reaction temperature of 400-450°C, the company has reached conversion rates of 80-90% for plastics, and about 45% for waste tires. The process requires 60m^3 of water a month, and 244 kWh/day of power to run. The carbon black and combustible gas yield rates are 10-15% and 5-10% respectively [50].

2.3.4 Case 4: Berkeley Vale Project New South Wales

This plant processes 50 tpd of household non-recyclable plastic into fuel that can be used for various road applications. Using a catalytic process of restructuring, the technology heats the plastic to above 400°C in the absence of oxygen, destroys the large polymeric bonds and restructures them into the smaller chained hydro-carbon suitable as fuel for use in vehicles.

The plant cost €3.69 Million, and operates on a feedstock costing €230 per ton, with the estimates of producing 49 Million liters of diesel and 6 million liters of petrol by June 2017. It was designed by the Beston (Henan) machinery Co., Ltd [51] [52].

At a market price of €1.42 per liter of diesel and €1.35 per liter of petrol [53], the revenue is forecast at €69.58million in sales of diesel, €8.1million in sales of petrol, and a declining cost for plastic waste year on year. The case of the New South Wales is proof of concept that a plastic to oil pyrolysis plant can be commercially feasible.

3. COMPARISON BETWEEN WTE MASS INCINERATION PLANTS AND PYROLYSIS PLANTS

3.1 Environmental concerns

Mass incineration processes are regarded as being relatively cheaper, as they only remove radioactive waste and do not separate the waste to be burned. However, in a comparative study using the life cycle analysis tool, Adisa Azapagic [8] summarizes the problem of the growing social dissatisfaction with mass incineration and addresses the question of which is more environmentally friendly between mass incineration and pyrolysis/gasification. Namely, "if the main aim is to reduce the amount of solid waste being landfilled (while still recovering energy), then large scale incineration appears to be an environmentally more sustainable technology overall. If on the other hand, the main aim is to recover energy from waste, small scale pyrolysis with gasification is an environmentally better option" [8].

W.K Buah et al conclude that despite the numerous advantages from incineration of municipal solid waste in the forms of heat recovery, the release of large volumes of flue gases; hazardous waste streams from fly-ash and poor public perception make this technology less suitable as a more sustainable method of energy generation. They also argue that though landfilling is less expensive [54], the increasing costs of long-distance haulage to landfill sites [55] and the European Union Waste Landfill Directive 1999 31/EC (1999) to reduce the levels of biodegradable waste input in landfills from 1999 levels to 35% by 2020 through increased recovery and improved recycling of the waste necessitate a preferable method of waste treatment [56][57].

In terms of carbon footprint, through the pyrolysis route, utilizing waste as a source of fuel oil can reduce the dependence on fossil fuel, saving fossil fuel consumption and freeing up resources for energy budget. The high energy content char can also be briquetted and used as replacement to logged wood. With less deforestation, carbon uptake by plants will help offset emissions from other carbon intensive sectors.

3.2 Motivation for selecting plastic component for pyrolysis

Given the high investment costs and limited data on the establishment of a PPP, investing right into a pilot plant is not without its risks. However, another route to maximize the benefits of pyrolysis is to combine PPP cycles with already existing WTE processes. Pyrolysis plants optimize the production of oil, and more recently, the char products. Waste compositions that can maximize these outputs are target materials. While the oil can be refined further and upgraded for uses in aviation, transportation, or burnt for heat alongside with shale oil, the solid residue has found uses in activated coal production, industrial heating, and for use in manufacture of dyes.

It is thus important to optimize the reaction parameters to produce the desired quantity and composition of pyrolysis products. The results summarised in table 3.2 highlight the output of mixed waste plastic pyrolysis aided with catalyst for production of the highest quantities of oil. The decision to utilize the plastic component for this energy carrier is based on

- the medium to high abundance in waste composition,
- higher energy content compared to the other components of waste,
- relatively higher yield of value adding products,
- The lower processing cost compared with biomass.

3.2.1 Large composition

As previously established in section 1.3, large quantities of high energy content segments of MSW are required to run a PP with high throughput. Different organic feedstocks have been evaluated for gas yield, oil yield and char yield under changing temperature and reactor types.

3.2.2 Energy content

In an investigation of MSW pyrolysis optimization through the use of Refuse Derived Fuel (RDF) pellets an improved method of increasing the calorific value of the waste, improving the flexibility of usage, and better control over the waste products can be achieved. Higher calorific value gases have been produced, and the char can be turned into a potential feedstock for higher value activated carbon manufacture [56].

The plastic component of the waste composition shows the highest energy content. PPO700 has a LHV of 38.2 MJ/kg, compared with 42.9 MJ/kg from diesel, and a comparative ash content of less than 0.001wt% [58]. With catalytic processing, improved energy content up to 43.7 MJ/kg was reached. [59] The heating value of the EOS is 5-8.6 MJ/kg [60] while biomass heating value range from 14-19 MJ/kg [61]. Optimum yield rates of oil can be obtained using mixed plastic wastes aided by catalysts at 500^{o}C.

3.2.3 Oil yield

From table 3.1, we saw the oil yield rate of mixed plastics wastes reached 82%. The oil yield rate of oil shale ranges from 60% to 67.7% using the Fisher Assay process [62].

Maximum oil yields of about 60% was attained at optimum temperatures of 450-550°C [63] for biomass obtained oil.

Table 3.1: Different yield rates of pyrolysis processes with different inputs

	Feedstock	Reactor Type	Pyrolysis Temperature °C	Gas Yield %	Oil yield %	Char Yield%	Source
1	Pine (Soft wood)	Fixed Bed	370	20	59	21	[64]
2	Wastepaper	Vacuum pyrolysis, 5mmHg	450	17.74	47.03	35.23	[65]
3	Waste textiles	Batch Bed	900	10	42	48	[66]
4	LDPE	Stirred batch Reactor	425-500	10-47	89.5-37.5	0.5-15.5	[67]
5	Poly Propylene	Micro Reactor	300-400	28.84-31.07	69.82-63.23	1.34-5.7	[37][68]
6	Waste plastics	Semi Batch Reactor	500	25.6	40.9	28.2+5.3	[69][37]
7	Rubber waste tyres	Fluidized bed	500	3.5	65	31	[70]
8	Waste plastic aided with catalyst	Fixed Bed; Two Stage batch	500	8	82	10	[71][72] [37]

The Fluidized bed reactor with fast pyrolysis, with biomass pyrolysis, this reactor has achieved a consistent 75% throughput [73], with aided catalyst and plastic or rubber, a higher yield is possible. This research is based on the two-stage continuous pyrolysis prices. Also, considering the separation/sorting cost, this method reduces the problem of sorting, and can accommodate a wide range of waste purity.

3.2.4 Cost of processing

The cost of PPO is significantly lower than the cost of EOS, and Pyrolysis Bio Oil (PBO), however, the grade of oil produced affects its marketability, and the focus on the revenue process product will determine the profitability. BPP was shut because it was not economically competitive in comparison with the 72 existing waste incineration plants (in 2007); as at 2015, it was 65€/ton more expensive to operate the plastic pyrolysis plant than the waste incineration plants [74]. With advances in pyrolysis technologies, the cost of liquefaction has significantly reduced.

Biofuel processing costs decrease exponentially on the volume of oil processed, the distance of the processing plant to the source of materials, and the nature of the biofuel used. At a processing rate of 10tpd, the cost of 1 ton of produced oil from rice husk is extrapolated at €525.78/ton [75] while oil shale oil costs of production similarly range between €491.6-€786.5/ton

[76]. The recalculations to SI unit were made with the converters below.

† 1 ton of oil is equivalent to 285.75 gallons of diesel quality oil [77],

‡ 1 ton is equivalent to 17.81barrels of oil equivalent [78].

From feasibility studies of a 10tpd, the cost of 1 ton of pyrolysis oil with some components of carbon black and steel cost €169 which is comparable to values calculated from other plants [48]. PPO produced with slow pyrolysis and Natural Zeolite (NZ) assisted was shown to have comparable energy values as diesel, as such it can be sold at a discount to the market price for high grade diesel.

3.2.5 Ease of retrofitting to the incineration plant

Drawing from existing technologies for processing oil shale, waste pyrolysis can easily be retrofitted to the already existing plant. The availability of enough waste stream ensures that if the plant should be run in pyrolysis mode, oil output would be reached without affecting the electricity or heat production.

The pyrolysis reactors can be fitted to operate within the combustion parameters in the incineration zone using continuous production mode, or a batch mode with indirect heating fed from the incinerator. The temperatures are compatible with the pyrolysis requirement, and catalysts can be used to reduce the heat demand.

The major consideration for PP includes the economics of setting up a PPP. This is explained in further detail in section 4.

Table 3.2 Comparing the performance of plastic pyrolysis oil, shale oil and biomass oil under different indices.

	PPO	**EOSO**	**BMO**
Heating Value (MJ/kg)	38.2MJ/kg [58]	8.6 MJ/kg [79]	14-19MJ/kg [61]
Oil yield (wt%)	82% [71][72]	60-67%[62]	60% [63]
Cost of production €/ton	€169 (Using the Henan doing case model) [48]	491.6-786.5 €/ton [76]	€525.78/ton [75]

3.2.6 Technical Lifetime of a Plastic Pyrolysis Plant

Pyrolysis is an endothermic process and requires huge financial investments to build and make it more profitable. The profitability of a pyrolysis plant depends on the lifespan of the plant, operation cost, and investment costs as well as several related factors.

In a study investigating the economic, environmental and social benefits of adoption of pyrolysis process of tires, researchers designed a pilot plant that runs on rubber with a life span of 10 years, a feed rate of 100kg/h batch flow [6] and profitability of over €3 million a year. The main output revenue sources of this plant are the carbon black, metal, oil and syn gas which is re used by the plant.

Henan Doing boasts of creating a pyrolysis machine with a lifespan of 8-9 years [50], while financial comparison of different fast pyrolysis routes puts the life time of plant at 15 years [80] in practice, pyrolysis plants have much longer life cycles. The Burgau pyrolysis plant (BPP) in Germany operated for 30 years (1985 till 2015) and was closed due to non-profitability. In theory if a pyrolysis plant is operated, it should produce revenue in terms of electricity, district heating water and liquefaction products and should be both competitive, cleaner and profitable as waste is a resource. However, since liquefaction companies have closed as they could not remain profitable, it is important to investigate the feasibility studies and the loopholes of previous pyrolysis plants.

Notably however, the high energy content solid component was sent to the landfills rather than sold for additional income [74] and the focus of the process was on gas yield, rather than oil. More recently, pyrolysis plant manufacturers use technologies that are modular, smaller and less expensive, and flexible in both feedstock and process. They allow more efficient oil production at lowered cost and thus can significantly improve the economic efficiency of the pyrolysis plant.

3.3 Economic figures of a mass incineration plant

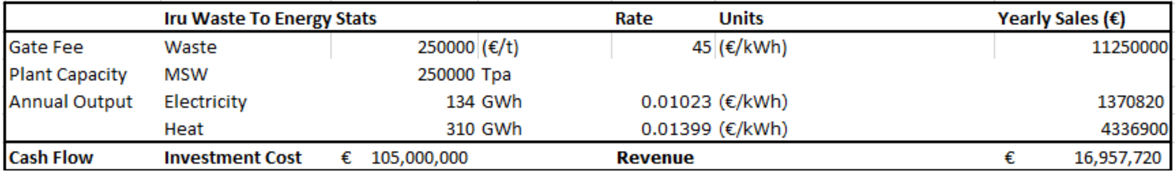
Considering that the mass incineration technologies currently practiced to some extent can be replaced with more sustainable pyrolysis, it is important to consider the available information on mass incineration plants in comparison to pyrolysis routes. The table below compares some available data of some WtE by mass incineration plants. It is assumed that since the waste production, waste compositions and calorific conversion to energy are similar as the regional economy, the consumption pattern and the waste production profiles are similar.

Table 3.1 Comparison of Waste to Energy Incineration Plants in Estonia and Lithuania [81]–[83]

Company, location	**Waste input/ capacity (tons/year)**	**Electrical capacity (MW)**	**Thermal capacity (MW)**	**Investment cost (Million Euros)**
Iru Waste to energy (Estonia)	248,000	17	50	105
Kauno Kogeneracine Jegaine (Lithuania)	200,000	24	70	150
Vilnius Kogeneracine Jegaine (Lithuania)	160,000	20	55	147

The yearly revenue from sales of heat and electricity are estimated below using the average price of electricity Nordpool market rate 10.23 €/MWh [84] and the rate for heating in Estonia which varies between 33.54 €/MWh -88.57€/MWh, with the average weighed mean 64.37 €/MWh [85]. Operational costs are excluded as well as the gate fee charged for waste processing. Plant profitability should factor in these variables and correct for the time value of money.

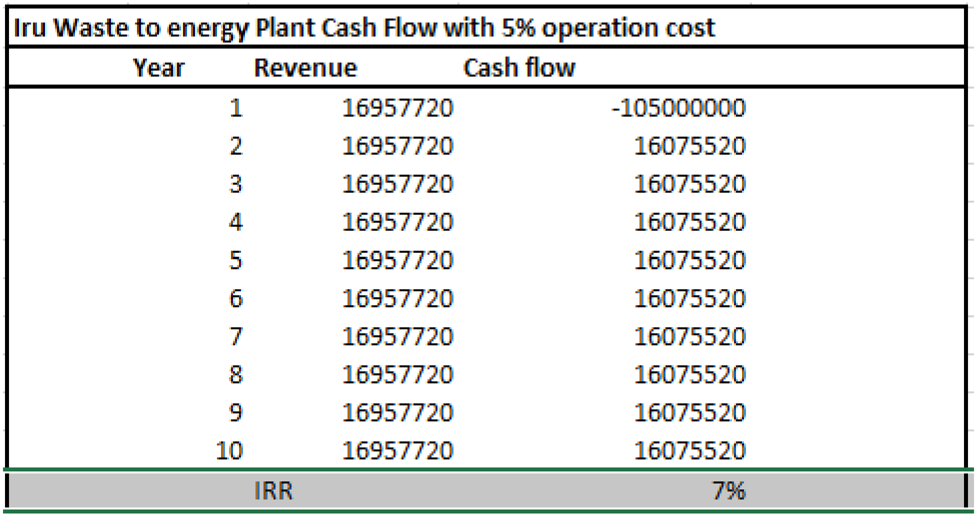
Table 3.2 Financial performance markers for Iru Waste to Energy plant



	Iru Waste To Energy Stats			**Rate**	**Units**	**Yearly Sales (€)**
Gate Fee	Waste	250000	(€/t)	45	(€/kWh)	11250000
Plant Capacity	MSW	250000	Tpa			
Annual Output	Electricity	134	GWh	0.01023	(€/kWh)	1370820
	Heat	310	GWh	0.01399	(€/kWh)	4336900
Cash Flow	**Investment Cost**	€ 105,000,000		**Revenue**		€ 16,957,720

From the investment cost and output of the Iru WtE and the current market rates for electricity and heat, the forecast payback period occurs in the third year and a internal rate of return at 7%.

Table 3.3 Payback time of the Iru Waste to Energy plant



Iru Waste to energy Plant Cash Flow with 5% operation cost		
Year	Revenue	Cash flow
1	16957720	-105000000
2	16957720	16075520
3	16957720	16075520
4	16957720	16075520
5	16957720	16075520
6	16957720	16075520
7	16957720	16075520
8	16957720	16075520
9	16957720	16075520
10	16957720	16075520
	IRR	7%

3.4 Financial modelling for a plastic pyrolysis plant

Mohammed et al [75] posit the cost of pyrolysis plants through their working lifetime from equations given below;

Annual cost (€) = Annualized capital cost+ Operating Cost-annualized salvage value

Where the annualized capital cost is

ACC= $\frac{(\text{total plant Cost+ Construction cost})}{(1-(1+i)^{-Np})}$ x ip [86]

Where ACC is the annualized capital cost per year,

ip is the interest rate

and Np is the lifetime.

The construction cost is given by;

Construction cost =$\sum_{j=1}^{Nc} \frac{(\text{total plant Cost})}{Nc} jic(1+i)^{Nc-j+1}$ [87]

Average investment costs vary depending on the capacity of the plant and the process design. Innovations in pyrolysis technologies account for reduced investment costs. In China, an investment of €6,490,000 would be required for a 10 tpd [48], while the Integrated Green Energy pyrolysis plant in Australia required only €3,720,000 for a 50 tpd plant investment.

Table 3.4 Comparisons between investment costs, capacities and outputs of various pyrolysis plants

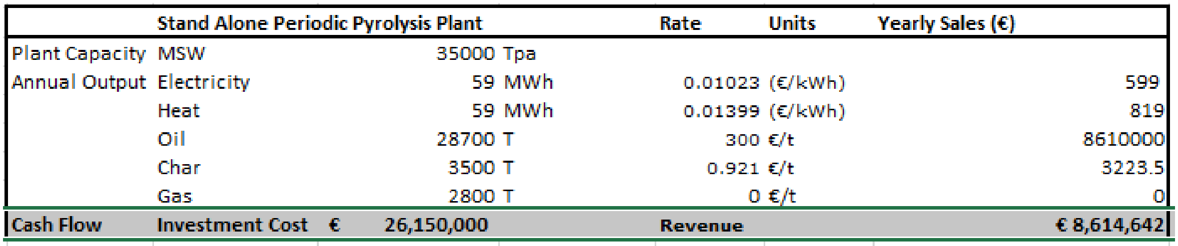
Pyrolysis Plant	**Waste input (tpa)**	**Electricity output**	**Heat output**	**Products**	**Life Cycle (years)**	**Investment (€ Million)**	**Source**
Burgau Pyrolysis Plant	35,000	2.2MW	n/a	Gas Electricity Solids sent to landfill.	30	11.4	[74][88]
Sapporo Plastic Recycling	14,000	4MW	4MW	Solid: 3,000t Hydrochloric Acid: 150t Oil: 9,176t Oil:	10	N/ana	[48]
Henan Doing	36,500	-0.244MW	None	Oil Carbon black Combustible gas	n/a	6.5	[48]
Integrated Green Engineering	18,250	N/A	N/A	Diesel Petro Negligible Gas	+4years	3.72	[51]

The (-) negative here indicates that the plant does not produce electricity; rather, electricity is required to run the plant.

3.5 Comparison between economic figures of a plastic pyrolysis plant and a waste to energy mass incineration plant

If a PPP operated on the same quantity of input as the WtE, the yearly revenue would exceed € 61Million in a year; 150% of the Iru WtE revenue at maximum feed rate. Although such a large feed rate capacity would require more investment. This is discussed further in the sensitivity analysis section (4.7).

Table 3.5 Iru WtE statistics compared with a pyrolysis plant of 14% the Incinerator input



	Stand Alone Periodic Pyrolysis Plant			Rate	Units	Yearly Sales (€)
Plant Capacity	MSW	35000	Tpa			
Annual Output	Electricity	59	MWh	0.01023	(€/kWh)	599
	Heat	59	MWh	0.01399	(€/kWh)	819
	Oil	28700	T	300	€/t	8610000
	Char	3500	T	0.921	€/t	3223.5
	Gas	2800	T	0	€/t	0
Cash Flow	Investment Cost	€	26,150,000	Revenue		€ 8,614,642

From tables 3.1 and 3.3 above, investment costs for incinerators are much higher than for pyrolysis, resulting in higher investment to waste capacity. Comparing investment cost to the waste treatment capacity of the plants, incineration plants have much higher cost per quantity of waste treated compared with pyrolysis plants as shown by the figure below.

We cannot compare the cash flows from both plants as the investment and maintenance costs required for such a large-scale pyrolysis plant is unknown. From an investment to waste treated standpoint however, investments in pyrolysis treatment is justified.

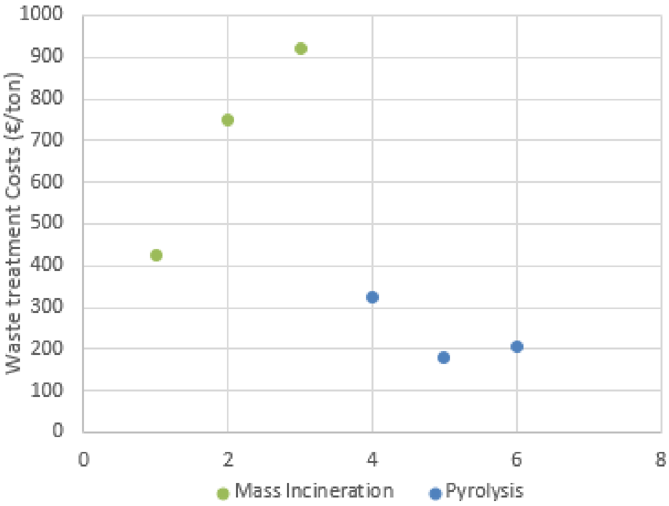


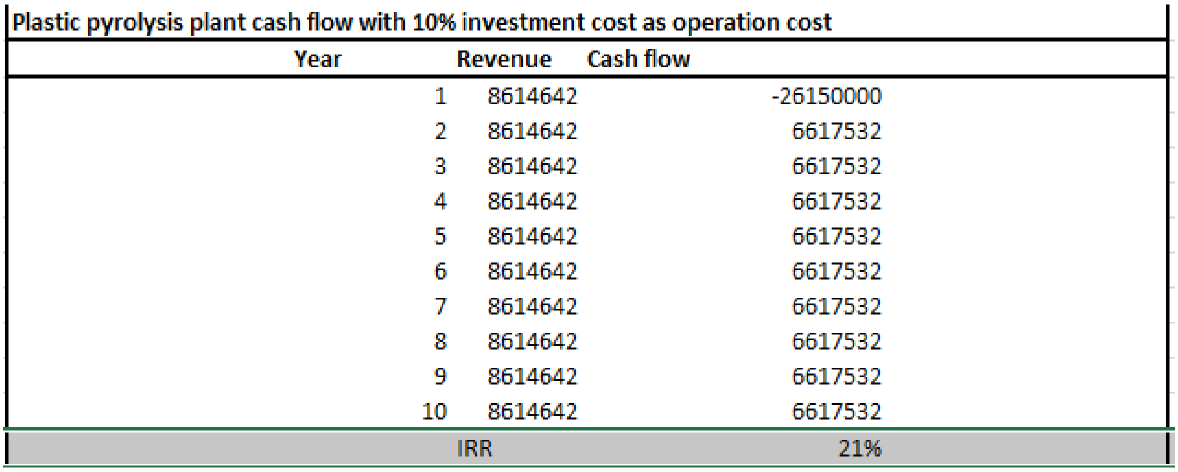
Figure 3.2 Investment Costs of WtE and Pyrolysis Plants 2. 3. 4. 5. 6. 7.

1	2	3	4	5	6
Iru Waste to Energy	Kauno Kogeneracine Jegaine	Vilnius Kogeneracine Jegaine	Burgau Plastic Plant (BPP)	Henan Doing	Integrated Green Engineering

From fig 3.1, and 3.4 above, WtE plants from an economic point of view are justifiable. Although the treatment costs are higher in incineration than the pyrolysis costs for the same waste for the same quantity of waste pyrolyzed as incinerated, plastic pyrolysis route is significantly more profitable, and the payback period is shorter. Unfortunately, quantity of waste plastic input is lower, and more plastic would need to be bought to keep production high. Alternatively, suggested is the potential of periodic co pyrolysis.

Inherently pyrolysis is less more sustainable as it gives less pollutants and reduces the demand for fossil fuels. The plastic pyrolysis route is not extensively utilized as such there is not much information about the investment cost required for installing and operating a plastic WtE cogeneration pyrolysis plant.

Table 3.6 Financial cash flow forecast of a pyrolysis plant working on 10 % operational cost.



Plastic pyrolysis plant cash flow with 10% investment cost as operation cost

Year	Revenue	Cash flow
1	8614642	-26150000
2	8614642	6617532
3	8614642	6617532
4	8614642	6617532
5	8614642	6617532
6	8614642	6617532
7	8614642	6617532
8	8614642	6617532
9	8614642	6617532
10	8614642	6617532
	IRR	21%

4. PROCESS FEASIBILITY OF PYROLYSIS PLANT IN ESTONIAN CONDITIONS

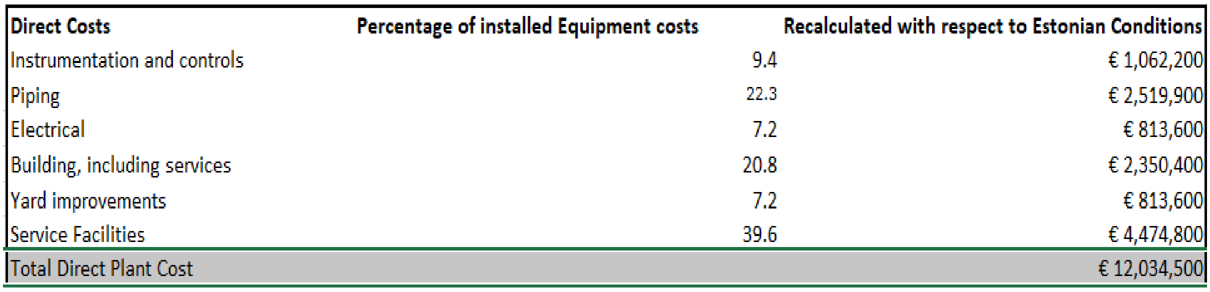
PP investment costs vary considerably by the region they are operated in; the capital costs for an Advanced Thermal Treatment Plant (TTP) which include waste gasification/pyrolysis in the U.K range from €10.35M to €63.27M, for a capacity of 25ktpa to 100ktpa [30], while a similar bio oil pyrolysis plant in Oregon has a lower plant cost of €11.3M for a pyrolysis system of 73ktpa [80]. To estimate pyrolysis investment cost for Estonian conditions, the 2-stage continuous extraction process was used, and the contingency cost was recalculated based on the additional costs from shipping, inflation rate and regional variance. In the sensitivity analysis, different investment costs are observed.

4.1 Capital costs operation and maintenance costs of a stand-alone pyrolysis plant

As not many countries are currently using the periodic co-pyrolysis plastic pyrolysis route, there is little specific information about the investment and operational financing required for installing and operating a plastic WtE cogeneration pyrolysis plant or a detailed lifecycle analysis. However, using data from similar existing plants accessible, calculations from pyrolysis plant machine manufacturers and similar technologies in biomass pyrolysis, the average capital cost of a 35,000 ton capacity plant is estimated using direct investment costs of €11,300,000 [44][80][88].

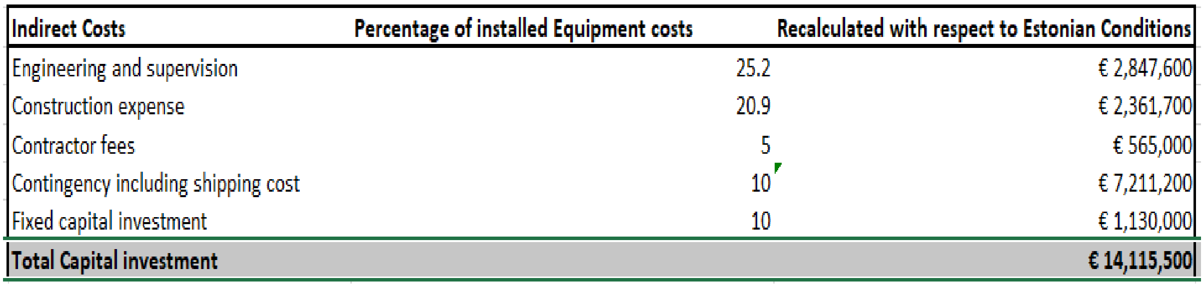
The figures are modelled after a wood pyrolysis process, and the current technology of Henan doing is used to incorporate the technical requirements [89]. In practice, cost of processing should be lowered as yield from plastic pyrolysis is higher than from wood pyrolysis. Below are recalculations of a pilot liquefaction plant to Estonian conditions of plastic yield;

Table 4.1 Direct costs of a pyrolysis plant 2 stage continuous extraction process recalculated for a 78tpd process [90]



Direct Costs	Percentage of installed Equipment costs	Recalculated with respect to Estonian Conditions
Instrumentation and controls	9.4	€ 1,062,200
Piping	22.3	€ 2,519,900
Electrical	7.2	€ 813,600
Building, including services	20.8	€ 2,350,400
Yard improvements	7.2	€ 813,600
Service Facilities	39.6	€ 4,474,800
Total Direct Plant Cost		€ 12,034,500

Table 4.2 The total capital investment and indirect costs of a pyrolysis plant 2 stage continuous extraction process recalculated for a 78tpd process



Indirect Costs	Percentage of installed Equipment costs	Recalculated with respect to Estonian Conditions
Engineering and supervision	25.2	€ 2,847,600
Construction expense	20.9	€ 2,361,700
Contractor fees	5	€ 565,000
Contingency including shipping cost	10	€ 7,211,200
Fixed capital investment	10	€ 1,130,000
Total Capital investment		**€ 14,115,500**

From Table 4.1 and 4.2 above, the costs of using a 2 stage continuous reactor for pyrolyzing a waste stream of 78tpd (35000tpa) is given, using the waste composition of 14% plastics as the base parameter [90]. As discussed previously, numerous plastic pyrolysis plants have failed over the years due to economic feasibility problems, technical issues or a combination of factors. From a worst-case scenario, the installation of a stand-alone pilot plant is favorable thus investment costs for combined plant can reduce by more than 50% in piping, building and servicing of facilities, as these costs can be shared by the incinerator and pyrolysis section. Also combined with high efficiency catalysts with a consequent yield of 82%; IRR of 21% can be reached, with an initial investment of about €26,150,000.

A summary description of the Iru waste to Energy plant is provided below for reference to the proposed Modified Periodic Plastic Pyrolysis Route.

4.2 Iru WtE Process Flow Description

Waste handling companies drop off their mixed municipal waste from segmented bins within the city and pay a gate fee to the Iru Wte plant. This gate fee is less than the charge to dump untreated wastes into landfills. Trucks containing the MSW feed in presorted waste into a fixed batch hopper.

Radioactive sensors fitted into the incinerator inlet detect radioactive materials which are then sorted out to prevent their incineration. The selected waste is fed into the Martin grate combustion system at a rate of 31ton per hour and is pre heated with hotter stream from the gas treatment unit. An air pump feeds atmospheric air at standard temperature and pressure into the boiler system to assist combustion.

Heat energy is transferred from the incinerated waste to water in the boiler raising the water to super-heated steam, which subsequently is used to power turbine for electric power generation. The heated steam leaves the turbine after expending energy;

changes phase and is condensed into heated water which is piped to provide District heating (DH) to nearby residential homes and industries. The bottom ash is removed from the Martin Grate combustion system and hauled to a landfill.

The toxic gaseous effluents (NOx, SOx, heavy metals and dioxins etc) from combustion are neutralized by Selective Non-Catalytic Reduction (SNCR) system in a DeNox system block before being released to the atmosphere. The schematic diagram is provided below; [91]

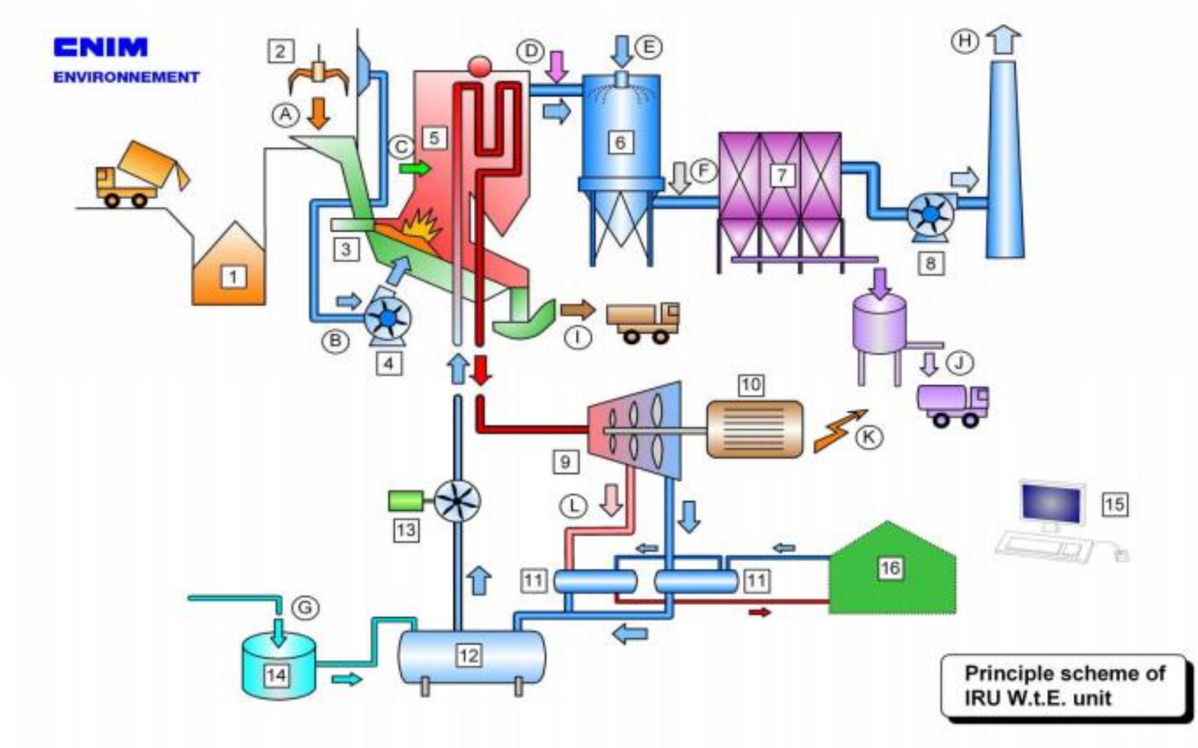


Figure 4.1: 1. Waste bunker 2. Waste transport line and lifting equipment 3. Martin GmbH type waste incinerator 4. No air intake system 5. CNIM heat exchanger 6. Semi-dry filter system 7. Fine filter system 8. Induction fan 9. Steam turbine 10. Generator 11. District heating unit 12. deaerator and circulating water tank 13. Circulating water pump 14. Circulating water treatment block 15. Control centre 16. District heating network system

To reduce investment risk required for construction of a pilot plant while ensuring constant source of feedstock, the option of retrofitting the Iru waste to energy plant to accommodate for plastic pyrolysis is more feasible. As discussed in section 3, there are advantages afforded by this method which deduce payback time and increase the rate of return.

4.3 Optimising the seasonal waste variation pattern

The decision of choosing continuous pyrolysis with a steady input, or batch pyrolysis is influenced by observing the energy demand curve served by the Iru WtE Fig 4.2 below; the technical feasibility of either method and the waste generation pattern.

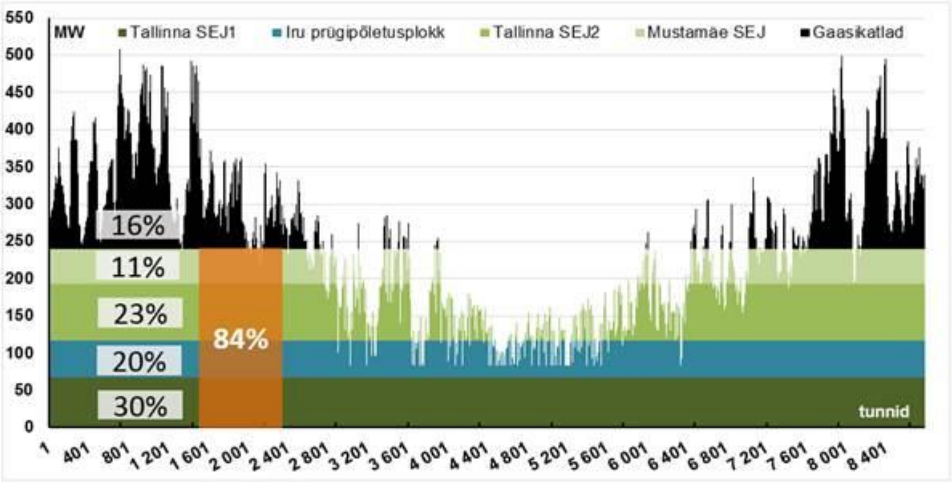


Figure 4.2 Energy consumption distribution by plants in Estonia 🟩Tallinna SEJ, 🟦Iru waste to energy 🟩Tallinna SEJ 2 🟩Mustamae SEJ ⬛Gas boilers

In summer, energy consumption reduces on average of 5-10% of the maximum energy output. The energy output still produced by the plant remains the same; leading to an energy loss and lowered efficiency. Also, in the summer months, the quantity of waste particularly plastic and packaging wastes increases due to increased tourism and increased spending, as established in Chapter 1 and seen in Fig 4.3 below. This produces a material surplus which can be exploited by the WtE plant if redesigned to process liquefaction oil during this period. In the waste burning profile for 2019, the plant was closed for overhaul and maintenance, thus no waste was waste combusted in July. It should be noted that this is not the usual case; the Iru waste to energy plant continuously burns waste all year round, however, this data goes to emphasize that the demand is significantly lowered in the summer, leading to reduced revenue.

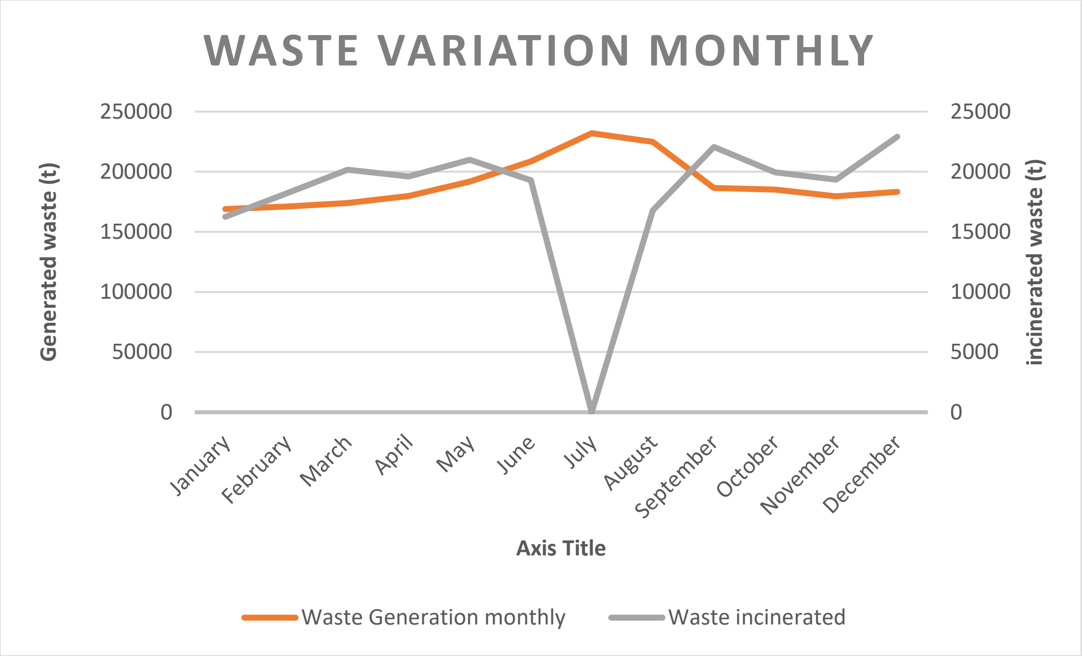


Figure 4.3 Yearly distribution of waste in Tallinn using a simplified mathematical model and data; showing significant correlation to the increase in population during the summer months [88-91]

The importance of this waste production pattern underscores the need for waste storage and sorting to help energy engineers plan production better particularly in the months of reduced heating demand.

4.4 Continuous or planned periodic pyrolysis model

Running a co-pyrolysis system will have an impact on the energy available to be delivered to the incinerator. Removing plastics which all year round will make a significant energy reduction in the total waste feed and reduce the output of electricity and heat which are important products of the Iru incinerator. A continuous production method will impact on the revenue of the incinerator for a sustained duration however, if the planned periodic pyrolysis is used, the period of lowered energy demands can be exploited to carry out the pyrolysis without affecting the plant profit. Also, it is preferable to take advantage of the waste trend, rather than produce all through the year.

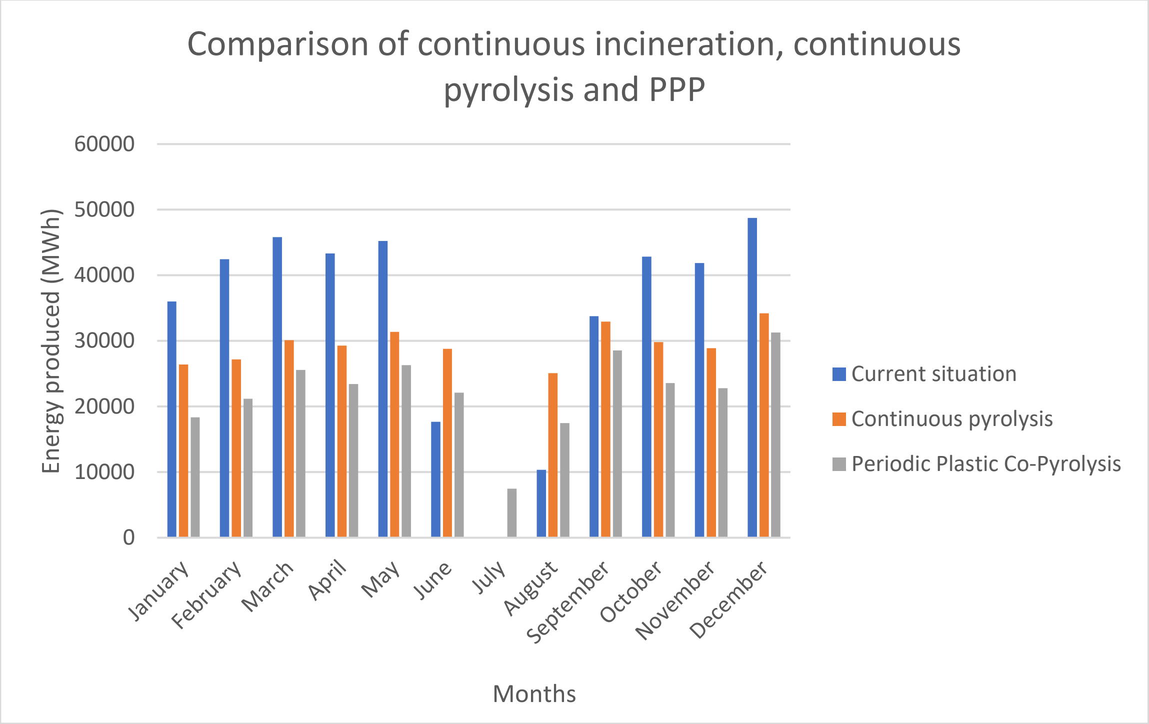


Fig 4.4 Scenarios of energy available to the incinerator with nominal working conditions, continuous plastic removal and periodic plastic removal

During the summer, energy saving can be attained by recalculating the fuel consumption to the energy demanded for electricity. Using previous data history match, fuel uptake can be reduced during the energy surplus, with the plastic components stored and pretreated with residual heat during the period of reduced heat demand. The pattern of operation may be concurrent with the daily incineration, however, a seasonal approach is advised and modeled in this research.

4.5 Combined pyrolysis and incineration process flow

Main process modification includes the preselection of high energy content valorizable plastic feedstock, storage of this feedstock and periodic co pyrolysis;

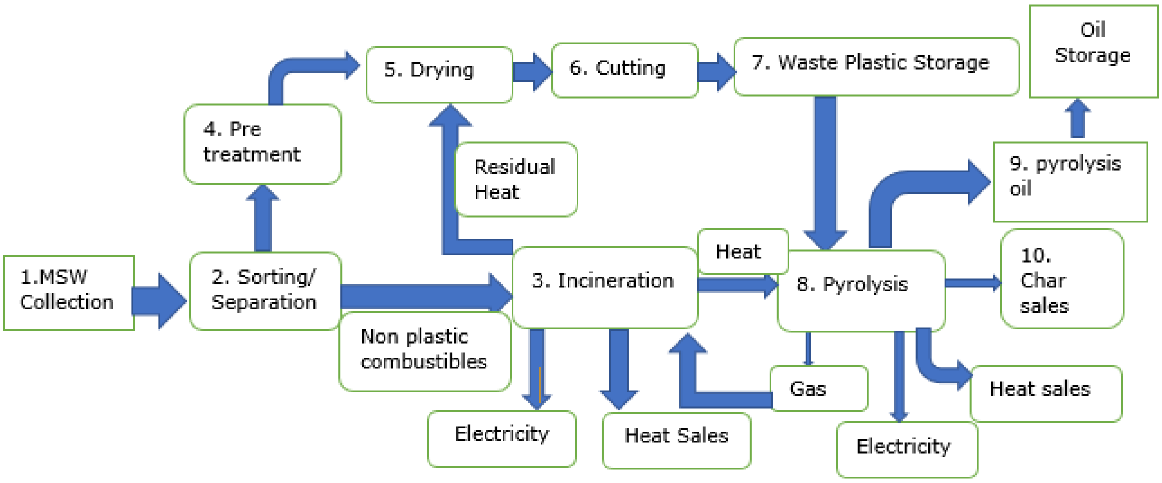


Figure 4.5 Process flow schematic for a combined incineration and Periodic Optimized Plastic Pyrolysis Plant

4.5.1 Collection and Sorting

The current trend of waste handling in Estonia involves the collection of municipal wastes into already classified bins from collection centers; sorting these into recyclable and non-recyclable components. The non-recyclable components are then burned in the Waste to Energy plant at Iru WtE Power Plant. Economically, this is feasible as waste collection and disposal companies pay lesser to dispose the waste to the Waste to Energy plants than they would to have the waste in landfills. The political framework is in favor of waste recycling and disposal. Going further, this scheme can be maximized with less labour used in separating waste plastic from the other waste constituents.

Comparing three plant separation trial processes in Spain, Netherlands and Germany, the results of the Wijster plant is recommended for guidance as it uses less labour, and has a higher recovery of plastics, while retaining a simpler separation route. By comparison, the Trier and Barcelona trial plants have advantages, but may be too complex or human labour intensive to retrofit into the Iru mass incineration plant [93].

Another suggestion is to buy the required plastic. Currently the provision for plastic waste buying is not fully developed in Estonia although the option of importing exists. An estimation for the cost of waste plastic can be made on a markup of 10% more than the plastic waste sold to the recycling companies at the market rate of 3696 €/t [94] for recycling. While this option may ensure high quality plastic waste and consequently high oil quality, compared to pyrolysis oil market rates of 300€/t, this method looks unattractive and will lose in processing cost as well as the additional revenue from gate fee.

The advised method of sorting still appears to be from the source, with the waste collection companies encouraging people to segregate their waste so plastic components will require the least amount of effort to be separated at the pyrolysis plant. Allowance for inefficiency should be given as that will improve the calorific value of the non-plastic combustibles. A high separation efficiency is not an important requirement.

4.4.2 Material balance of a plastic pyrolysis plant in Estonian conditions

As established in previous section, waste generated by residents of Tallinn and tourists in a year are modelled to amount to 1.9Million tons. However, some of this is recycled, composted or sent to the hazardous wastes landfill and so is not factored into the pyrolysis input model. The Iru Waste to energy plant consumes more than 250,000 tons of waste yearly [83]; and out of this, 14% is plastic waste [5]. Thus, the yearly plastic yield of 35000 tons of plastic. More waste may be produced by other counties not within the Tallinn municipality, but transportation costs increase the carbon print and total cost of processing; making them unpreferable. Therefore, this model is limited to the Tallinn municipality.

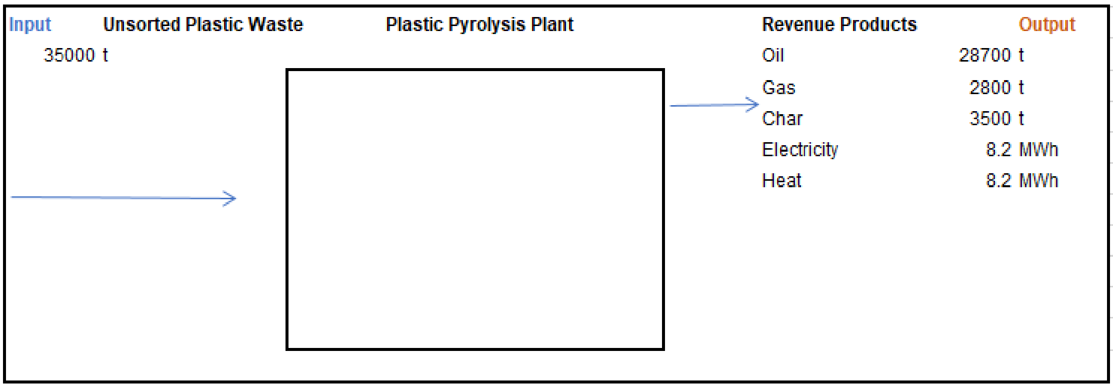


Figure 4.6 Material balance of a plastic pyrolysis plant in a year using Tallinn waste composition [5][83]

The values above (for the heat energy and electrical energy production) are modelled from the Sapporo liquefaction plant above and optimized using the NZ catalyst in the fixed bed two stage continuous reactor. The removal of plastic from the total MSW input of the Iru incinerator will have some effect on the calorific value of the new input, thus using the Iru steam data in the Appendix section, the new electricity and heat available can be recalculated. Also, pyrolysis will further reduce some of the energy available to the turbine and heat exchangers. To keep the temperature of the incineration chamber up, the gas produced from pyrolysis can be reused as it is a high calorific gas.

4.6 Feasibility calculations; material variables

In addition to the gate fee, additional sources of income for a pyrolysis plant include the revenue generated from the sales of energy, char, oil, heat and electricity. The rates for calculation from 4.1 above and the current market prices.

4.6.1 Char price

The information on the price of pyrolysis char is not sufficient, however, the price of bio char in the market is 18.50 €/t [95][80]. A discount of 20% off this price can be used as a markup base for sensitivity analysis, with the assumption that pyrolysis char is a less valuable resource than bio char.

4.6.2 Electricity price

In Estonia, the average price of electricity is 0.153 €/kWh for household consumers and 0.092 €/kWh for industrial consumers [85].

4.6.3 Oil price

With a pyrolysis oil standard of SH/T0356-1996 No 4 Light Fuel Oil, current oil price of a No 4 Light Fuel oil amounts to 300 €/t [48].

4.6.4 Heat price

The prices of heating in Estonia varies between 33.54 €/MWh -88.57 €/MWh, [85], the price paid by the house hold users is 0.01399 €/kWh [96]. The rates for electricity and heat revenues used here are also used for calculating the revenue of the Iru Waste to energy plant. See section 3.3.

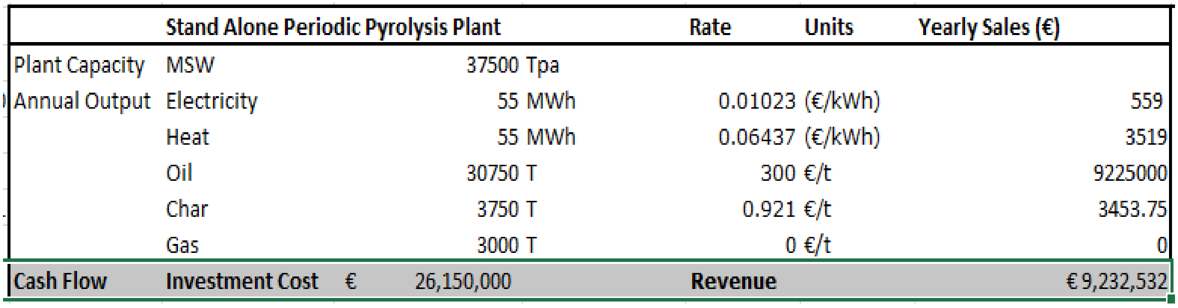
4.6.5 Carbon black price

The current price of Carbon black on the market is 21 €/t [97]. The Carbon black price is included for the contingency of a material shortage, and the need to include rubber tires into the pyrolysis plant.

4.6.6 Gate Fee

The Iru charges 45-53 €/T [98], which is lower than the landfill disposal cost.

Table 4.3 Projected Revenue stream from a 78tpd PPP (14% of the MSW fed to incinerator)



	Stand Alone Periodic Pyrolysis Plant		**Rate**	**Units**	**Yearly Sales (€)**
Plant Capacity	MSW	37500 Tpa			
Annual Output	Electricity	55 MWh	0.01023	(€/kWh)	559
	Heat	55 MWh	0.06437	(€/kWh)	3519
	Oil	30750 T	300	€/t	9225000
	Char	3750 T	0.921	€/t	3453.75
	Gas	3000 T	0	€/t	0
Cash Flow	**Investment Cost**	€ 26,150,000	**Revenue**		€ 9,232,532

The prices of electricity and heat produced are very little. This indicates that the plant in pyrolysis mode will not be making much income from the sales of these output; rather it would be making more money by sale of the new products. For this reason, the energy planning should target pyrolysis during period of lowered energy demands.

4.7 Technical Requirements of the combined system

Using a fixed bed two stage continuous reactor; slow pyrolysis at 500°C and aided with spent NZ catalyst, the expected yield rate is 30,750 tons of oil, 3750 tons of char, and 3000 tons of gas. The produced gas is not factored into the calculations, as it is burnt on site to reduce the energy and fuel demand required to run the process [99]. The temperature requirement is compatible with the Martin Grate Combustion System medium to high temperature zones.

Additional storage space for plastic accumulation, shredding and oil storage can also be fitted to the plant. Gas delivery for the produced syn gas will be fed back into the incineration side to maintain temperature throughout the burner. Char can be further processed to high quality briquettes in drying and compression units.

4.8 Economic feasibility of optimized periodic pyrolysis/ incineration model

Advantage of combining the two plants results in continuous income for the plant. In summer, it is noted that the sales of heat from the plant drop due to reduced demand. This reduction in revenue can be compensated for by increased revenue in oil sales. While this may result in lowered electricity production, the total yearly revenue increases, and down time losses are covered.

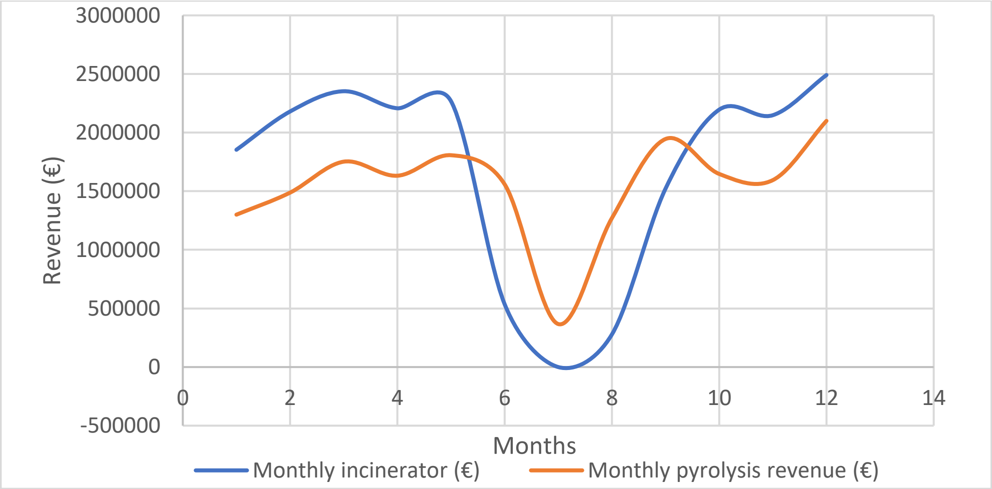
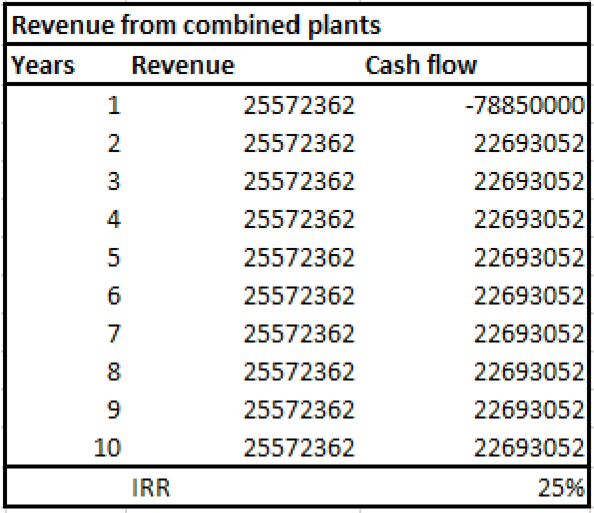


Figure 4.7 Payback of standalone Iru Waste to Energy plant and combined continuous plastic pyrolysis plant.

Relative internal rates of return of 21% for PPP and 7% for WTEMI from investments in a 35000t plant (shown from the tables 3.3 and 3.6 above) and a 250,000t capacity incinerator obtained for separate investments in both routes. With a combined approach, the investment costs are reduced and the revenue increases.

Table 4.4 Internal rate of return from investing in a combined incineration and pyrolysis plant



Revenue from combined plants		
Years	Revenue	Cash flow
1	25572362	-78850000
2	25572362	22693052
3	25572362	22693052
4	25572362	22693052
5	25572362	22693052
6	25572362	22693052
7	25572362	22693052
8	25572362	22693052
9	25572362	22693052
10	25572362	22693052
	IRR	25%

The new internal rate of return on the combined investment becomes 25% with increased revenue sources coming from the sales of oil, char, electricity and heat. Investment costs are significantly reduced to only the costs required for the reactor, instrumentation, piping, electrical, service facilities. In all cases, the investment is made in the 1st year of the plant operation, and cash flow include an operating cost of 10%.

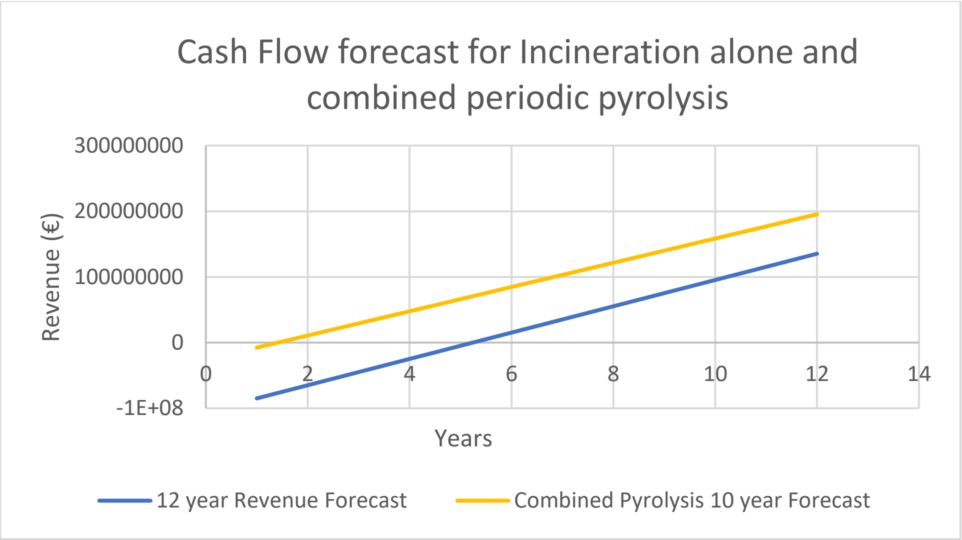


Fig 4.8 showing the projected cash flow forecast of combining the periodic pyrolysis into the Iru Waste to Energy plant.

4.9 Sensitivity

Factors affecting the productivity of the plant depend on the yield, (which is influenced by the process parameters; temperature and catalysts); the market price of pyrolysis oil and char; the percentage of plastic removed for processing and the investment cost of the pyrolysis set up. Attached below (A.6-A.10) are sensitivity variations on operational cost, varying market prices, pyrolysis plastic redistribution percentage, yield ranges from 75% to 82%.

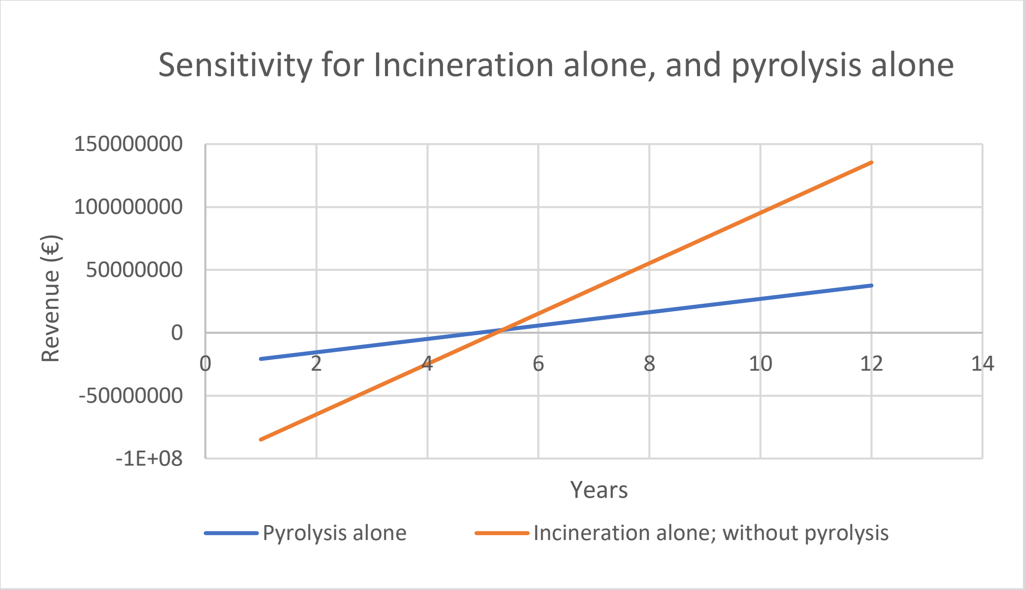


Fig 4.9 Sensitivity for revenue without electricity and heat sales (pyrolysis alone), and without oil or char sales (incineration alone)

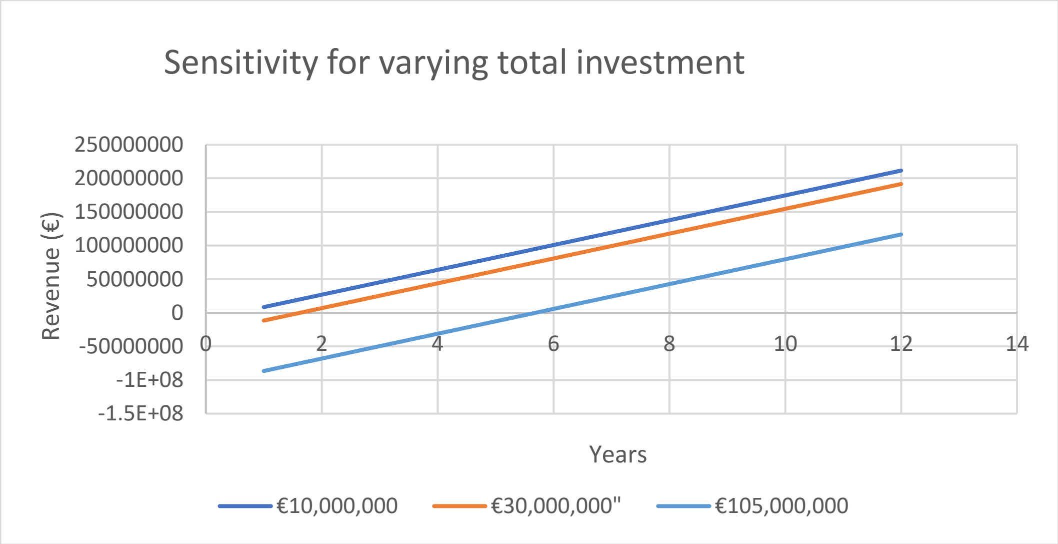


Fig 4.10 Sensitivity for varying total investment including operation cost

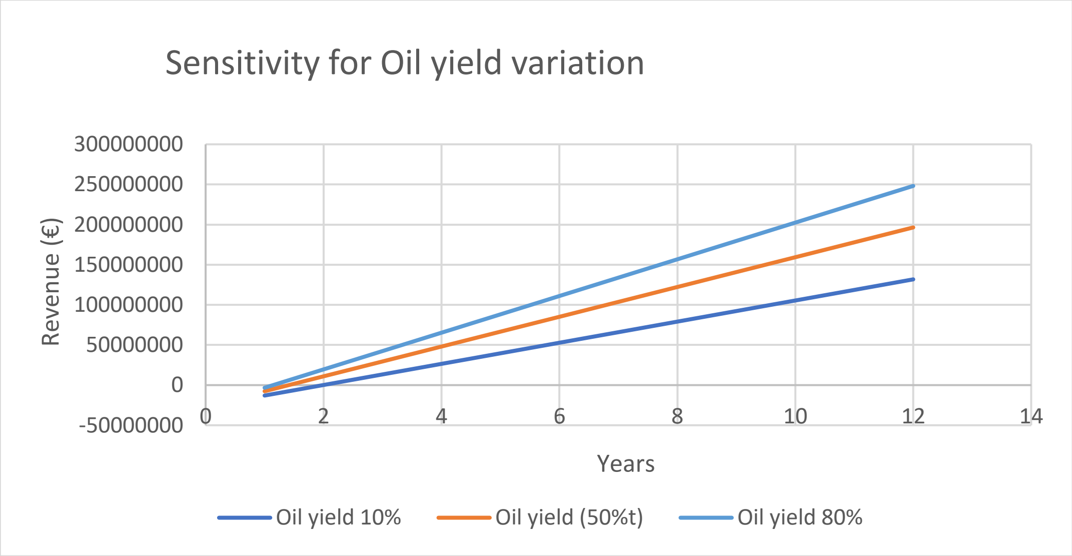


Fig 4.11 Sensitivity for oil yield variation

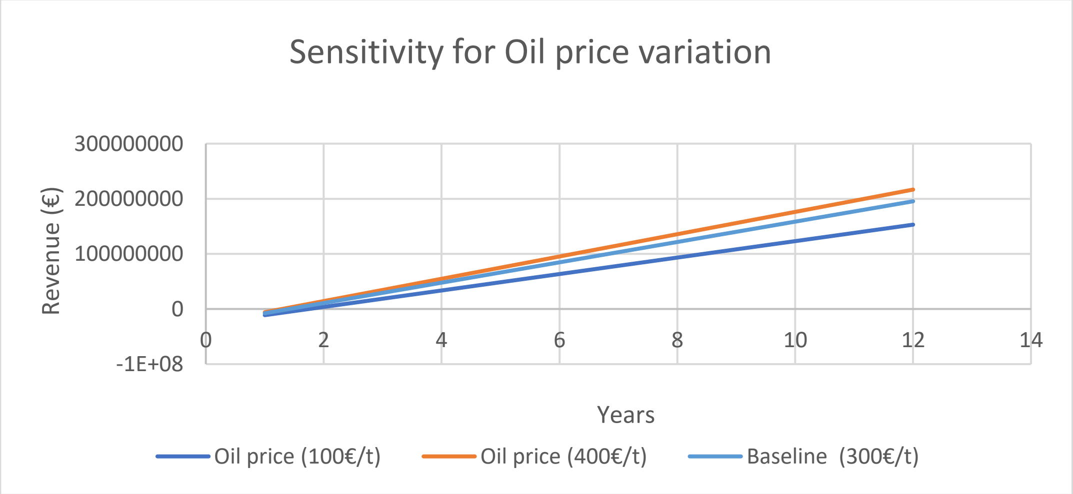


Fig 4.12 Sensitivity for oil price variation

CONCLUSION

Plastic pollution is fast becoming a huge growing environmental concern characterized by long decomposition cycle, and numerous land and aquatic animals ingesting plastic waste. However, with energy recovery, this waste can be used as a resource for sustainable energy. With plastic waste typically increasing in summer due to increased touristic activities, increased spending, and less need for heat and electrical energy, an opportunity for energy planning can turn this resource into a higher energy carrier with improved efficiency and plant process management.

Feasibility concerns over pyrolysis were addressed. While pyrolysis seems like the ideal solution for the plastic problem, it has been noted that many companies that operated this technology failed due to difficulties in sourcing the waste plastic, financial problems, and technical issues. With improved reactor thermochemistry, catalysts and sorting processes, these issues have been eliminated in the combined pyrolysis approach design. From the preceding above, the combined operation is favoured if;

- pyrolysis oil quality is comparable to diesel grade,
- pyrolysis oil price is more than 300€/t; which is a function of the market price of crude oil,
- cost of buying waste plastics is avoided,
- investment costs are kept to the minimum,
- routine maintenance is scheduled in the collection phase of the incineration cycle,
- policies that encourage effective waste collection and sorting are improved and continued.

The major change to the cash flow forecast occurs if the investment cost of retrofitting the pyrolysis plant is more than €30,000,000. In this case pay back on investment would occur after three years. This is unlikely as the approach of combining these two methods listed above will significantly reduce some of the capital expenditure otherwise incurred in the building of a new pilot plant.

If a cleaner technology is being considered to replace the EOS, pyrolysis from waste plastic shows a huge potential for producing high quality diesel oil at the lowest price and highest efficiency. In terms of carbon impact, it can reduce the dependence on fossil fuel for transportation, district heating and manufacture of some chemical compounds. Additional benefit is observed by reducing deforestation for heating, as the waste from pyrolysis can be briquetted and provides a high energy content fuel instead of charcoal, or wood.

To compensate for lowered plastic volume, a pyrolysis plant that can also run on rubber tires can be installed. Observing that previous plants that ran only on rubber tires failed, this may be a better approach to reduce cost, and improve material input consistency. As existing research has been invested in by Rubber pyrolysis-based companies which are still profitable and technically viable, consultation from their experts can reduce the time required to make a sustainable business model from waste plastic and waste tire co-generation technologies.

SUMMARY

Pyrolysis seems like an ideal solution to solving fossil fuel emission by providing an efficient way to use plastics thus reducing dependence on fossil fuel oil; it has been shown that it is less expensive than investments in bio oil pyrolysis and oil shale pyrolysis. However, considering that some previous companies shut down as they were entirely based on this technology, suggestions to combine it with already existing waste incineration plant was made with the idea to cut cost of buying high grade materials, avoiding the cost of installing a new pilot system, and improving the incinerator down time through improved yield. Improvements in pyrolysis combined with new catalysts have reduced the energy demand, making them more efficient and profitable.

This paper shows that it is feasible from a sustainability perspective as well as economically to implement this technology as a hybrid. Drawing from previous works, a flexible pyrolytic plant that can also run on rubber would improve plant performance efficiency as well as provide cleaner and more sustainable energy. Catalytic pyrolysis has been shown to reduce the energy input required for the smooth running of a Waste to oil plant, thus reducing the costs required to run a pyrolysis plant.
Recommendation and challenges for further research include the redesign of the waste to energy plant may be needed to accommodate the new capacity of the plant.

Although the current waste handling method is efficient, further measures to reduce the sorting requirement and legislation to improve waste management can greatly improve the quality of pyrolysis oil aimed at during production.

The Iru Waste to energy plant loses some of the useful energy during the summer as heat because residents do not need heat at that time of the year. If modifications to the process are made during the summer, an additional source of income to the summer income can be made. Solar pyrolysis can be considered for investigation as this would make the most of the free energy resource, and not interrupt the incineration process. It is a greener energy option for energy recovery and can utilize some of the heat from the combined process for drying and pretreatment.

The plant production is most strongly affected by the investment cost than any other factor, it is advised that further research on combined rubber and plastic pyrolysis can be undertaken to maximise these resources, while minimising investment costs. Further prospects of retrofitting for the pyrolysis of rubber tires will significantly solve the growing tire disposal issue in an economically feasible manner.

LIST OF REFERENCES

[1] D. Briggs, "Environmental pollution and the global burden of disease.," *Br. Med. Bull.*, vol. 68, pp. 1–24, 2003.

[2] T. W. Bank, "Solid Waste Management," *IBRD. IDA*, 2019.

[3] "Collection of Municipal Waste in Estonia," Tallinn, Estonia, 2017.

[4] Estonian Institute for Sustainable Development, "Improving the Recycling System of Municipal Waste in Tallinn Based on The Examples of Best Practices," 2014.

[5] D. R. Tobergte and S. Curtis, "7. Waste production and management," *J. Chem. Inf. Model.*, vol. 53, no. 9, pp. 1689–1699, 2013.

[6] G. Oliveira Neto, L. Chaves, L. Pinto, J. Santana, M. Amorim, and M. Rodrigues, "Economic, Environmental and Social Benefits of Adoption of Pyrolysis Process of Tires: A Feasible and Ecofriendly Mode to Reduce the Impacts of Scrap Tires in Brazil," *Sustainability*, vol. 11, no. 7, p. 2076, 2019.

[7] P. J. Reddy, *Energy Recovery from Municipal Solid Waste by Thermal Conversion Technologies*. CRC PRess Balkema, 2003.

[8] A. Azapagic, "Energy from municipal solid waste: Large-scale incineration or small-scale pyrolysis?," *Environ. Eng. Manag. J.*, vol. 6, pp. 337–346, Sep. 2007.

[9] IEA, "Data and Statistics," 2020. [Online]. Available: https://www.iea.org/data-and-statistics?country=ESTONIA&fuel=Energy consumption&indicator=Total final consumption (TFC) by source. [Accessed: 26-Apr-2020].

[10] P. O. M. and C. Onsongo, "OPerationalising Municipal Solid Waste Management," *Intech*, p. 13, 2012.

[11] OECD (2019), "No Title," *Municipal waste (indicator).*, 2019. [Online]. Available: data.oecd.org/waste/municipal-waste.htm. [Accessed: 14-Nov-2019].

[12] V. Misra and S. D. Pandey, "Hazardous waste, impact on health and environment for development of better waste management strategies in future in India," *Environ. Int.*, vol. 31, no. 3, pp. 417–431, 2005.

[13] B. Adhikari, K. R. Dahal, and S. Nath Khanal, "A Review of Factors Affecting the Composition of Municipal Solid Waste Landfill Leachate 1*," *Certif. Int. J. Eng. Sci. Innov. Technol.*, vol. 9001, no. 5, pp. 2319–5967, 2008.

[14] R. LeBlanc, "How long does it take garbage to decompose," *Richl. Cent.*, pp. 1–3, 2015.

[15] V. Chhabra, S. Bhattacharya, and Y. Shastri, "Pyrolysis of mixed municipal solid waste: Characterisation, interaction effect and kinetic modelling using the thermogravimetric approach," *Waste Manag.*, vol. 90, pp. 152–167, 2019.

[16] M. E. Edjabou, A. Boldrin, and T. F. Astrup, "Compositional analysis of seasonal

variation in Danish residual household waste," *Resour. Conserv. Recycl.*, vol. 130, no. August 2017, pp. 70–79, 2018.

[17] G. Gómez, M. Meneses, L. Ballinas, and F. Castells, "Seasonal characterization of municipal solid waste (MSW) in the city of Chihuahua, Mexico," *Waste Manag.*, vol. 29, no. 7, pp. 2018–2024, 2009.

[18] Y. Zeng, K. M. Trauth, R. L. Peyton, and S. K. Banerji, "Characterization of solid waste disposed at Columbia Sanitary Landfill in Missouri," *Waste Manag. Res.*, vol. 23, no. 1, pp. 62–71, 2005.

[19] G. Denafas *et al.*, "Seasonal variation of municipal solid waste generation and composition in four East European cities," *Resour. Conserv. Recycl.*, vol. 89, pp. 22–30, 2014.

[20] A. Kamran, M. N. Chaudhry, and S. A. Batool, "Effects of socio - economic status and seasonal variation on municipal solid waste composition : a baseline study for future planning and development," *Environ. Sci. Eur.*, 2015.

[21] P. Stanchev, E. Katsou, S. Pons, A. Vlasopoulos, N. Spencer, and R. Krzy, "Municipal solid waste management and waste-to-energy in the context of a circular economy and energy recycling in Europe," vol. 141, 2017.

[22] K. Kaplan Mintz, L. Henn, J. Park, and J. Kurman, "What predicts household waste management behaviors? Culture and type of behavior as moderators," *Resour. Conserv. Recycl.*, vol. 145, no. January, pp. 11–18, 2019.

[23] E. Energia, "Renewable Energy," 2020. [Online]. Available: https://www.enefitgreen.ee/en/energia-tootmine. [Accessed: 12-May-2020].

[24] C. F. Etc, S. C. P. February, and A. Reichel, "Municipal waste management in Estonia," no. February, 2013.

[25] OECD, "OECD Environmental performance reviews: Estonia Highlights 2017," *Environ. Perform. Rev.*, 2014.

[26] B. H. Moora, E. Piirsalu, and T. Viilvere, "Analysis of food waste in the Estonian food trade sector and the food industry Summary," pp. 1–2.

[27] M. Allen *et al.*, "IPCCC 1.5C: Summary for Policymakers," *Aromar Revi*, 2018.

[28] WBDG, "Biomass for Heat," 2016.

[29] A. U. Zaman, "Comparative Study of Municipal Solid Waste Treatment Technologies Using Life Cycle Assessment Method Comparative study of municipal solid waste treatment technologies using life cycle assessment method," no. March 2010, 2014.

[30] "Advanced Thermal Treatment of Municipal Solid Waste," no. February, 2013.

[31] M. Rehan *et al.*, "Pyrolytic liquid fuel: A source of renewable electricity generation in Makkah," *Energy Sources, Part A Recover. Util. Environ. Eff.*, vol. 38, no. 17, pp. 2598–2603, 2016.

[32] J. Shiju Easo and C. Nanjunda Swamy, "Design of incinerator for the treatment of bio-medical solid waste in chikmagalur city," *J. Ind. Pollut. Control*, vol. 27, no. 2, pp. 173–179, 2011.

[33] J. Pilusa, M. Shukla, and E. Muzenda, "Economic Assessment of Waste Tyres Pyrolysis Technology : A Case study for Gauteng Province, South Africa," *Int. J. Res. Chem. Metall. Civ. Eng.*, vol. 1, no. 1, pp. 41–49, 2014.

[34] European Commission, *Best Available Techniques (BAT) Reference Document for Waste Treatment*, no. 9781461457510. 2018.

[35] UmweltBundesAmt, "Draft of a German Report with basic informations for a BREF-Document "Waste Incineration"," no. December, 2001.

[36] D. Cavegn, "Eesti Energia's Waste to energy plant a continuing success," 2016. [Online]. Available: https://news.err.ee/120197/eesti-energia-s-waste-to-energy-plant-a-continuing-success. [Accessed: 29-Apr-2020].

[37] D. Czajczyńska *et al.*, "Potential of pyrolysis processes in the waste management sector," *Therm. Sci. Eng. Prog.*, vol. 3, pp. 171–197, 2017.

[38] B. Wyrzykowska-Ceradini, B. K. Gullett, D. Tabor, and A. Touati, "PBDDs/Fs and PCDDs/Fs in the Raw and Clean Flue Gas during Steady State and Transient Operation of a Municipal Waste Combustor," *Environ. Sci. Technol.*, vol. 45, no. 13, pp. 5853–5860, Jul. 2011.

[39] B. Wyrzykowska-Ceradini, B. K. Gullett, D. Tabor, and A. Touati, "Waste combustion as a source of ambient air polybrominated diphenylethers (PBDEs)," *Atmos. Environ.*, vol. 45, no. 24, pp. 4008–4014, 2011.

[40] D. Chen, L. Yin, H. Wang, and P. He, "Pyrolysis technologies for municipal solid waste: A review," *Waste Manag.*, vol. 34, no. 12, pp. 2466–2486, 2014.

[41] K. Raveendran, K, Ganesh, A., Khilart, "HEating Value of biomass and biomass pyrolysis products," *Fuel*, pp. 1715–1720.

[42] P. T. Williams, "Pyrolysis of waste tyres: A review," *Waste Manag.*, vol. 33, no. 8, pp. 1714–1728, 2013.

[43] N. Nkosi and E. Muzenda, "A review and discussion of waste tyre pyrolysis and derived products," *Lect. Notes Eng. Comput. Sci.*, vol. 2, pp. 979–985, 2014.

[44] J. Scheirs and W. Kaminsky, "Feedstock Recycling and Pyrolysis of Waste Plastics: Converting Waste Plastics into Diesel and Other Fuels," *Feed. Recycl. Pyrolysis Waste Plast. Convert. Waste Plast. into Diesel Other Fuels*, pp. 1–785, 2006.

[45] R. Chowdhury and A. Sarkar, "Reaction Kinetics and Product Distribution of Slow Pyrolysis of Indian Textile Wastes," *Int. J. Chem. React. Eng.*, vol. 10, no. 1, 2012.

[46] B. Biswal, S. Kumar, and R. K. Singh, "Production of Hydrocarbon Liquid by

Thermal Pyrolysis of Paper Cup Waste," *J. Waste Manag.*, vol. 2013, p. 731858, 2013.

[47] DGEngineering, "Waste Pyrolysis Plant 'Burgau,'" no. July, pp. 1–16, 2009.

[48] Y. Lin, "Industrial-scale Processes for Transforming Mixed Plastic Wastes to Oil," no. December, pp. 1–46, 2018.

[49] K. I. Inc, "Klean Industries," 2015. [Online]. Available: http://www.kleanindustries.com/s/sapporo_plastics_pyrolysis_recycling_plant.asp.

[50] H. Doing, "Pyrolysis Plant Specification," 2020. [Online]. Available: https://www.wastetireoil.com/Pyrolysis_plant/Pyrolysis_Plant/plastic-to-oil-257.html. [Accessed: 23-Mar-2020].

[51] B. H. Machinery, "50 TPD Plastics to Diesel Plant Produces First Batch in Austraia," 2015. [Online]. Available: https://plasticpyrolysisplants.com/50-tpd-plastics-to-diesel-plant-produces-first-batch-in-australia/. [Accessed: 20-Apr-2020].

[52] W. M. World, "50 TPD Plastics to Diesel Plant in Australia," 2020. [Online]. Available: http://www.waste-management-world.com/articles/2015/05/50-tpd-plastics-to-diesel-plant-produces-first-batch-in-australia.html. [Accessed: 05-Jan-2020].

[53] TheAA, "March 2020 Fuel Prices," *Reports, AA Fuel Price*, 2020. [Online]. Available: https://www.theaa.com/driving-advice/driving-costs/fuel-prices. [Accessed: 19-Apr-2020].

[54] J. C. Powell, "The Evaluation of Waste Management Options," *Waste Manag. Res.*, vol. 14, no. 6, pp. 515–526, Nov. 1996.

[55] S. Nagano, H. Tamon, T. Adzumi, K. Nakagawa, and T. Suzuki, "Activated carbon from municipal waste," *Carbon*, vol. 38, no. 6. pp. 915–920, 2000.

[56] W. K. Buah, A. M. Cunliffe, and P. T. Williams, "Characterization of products from the pyrolysis of municipal solid waste," *Process Saf. Environ. Prot.*, vol. 85, no. 5 B, pp. 450–457, 2007.

[57] P. T. Williams, "Pericles_Exported_Citations." John Wiley and Sons.

[58] I. Kalargaris, G. Tian, and S. Gu, "The utilisation of oils produced from plastic waste at different pyrolysis temperatures in a DI diesel engine," *Energy*, 2017.

[59] R. Miandad *et al.*, "Catalytic pyrolysis of plastic waste: Moving toward pyrolysis based biorefineries," *Front. Energy Res.*, 2019.

[60] K. Urov and A. Sumberg, "Characteristic of oil shales and shale-like rocks of known deposits and outcrops," *Oil Shale*, vol. 16, no. 3, pp. 1–64, 1999.

[61] S. C. and F. Preto, "Biomass Burn Characteristics," 2019.

[62] V. Oja, A. Elenurm, I. Rohtla, E. Tali, E. Tearo, and A. Yanchilin, "Comparison of

oil shales from different deposits: Oil shale pyrolysis and co-pyrolysis with ash," *Oil Shale*, 2007.

[63] J. Akhtar and N. Saidina Amin, "A review on operating parameters for optimum liquid oil yield in biomass pyrolysis," *Renewable and Sustainable Energy Reviews*. 2012.

[64] Z. Wang, J. Cao, and J. Wang, "Pyrolytic characteristics of pine wood in a slowly heating and gas sweeping fixed-bed reactor," *J. Anal. Appl. Pyrolysis*, vol. 84, no. 2, pp. 179–184, 2009.

[65] A. Sarkar and R. Chowdhury, "Co-pyrolysis of paper waste and mustard press cake in a semi-batch pyrolyzer—optimization and bio-oil characterization," *Int. J. Green Energy*, vol. 13, no. 4, pp. 373–382, Mar. 2016.

[66] M. A. Nahil and P. T. Williams, "Activated carbons from acrylic textile waste," *J. Anal. Appl. Pyrolysis*, vol. 89, no. 1, pp. 51–59, 2010.

[67] J. A. Onwudili, N. Insura, and P. T. Williams, "Composition of products from the pyrolysis of polyethylene and polystyrene in a closed batch reactor: Effects of temperature and residence time," *J. Anal. Appl. Pyrolysis*, vol. 86, no. 2, pp. 293–303, 2009.

[68] I. Ahmad *et al.*, "Pyrolysis study of polypropylene and polyethylene into premium oil products," *Int. J. Green Energy*, vol. 12, no. 7, pp. 663–671, 2015.

[69] A. Adrados, I. de Marco, B. M. Caballero, A. López, M. F. Laresgoiti, and A. Torres, "Pyrolysis of plastic packaging waste: A comparison of plastic residuals from material recovery facilities with simulated plastic waste," *Waste Manag.*, vol. 32, no. 5, pp. 826–832, 2012.

[70] G. Lopez, M. Olazar, M. Amutio, R. Aguado, and J. Bilbao, "Influence of tire formulation on the products of continuous pyrolysis in a conical spouted bed reactor," *Energy and Fuels*, 2009.

[71] J. A. Onwudili, C. Muhammad, and P. T. Williams, "Influence of catalyst bed temperature and properties of zeolite catalysts on pyrolysis-catalysis of a simulated mixed plastics sample for the production of upgraded fuels and chemicals," *J. Energy Inst.*, 2019.

[72] C. Muhammad, J. A. Onwudili, and P. T. Williams, "Catalytic pyrolysis of waste plastic from electrical and electronic equipment," *J. Anal. Appl. Pyrolysis*, 2015.

[73] G. V. C. Peacocke, C. M. Dick, R. A. Hague, L. A. Cooke, and A. V Bridgwater, "COMPARISON OF ABLATIVE AND FLUID BED FAST PYROLYSIS PRODUCTS: YIELDS AND ANALYSES," P. Chartier, G. L. Ferrero, U. M. Henius, S. Hultberg, J. Sachau, and M. B. T.-B. for E. and the E. Wiinblad, Eds. Oxford: Pergamon, 1996, pp. 1632–1637.

[74] K. Wiemer, "Thermal Treatment of Municipal Solid Waste," *Foro Internatcional*

2015 Valorización Energética Residuos Urbanos, pp. 1–65, 2015.

[75] M. I. Jahirul, M. G. Rasul, A. A. Chowdhury, and N. Ashwath, “Biofuels production through biomass pyrolysis- A technological review,” *Energies*. 2012.

[76] Easac, “A study on the EU oil shale industry – viewed in the light of the Estonian experience,” *Energy*, no. May, pp. 1–65, 2007.

[77] “Convert gallon to ton.” [Online]. Available: https://www.convertunits.com/from/gallon+[U.S.]+of+diesel+oil/to/tonne+of+oil+equivalent. [Accessed: 06-May-2020].

[78] “Convert barrel to ton,” 2020. [Online]. Available: hhttps://www.unitconverters.net/volume/barrel-oil-to-ton-register.htm. [Accessed: 06-May-2020].

[79] K. Plamus, *The Impact of Oil Shale Calorific Value on CFB Boiler Thermal Efficiency and Environment*. 2012.

[80] G. S. Theses and C. B. Sorenson, “A COMPARATIVE FINANCIAL ANALYSIS OF FAST PYROLYSIS PLANTS IN SOUTHWEST OREGON.,” 2010.

[81] E. Commission, “Municipal Waste Used for Energy recovery in Vilnius,” 2018. [Online]. Available: https://ec.europa.eu/regional_policy/en/projects/lithuania/municipal-waste-used-for-energy-recovery-in-vilnius. [Accessed: 21-May-2020].

[82] V. Petrova, “Renewables Now,” 2020. [Online]. Available: https://renewablesnow.com/news/construction-starts-on-waste-to-energy-plant-in-lithuania-report-594208/. [Accessed: 21-May-2020].

[83] E. Energia, “Renewable Energy,” 2020. [Online]. Available: https://www.enefitgreen.ee/en/energia-tootmine. [Accessed: 02-May-2020].

[84] NordPool, “Nord Pool Market Data,” 2020. [Online]. Available: nordpoolgroup.com/Market-data1/#/nordic/table. [Accessed: 16-May-2020].

[85] R. Raudjärv and L. Kuskova, “Kas Energia on Odav Või Kallis?,” no. April, pp. 65–71, 2011.

[86] M. N. Islam and F. N. Ani, “Techno-economics of rice husk pyrolysis, conversion with catalytic treatment to produce liquid fuel,” *Bioresour. Technol.*, 2000.

[87] B. L. Polagye, K. T. Hodgson, and P. C. Malte, “An economic analysis of bio-energy options using thinnings from overstocked forests,” *Biomass and Bioenergy*, 2007.

[88] D. Sorenson, “Progressive Energy Technologies.”

[89] H. Doing, “Waste Tire Continuous Pyrolysis Plant Project Investment Proposal,” 2020.

[90] R. . K. J.A Knight, L.W. Elston, D.R Hurst, “Pyrolytic Oils; Characterization and Data Development for Continuous Processing,” *Oxford Univ.*, vol. XXX, p. 60,

1895.

[91] CNIM, “Jäätmeenergiaplokk WTE,” 2018.

[92] S. Estonia, “Tourism trends in Tallinn in 2019,” *Visit Estonia*, 2019. .

[93] M. Jansen, U. Thoden van Velzen, B. Ferreira, and T. Pretz, *Recovery of plastics from municipal solid waste in materials recovery facilities*. 2013.

[94] R. Leblanc, “Plastic Recycling Facts and Figures,” 2019. [Online]. Available: https://www.thebalancesmb.com/plastic-recycling-facts-and-figures-2877886. [Accessed: 17-May-2020].

[95] T. R. Brown, M. M. Wright, and R. C. Brown, “Estimating profitability of two biochar production scenarios: Slow pyrolysis vs fast pyrolysis,” *Biofuels, Bioprod. Biorefining*, 2011.

[96] “Konkurentsiametiga kookolastatud soojuse tootmise piirhinnad.” [Online]. Available: https://www.konkurentsiamet.ee/sites/default/files/kooskolastatud_tootmishinnad_08.05.2020.pdf . [Accessed: 21-May-2020].

[97] EChemi.com, “Carbon Black Price Analysis,” 2020. [Online]. Available: https://www.echemi.com/productsInformation/pd20150901230-carbon-black.html. [Accessed: 24-Apr-2020].

[98] “Andrei Vuhk and Dmitri Sirokov,” Enerfit Green, Tallinn, Estonia, 2020.

[99] M. A. Palma, J. W. Richardson, B. E. Roberson, L. A. Ribera, J. Outlaw, and C. Munster, “Economic feasibility of a mobile fast pyrolysis system for sustainable bio-crude oil production,” *Int. Food Agribus. Manag. Rev.*, 2011.

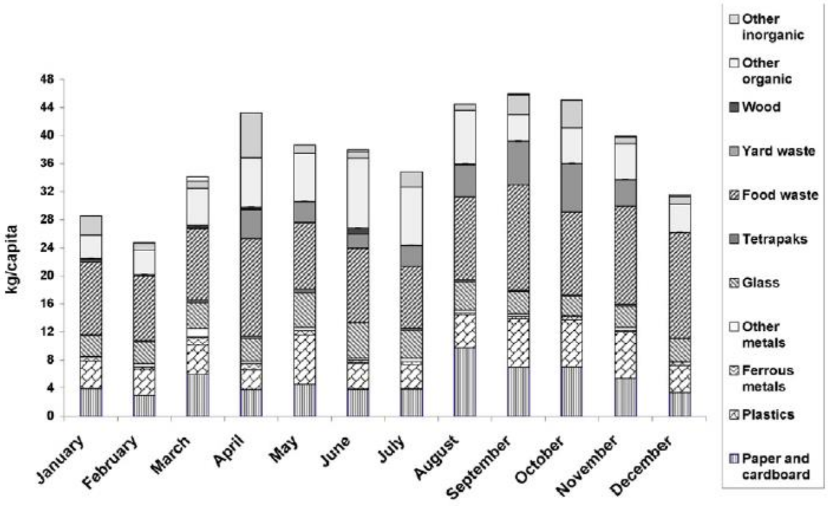
[100] D. Garcés, E. Díaz, H. Sastre, S. Ordóñez, and J. M. González-LaFuente, “Evaluation of the potential of different high calorific waste fractions for the preparation of solid recovered fuels,” *Waste Manag.*, 2016.

[101] L. J. R. Nunes, R. Godina, J. C. O. Matias, and J. P. S. Catalão, “Economic and environmental benefits of using textile waste for the production of thermal energy,” *J. Clean. Prod.*, 2018.

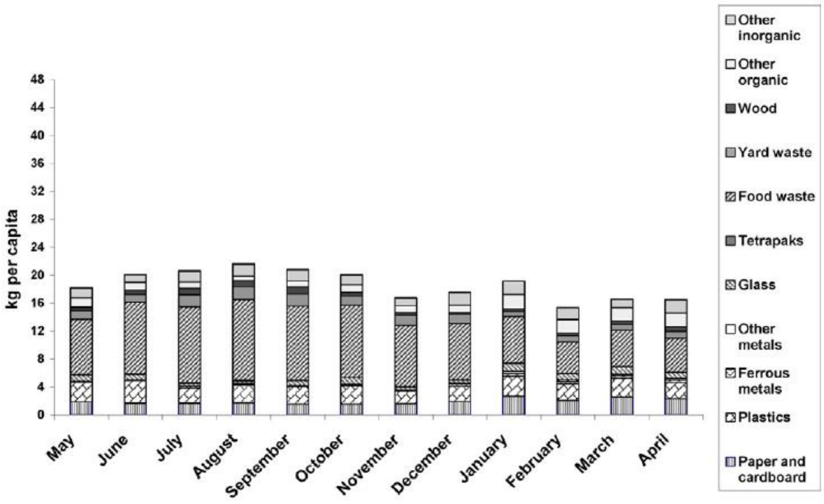
[102] J. Malat’ák, J. Velebil, and J. Bradna, “Specialty types of waste paper as an energetic commodity,” *Agron. Res.*, 2018.

[103] A. Merkisz-Guranowska, “Waste recovery of end-of-life vehicles,” *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 421, p. 32019, Oct. 2018.

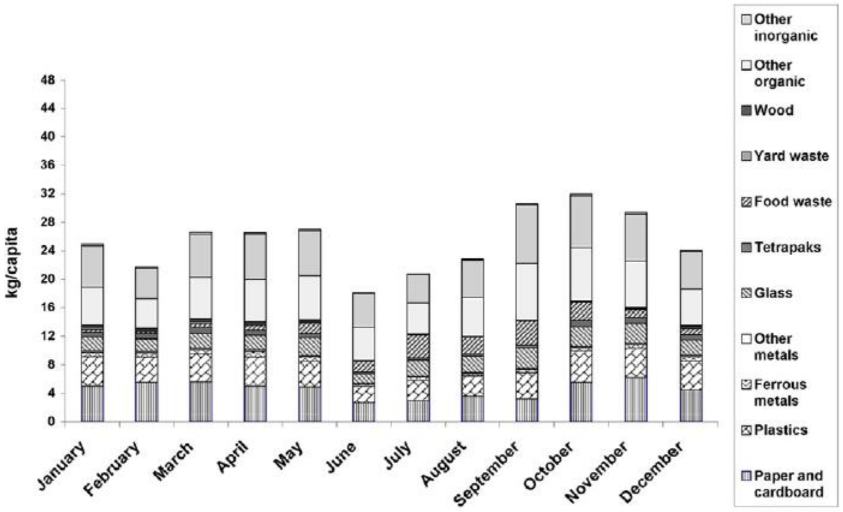
APPENDICES



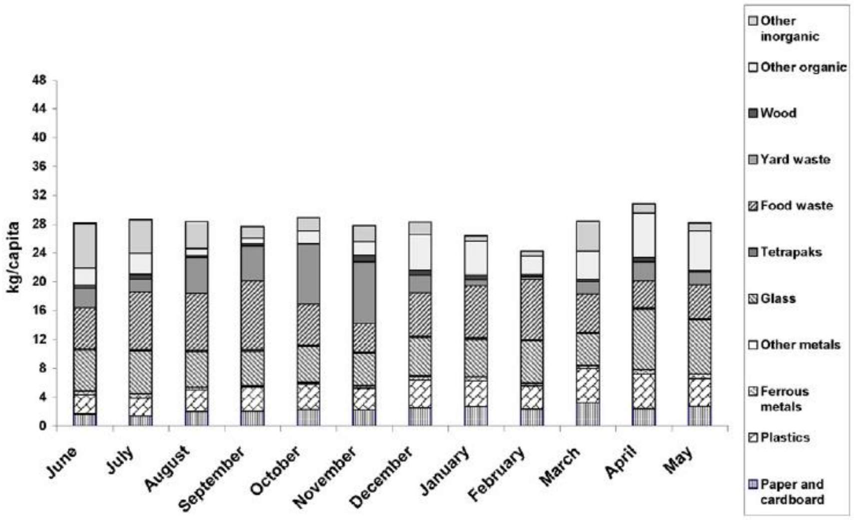
A.1 Seasonal Variation of MSW in Kaunas



A.2 Seasonal variation of MSW in Kutaisi



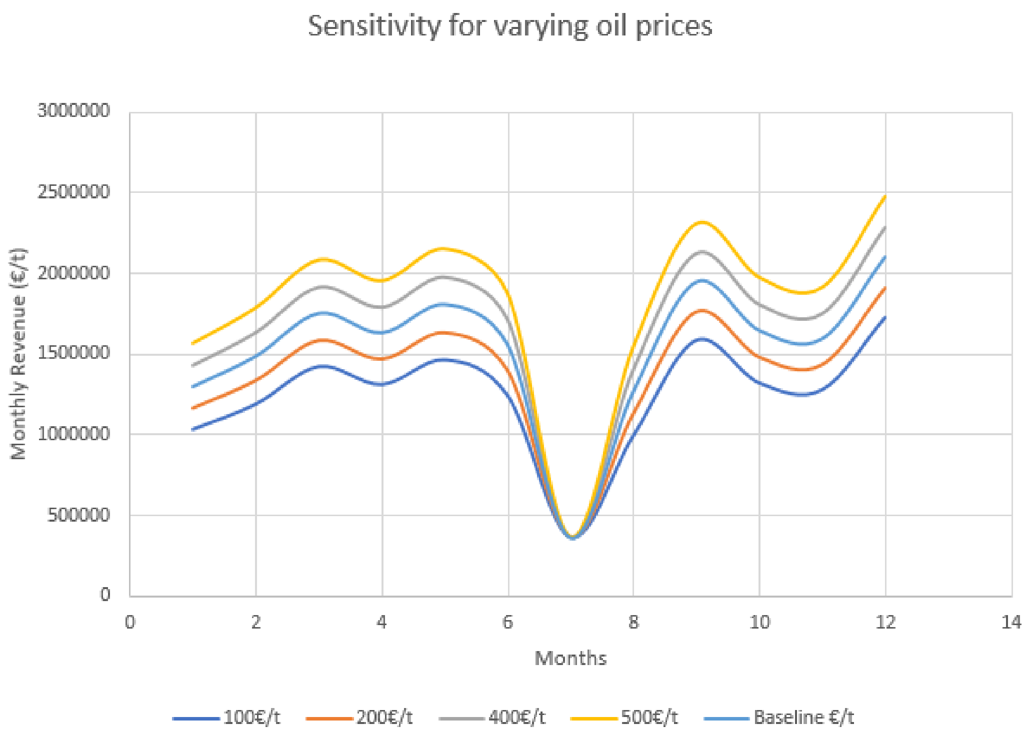
A.3 Seasonal variation of MSW in St Petersburg



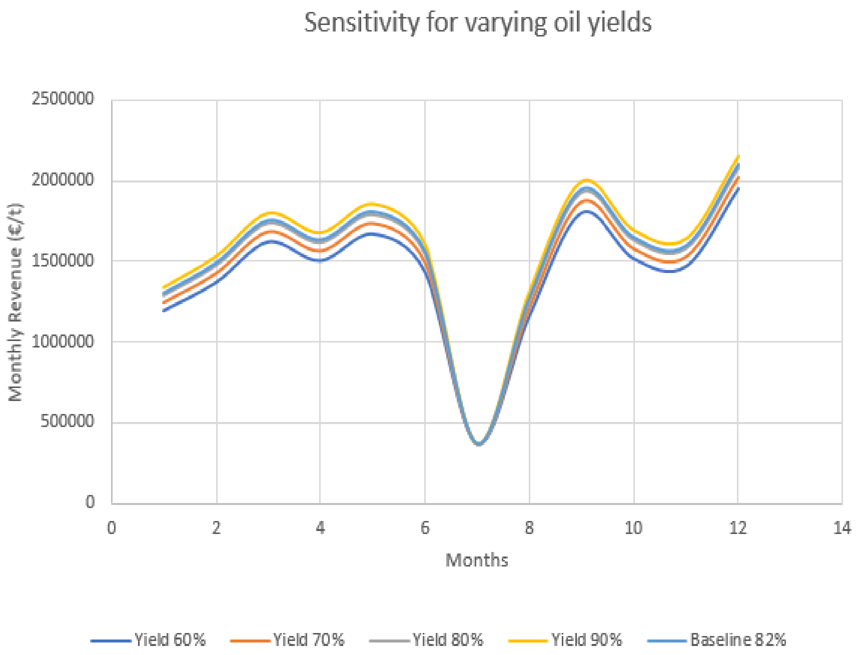
A.4 Seasonal variation of MSW in Boryspil

A1-4 One year cycle of waste generated for Kaunas, Kutaisi, St Petersburg and Boryspil [19]

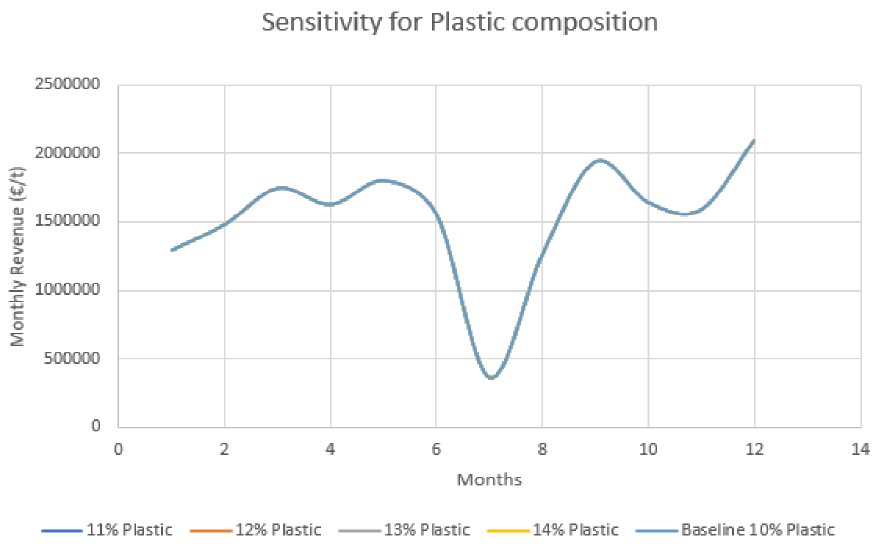
Monthly Sensitivity Analysis



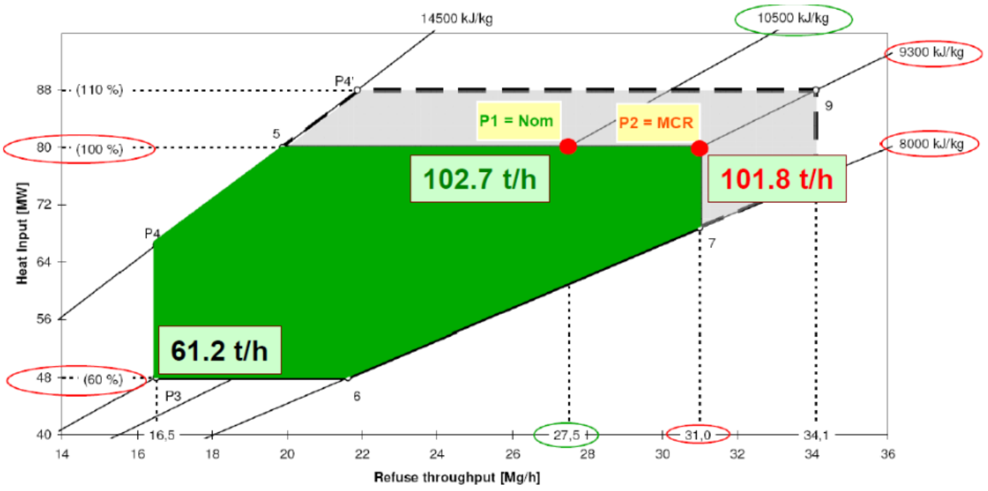
A.6 Cash flows and profitability analysis of a 78 tpd pyrolysis plant



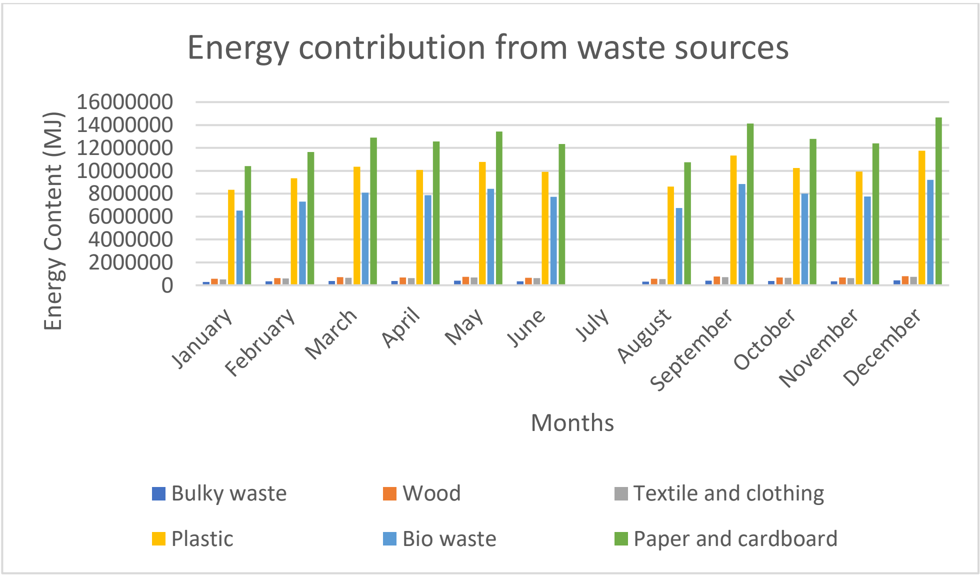
A.7 Monthly pyrolysis revenue variation with oil yield



A.8 Monthly pyrolysis revenue at different constant plastic composition



A.9 Steam diagram for the Iru waste to energy plant



A.10 Energy available from waste components monthly; [100] [101] [102] [103]