Master Thesis

Master in Energy Engineering

Techno-economic analysis for the construction of a waste-to-energy power plant

REPORT

Author: Angelantonio Pugliese
Director: Cesar Valderrama

Date: 26/10/2020

ETSEIB

Escola Tècnica Superior
d'Enginyeria Industrial de Barcelona

UPC

Abstract

Plastic is one of the most used materials in every-day life. Its implementation globally during the last century raised the standard of living of the population, thanks to its lightness, resistance, and wide range of applications.

Plastic becomes waste very quickly, and its increase all over the years is a dramatic issue for the natural environment. Mismanaged plastic waste (PW) often ends in the natural eco-system, and due to its chemical composition, thousands of years are necessary to let the PW decompose.

The European Academies Science Advisory Council has drawn up the so-called PW hierarchy, where the PW management (PWM) options are listed in order of preference: reduce, reuse, mechanically recycling, chemical degradation without or with energy recovery, incineration, landfill. However, most of the time, that hierarchy cannot be followed due to the complex composition of plastic materials and economic obstacles. The manufacturing of new plastic from scratch is cheaper than from recycling.

From this perspective, it often happens that thermal degradation of PW with energy recovery is the last option to avoid the PW to be landfilled. Mismanaged or landfilled PW dramatically impacts the environment, with consequences on terrestrial and marine life and land use. Three leading technologies exist for energy recovery from PW: gasification, pyrolysis, and incineration. This project thesis investigates the techno-economic feasibility for an existing thermal power plant to be converted into a waste to energy (WtE) plant. In particular, the project involves the possibility to incinerate PW that is daily produced in the nearby factories, mainly for the automotive sector.

After having analysed the heat demand of the local community, a Combined Heat and Power (CHP) has been selected as a possible solution for the WtE plant. The plant's size is designed to burn 30 000 tons of PW per year. Particular emphasis has been dedicated to the economic assessment of the project in order to verify the feasibility. Net present value (NPV) and internal rate of return (IRR) are the main parameters considered for the financial aspect. The outcomes on predicting the expected revenue calculated for different scenarios showed that the project can be economically profitable, and it can proceed to further stages.

Moreover, a sensitivity analysis has been performed in order to identify the parameters that will most influence the NPV of the project.

Another essential aspect that has been thoroughly treated is the environmental impact. A review of the current EU legislation has been carried out, and a Flue Gas Cleaning (FGC) equipment has been proposed. The systems proposed are reflected in the EU Implementing Decision on the Best Available Techniques (BAT) for waste incineration (WI), and therefore they are expected to guarantee the minimum environmental impact.

Finally, some further proposals are presented in order to enhance the quality of this project and increase social acceptance.

Index

ABSTRACT **3**
INDEX **4**
1. GLOSSARY **6**
1.1. List of abbreviations 6
1.2. List of Tables 8
1.3. List of Figures 8
2. PREFACE **10**
2.1. Origin of the project 10
2.1.1. Plastic waste and its management 10
2.1.2. PW recycling – state of the art and challenges 13
2.1.3. Use of plastics in the automotive industrial sector 15
2.2. Motivation 17
2.2.1. Plastic waste and circular economy 17
2.3. From plastic waste to energy 18
2.3.1. Gasification 20
2.3.2. Pyrolysis 21
2.3.3. Incineration 22
2.3.4. Remarks 23
3. CASE STUDY DESCRIPTION **25**
3.1. Scope of the project 26
3.1.1. Incineration 26
3.1.2. Heat demand 26
4. METHODOLOGY **30**
4.1. LHV of the fuel 30
4.2. Feedstock 30
4.3. Environmental impact 32
4.3.1. Current EU legislation 32
4.3.2. Air emissions limit values 33
5. ECONOMIC ANALYSIS **35**
5.1. Methodology for economic evaluation 35
5.1.1. Capital Expenditures 36

5.1.2. Operating Expenditures 40
5.2. Net present value and internal rate of return 44

6. RESULTS ________ 45
6.1. Waste Pre-treatment: collection, sorting, and process 45
6.2. Combustion process 45
6.3. Energy recovery 47
6.4. Power generation 47
6.4.1. Heat generation 48
6.4.2. Electricity generation 48
6.5. Economics 48
6.6. Cash inflows 50
6.6.1. Introduction 50
6.6.2. Gate fee 50
6.6.3. Energy 51
6.7. CapEx and OpEx 51
6.8. Expected revenue 53
6.9. NPV and IRR 54
6.10. Sensitivity analysis 56
6.10.1. Discussion 59
6.11. Cleaning system 60
6.11.1. Techniques for abatement of pollutants and flue gas cleaning 60
6.11.2. Final Remarks 63

7. CONCLUSIONS ________ 65
7.1. Further proposals 65

8. ACKNOWLEDGEMENTS ________ 68

9. REFERENCES ________ 69

APPENDIX I – EXCEL SHEETS EXAMPLE ________ 76

1. Glossary

1.1. List of abbreviations

PW	Plastic Waste
PWM	Plastic Waste Management
PE	Polyethylene
PET	Polyethylene Terephthalate
PS	Polystyrene
PP	Polypropylene
PVC	Polyvinylchloride
HDPE	High-Density Polyethylene
LDPE	Low-Density Polyethylene
PA	Polyamide
PUR	Polyurethane
ABS	Acrylonitrile butadiene styrene
POM	Polyoxymethylene
PMMA	Poly(methyl-methacrylate)
PC	Polycarbonate
EU	European union
US	United States of America
SPI	US Society of Plastic Industry
SDGs	Sustainable Development Goals
GHG	Greenhouse Gases
NG	Natural Gas
WtE	Waste-to-Energy
GWP	Global Warming Potential
MSW	Municipal Solid Waste

BFB	Bubbling Fluidized Bed
CFB	Circulating Fluidized Bed
RDF	Refused Derived Fuel
FGC	Flue Gas Cleaning
APC	Air Pollution Control
O&M	Operational and Maintenance
LCA	Life Cycle Assessment
DH	District Heating
BAT	Best Available Techniques
WI	Waste Incineration
LHV	Lower Heating Value
HHV	Higher Heating Value
TOC	Total Organic Compound
CO	Carbon Monoxide
CHP	Combined Heat and Power
GBP	Pound Sterlings
EUR	Euro
USD	US Dollars
CAD	Canadian Dollars
CZK	Czech Korunas
INV_0	Initial Investment
HP	High-Pressure
LCOE	Levelized Cost of Electricity
MWh_{el}	Megawatt-Hour Electric
MWh_{th}	Megawatt-Hour Thermal
GJ_{th}	GigaJoule Thermal
NPV	Net Present Value
IRR	Internal Rate of Return
ESP	Elettrostatic Precipitator

SCR	Selective Catalytic Reactor
SCNR	Selective Non-Catalytic Reactor

1.2. List of Tables

Table 1 - Fractions of treatment for plastic collected waste in Europe State Members [2].... 14
Table 2 - Index of recyclability per polymer [3], [6], [18]... 14
Table 3 - 2019 heat generation of the heating plant [Local DH]... 27
Table 4 – Theoretical heat generation at full capacity 27
Table 5 - Estimation of CF per month.. 28
Table 6 - Estimation of LHV of PW from the automotive sector... 31
Table 7 - C – Daily average emission limit values for the polluting substances (mg/Nm3) [49] 33
Table 8 - C – Half-hourly average emission limit values for the polluting substances (mg/Nm3) [49] 33
Table 9 – C - Average emission limit values (mg/nm3) for the following heavy metals over a sampling period of a minimum of 30 minutes and a maximum of 8 hours [49] 33
Table 10 – Values extracted from [36].. 37
Table 11 - Summary of the equations elaborated in section 5.1.. 49
Table 12 - Values of gate fees found.. 50
Table 13 - Typical cost build-up of WtE plants [36] and expectations.................................. 52
Table 14 - Typical operational costs of WtE plants [36]... 52
Table 15 - Expected annual revenue from the plant's operations.. 53
Table 16 - Variation of total annual revenue with respect to the gate fee 54
Table 17 - Economic evaluation of Scenario 1 with respect to the gate fee.......................... 55
Table 18 - Economic evaluation of Scenario 2 with respect to the gate fee.......................... 55
Table 19 - Economic evaluation of Scenario 3 with respect to the gate fee.......................... 55
Table 20 - Economic evaluation of Scenario 4 with respect to the gate fee.......................... 55
Table 21 - Economic evaluation of Scenario 5 with respect to the gate fee.......................... 56
Table 22 - Recalculation of the gate fee for the sensitivity analysis..................................... 57

1.3. List of Figures

Figure 1 - Plastics codes [6] 11
Figure 2 - Whale Shark eating a plastic bag in Asia [9] 11
Figure 3 - Waste Hierarchy [12]... 12

Figure 4 - Cumulative production, use, and fate of all plastic ever made, from 1950 to 2017, in Mtons [19] 15
Figure 5 - Circular Economy Flow [2] 18
Figure 6 - Plastic value chain and complexity [10] 19
Figure 7 - PWM hierarchy [10], [19], [31] 20
Figure 8 - Suitability of plastics for liquid hydrocarbon production [29] 22
Figure 9 - Estimation of CF monthly 28
Figure 10 - 2019 heat generation and trend line 29
Figure 11 - WtE capital costs vs. plant capacity [36] 37
Figure 12 - WtE capital costs (mln €) vs. plant capacity (ktons/y) (adapted from [36]) 38
Figure 13 - Comparison of capital costs (CAN$) for WtE facilities per installed capacity (Source: WSP) (*converted by Canadian Dollars using a conversion factor equal to 1 CAD = 0.65 € ([Google Currency Converter Tool]) 39
Figure 14 - WtE capital costs (mln €) vs. plant capacity (ktons/y) (adapted from [36]) 40
Figure 15 - WtE operating cost [36] 41
Figure 16 - WtE operational costs (mln €) vs. plant capacity (ktons/y) (adapted from [36]) .. 42
Figure 17 – Comparison of operational costs (CAD) for WtE facilities per installed capacity [36] 43
Figure 18 - Comparison of operational costs for WtE facilities per installed capacity (adapted from [36]) 43
Figure 19 - Main Stages of a typical WtE power plant [57] 45
Figure 20 - Classification of furnace types according to the flow gases and feedstock waste [48] 46
Figure 21 - Example of moving grate co-flow combustion chamber [30] 47
Figure 22 - WtE investment cost vs. cost per unit of capacity 49
Figure 23 - Obtained values of CapEx and OpEx 53
Figure 24 - Sensitivity analysis for scenario 1 58
Figure 25 - Sensitivity analysis for scenario 4 58
Figure 26 - Sensitivity analysis for scenario 5 59
Figure 27 - Typical bag fabric filter [36] 61
Figure 28 - Typical dry scrubber [36] 62
Figure 29 - Selective catalytic reactor working principle [30] 63
Figure 30 – Average daily measured emission of last week of Sep 2020 of WtE plant of Acerra [75] 64
Figure 31 - The Maishima incineration plant in Osaka [36] 66

2. Preface

2.1. Origin of the project

2.1.1. Plastic waste and its management

Since its global implementation in everyday life tools, plastic has become even more indispensable for our living standards due to its outstanding mechanical properties, cheap manufacture, flexibility and versatility of applications, lightness, and ease of transport. That might explain why, overall, more than 8.3 billion tons of plastic have been produced since the 1950s [1], and its production has sharply risen, from 0.35 million tonnes (Mtons) in 1950 to 330 Mtons in 2016 and 348 Mtons in 2017 [2]. With this rate, global plastic manufacturing is expected to double in 20 years [3].

In 1953, Hermann Staudinger was rewarded with the Nobel Prize in Chemistry *"for his discoveries in the field of macromolecular chemistry"*; he had discovered that some small molecules could join each other to compose big chains and increase their size. The bigger molecules deriving from the process are called polymers [4]. Staudinger's work put the basis for the manufacturing on large-scale synthetic materials; today, we call them plastics.

Plastic materials are divided, on a first level, between thermoplastics and thermosets. Thermoplastic materials are the ones of common use in everyday life, they present a flexible structure, and they are used for packaging, food, beverages, bags, and many more. Thermoplastic polymers are, for example, polyethylene (PE), polypropylene (PP), polyvinylchloride (PVC), and polyethylene terephthalate (PET). On the other hand, thermosets materials are used when high thermal and mechanical resistance is required, and therefore we can find them mainly in industrial manufacturing applications such as electrical components, the automotive sector, and building materials. Epoxy, phenolic resins, Polyurethane (PUR), and acrylonitrile butadiene styrene (ABS) are spread and known thermosets materials [5]. The US Society of Plastic Industry (SPI) introduced the so-called resin identification code (Figure 1). Its objective was to quickly identify plastics polymers to facilitate and recognize the most adapt end-of-life treatment (SPI, 1988).

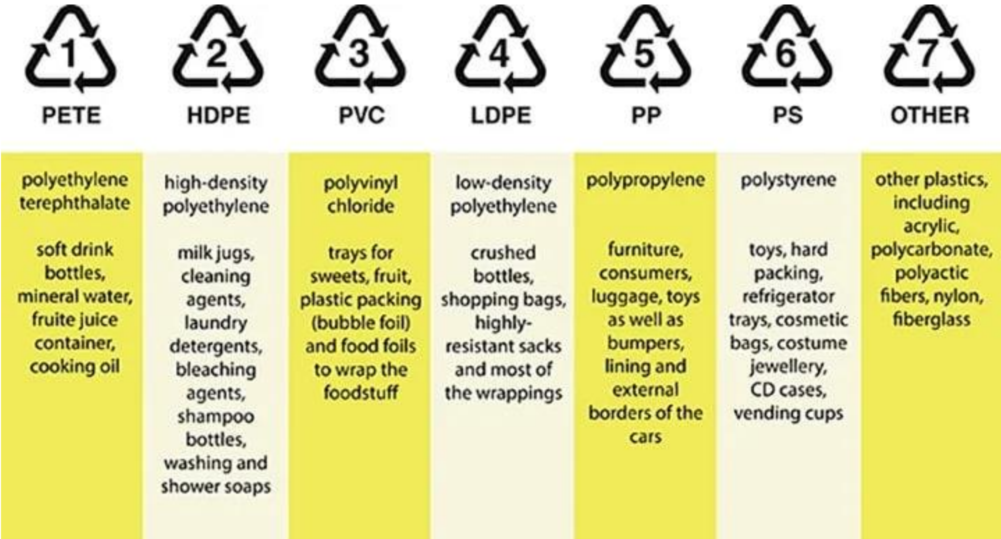

Figure 1 - Plastics codes [6]

Lately, plastic waste (PW) is becoming a crucial issue to deal with, which brought plastic from being a marvelous discovery to a global threat. Mismanaged plastics end to be released into the natural environment, with terrible land and marine life consequences (Figure 2). Most recent articles and scientific reports are alarming, as everybody now knows the garbage patches in the ocean. In the Pacific Ocean, considering the extensions of the prominent garbage patches, their full extension reaches a surface that is double the size of the United States [7]. An American explorer stated that he spotted a plastic bag at the bottom of the Atlantic Ocean, more than 11 km in depth [8].

Figure 2 - Whale Shark eating a plastic bag in Asia [9]

Globally, approximately 80 Mtons of mismanaged PW has been estimated to be produced in

2015, and this number is predicted to multiply by three times, up to about 250 Mtons in 2060, if the current management processes will remain as they currently are [3]. One primary problem is that not always plastic materials are made by a single one of the polymer types shown in Figure 1; indeed, most of the time, it is a combination of those, and it may also contain non-polymeric materials, e.g., in the case of packaging for beverages [10].

Plastic waste management (PWM) existing technologies, techniques, and processes are classified according to the type of treatment and the product's final use. Their order of preference (Figure 3) follows the so-called Plastic Waste Hierarchy designed by the European Academies Science Advisory Council [10]:

1. **Mechanical Recycling**
    a. **Upcycling**: the waste is reprocessed and converted into a material, of which the final application value is worthier than the previous one.
    b. **Recycling:** namely, reconverting a final use product in the same product (e.g., PET bottle to PET bottle). It is also defined as **closed-loop recycling.**
    c. **Downcycling:** recycling the waste to be reused in another product, different from the initial one. The quality of the new product will be lower than the one from which it was recycled. It is also defined as **open-loop recycling**.
2. **Chemical Recycling** - The original polymers are thermochemically cracked, and the final products are monomers that can be used to manufacture new polymers [11]. The main processes that belong to this category are chemical depolymerization, thermal cracking (pyrolysis), catalytic conversion, gasification.
3. **Energy Recovery**: using collected PW to extract its energetic value (incineration) or converting into liquid or gaseous fuel for energetic applications (gasification and pyrolysis).
4. Final disposal, **Landfilling** the waste.

Figure 3 - Waste Hierarchy [12]

It can be noticed that both gasification and pyrolysis (GP) appear in chemical recycling as in the energy recovery process. The reason is that the technologies exist for reprocessing PW, but the category they should be classified depends on the final product. If the thermal degradation product is a new monomer or polymer for manufacturing new plastic, GP falls within chemical recycling. On the other hand, when GP is used to produce a liquid or gaseous fuel, that is Energy Recovery, as the final product finds energetic applications. Energy Recovery technologies will be described in the following sections, as they represent the core of this thesis's scope.

2.1.2. PW recycling – state of the art and challenges

PW needs to be reprocessed before any recycling treatment takes place. It means that intermediate processes occur from the end of life PW and the final product of the mechanical recycling, including several steps to give rise to the conversion from waste plastics materials into new recycled materials; these are complex and may differ from firms to firms, but they can be summarized as follows [13]:

collection, sorting, baling, crushing, reprocessing, conversion, manufacturing.

Besides the issues related to its management, indeed PW is a valuable source of opportunity. The last technological discoveries are trying to convert the PW into a more valuable source. This is the case, for example, of a study conducted by Riverside University of California, where PET bottles have been used as a primary source to be transformed into a porous carbon nanostructure. This nanomaterial can find applications in both batteries for energy storage or supercapacitor, making their production more sustainable than using limited lithium sources. However, even though such research is still being developed, reality speaking is very few cases when PW can be transformed by increasing its value of application [14].

Purchasing collected PW can be profitable as long as its cost is lower than landfilling and reprocessing or if the final product has an attractive market that makes the recycling process economically viable. However, like any other feedstock, also PW price varies according to the quality and its suitability for a given process. The quality of performances of the process and the original plastic and final recycled product strongly depend on several factors [11], such as quality, colour, purity, polymer type, etc. For instance, the recycling of PET bottles is one of the most straightforward, but this does not mean that it is the cheapest too [10].

Therefore, it is complicated to assess an indicative price for this type of treatment, and it is worthy to remind that PW price for mechanical recycling is highly variable and unpredictable. Both purchasing and reprocessing are affected by some different factors about the quality, impurities, transparency/opacity, and many more.

At a European level, namely, EU27+UK/NO/CH, the decade from 2006 to 2016 registered a dramatic and promising increase both in PW collection and its treatment fractions. Total PW collected in 2016 was 27.1 Mtons compared to 24.5 Mtons in 2006, resulting in a percentage increase of 11% [2]. Inside this value, variations of different treatment processes are showed in Table 1.

Table 1 - Fractions of treatment for plastic collected waste in Europe State Members [2]

	PW collected (Mtons)		
Process	**2006**	**2016**	**Variation**
Recycling	4.7	8.4	+ 79%
Energy Recovery	7.0	11.3	+ 61%
Landfill	12.9	7.4	- 43%
TOTAL	24.6[1]	27.1	+ 11%

However, researchers agree that less than 10% of all the plastic ever produced has been adequately recycled [15]. It is mainly due to the complexity in the composition that post-consumer plastics are difficult to process, making mechanical and chemical recycling not always possible or cost-effective. In general, PWM – when a fine collection occurs – begins with centralized sorting occurring in waste disposal stations. After that, streams of HDPE, PP, or PET are sent for mechanical recycling; in contrast, the remaining fraction, consisting of between 40-60% of the sorted PW, will be either used for energy recovery processes or landfilled. [16]. Table 2 summarizes the feasibility of each polymer to be mechanically recycled and reused for its original purpose. Once again, it should be noticed that Table 1 refers to the pure polymers, and if these are combined with other substances, their recycling rate will decrease, together with its economic competitiveness due to previous separation processes required. In the rest of the World, numbers are more alarming. China's recycling rate is around 25% of PW generated in 2014, while in the US, only 9% of the total PW generated in the same year has been recycled. Even in 2014, incineration fractions on PW produced were recorded, approximately 39% in the EU, 30% in China, and 16% in the US [17].

Table 2 - Index of recyclability per polymer [3], [6], [18]

#	**Acronymous**	**Usage Rate**	**Recyclability**	**Recycling Rate**
1	PET	Single-Use	Very High	25%
2	HDPE	Single-Use	Very High	30-35%
3	PVC	Single-Use	Very Low	<1%
4	LDPE	Reusable	Medium	?
5	PP	Reusable	Mid-Low	3%

[1] 0.1% of difference between quantity reported in text and in table is probably due to approximations made by author of the literature source.

6	PS	Reusable	Medium	?
7	(others) PLA	Reusable	NOT recyclable but compostable	?

Consequently, despite the promising signs of progress recorded in Table 2, **additional waste treatment facilities must be implemented**, and different technologies need to be developed. In conclusion, Figure 4 (taken from Geyer, 2019 [19]) represents briefly and adequately how appropriate PWM is quite far to reach acceptable share values.

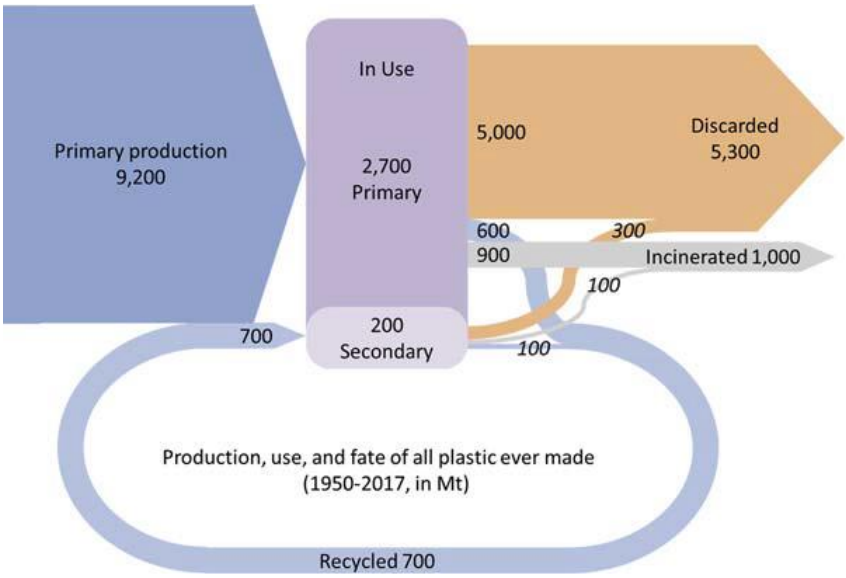

Figure 4 - Cumulative production, use, and fate of all plastic ever made, from 1950 to 2017, in Mtons [19]

2.1.3. Use of plastics in the automotive industrial sector

Lightweight plastics use in the automotive sector has been drastically increasing in the last decades. From a technological perspective, and due to several technical factors, these materials are more suitable than others in the final composition of a car [20]. For example, they allow a reduction in the weight of a vehicle, and it is demonstrated that a reduction in weight of 10% results in an improvement of fuel efficiency from 5% to 7% [21], with consequent benefits in fuel efficiency, fuel usage, and engine emissions. Currently, about 39 different types of plastics are used to create an automobile [22]. Among these, 13 guarantee high performances of the vehicle [23]. To give a sense of the amount of waste generated, in 2017, it is worth mentioning that 6.6 million end-of-life vehicles have been treated in shredder car facilities, and, in these, over 1 million tons of PW has been generated [24]
Among this relevant number of different plastic materials made by polymers and their combinations, the most common represent approximately 66% of plastics used in cars. A rough classification of them is reported, deriving from a literature review [24] [25]:
Most used:

- **Polypropylene (PP)** - around 32% of the plastic. Mainly used for bumpers, cable insulation, drink trays, and carpet fibers.

- **Polyurethane (PUR)** foam **-** around 17% of the plastic. Mainly used for foam seating, insulation panels, suspension bushings, cushions, and electrical compounds. It is also an effective noise reducer.
- **Polyvinyl Chloride (PVC) –** around 16% of the plastic. Mainly used for instrument panels, electrical cables, pipes, and doors.
- **Polyamides** (**PA**) – accounts for around 12% of thermoplastic parts and components in the automotive industry. Mainly used for engine hood application and always reinforced with fiberglass.

Others:

- **Acrylonitrile-butadiene-styrene copolymer (ABS)** – Car interiors, dashboards, covers, and linings.
- **Polyethylene (PE) –** It is not the most used in quantity, but it has got the broadest range of applications.
- **Polycarbonate (PC) –** the lowest share, used for headlamp lenses and security screens.

Besides these most used polymers, there is a variety of many more, used and combined for other automotive parts. However, their implementation is significantly lower than the previous ones mentioned. Among them: PET, polystyrene (PS), polyoxymethylene (POM), and Poly(methyl-methacrylate) (PMMA) [26].

Plastics materials currently account for 10%-15% of the mass percentage, on average, of a car. Anyway, these trends are expected to significantly increase, up to 35% by 2035 [24].

The good news is that a relevant fraction of these components is made of recycled plastic from industrial or household waste. Due to their degradation, these plastics are no longer suitable for their original applications, and they are increasingly being recycled into durable plastics to make new car parts [24]. For example, FIAT uses recycled PUR foam plastic in the seat cushions and wheel liners made with 64% recycled plastics [24]. Indeed, Volvo aims to integrate 25% of recycled plastic in cars by 2025 [27].

However, for what concerns the end-of-life of vehicles, the wide variety of plastics used in the automotive sector are almost in every case reinforced or completed with other materials, such as carbon fibers, glass, reinforced glass beads, and other rigid plastics. Recyclability of such composites is very challenging, if not impossible, and therefore it is necessary to find another way to manage its waste produced. Most of the plastics (and composites) processed in this sector are intended for junkyard facilities, and the resulting residues waste is landfilled [21]. Especially for thermosets materials, their permanent cross-link structure makes them impossible to be melted down and recycled [20]. That is why, in many European countries, new policies are being adopted to reduce the amount of material to be landfilled [26], and incineration is one of the possible strategies to exploit the maximum energetic value of waste that otherwise would be landfilled.

Moreover, the application of such complex materials would worsen the problem of shredder waste because there is no market for recycling [26]. Often, preliminary separation of polymers is necessary for allowing adequate recycling, but this operation is out of shredder waste companies' competence.

2.2. Motivation

2.2.1. Plastic waste and circular economy

In this perspective, switching from a linear economy to a circular economy is the most challenging target to comply with Sustainable Development Goals (SDGs) [17]. This kind of approach would maximize the use of plastics materials even after consumers' utilization, leading to a significant decrease in pollution and many benefits from an environmental point of view, resulting in a reduction of mismanaged litter and greenhouse gases (GHG) emissions (Figure 5). When reusing option is not possible, it should be convenient for the PW to be sent to the specialized recycling facilities to be reprocessed and converted into a new plastic product (mechanical/chemical recycling). This will reduce the hydrocarbons demand, with the consequent savings in CO_2 emissions and preventing the generation of additional waste. Unfortunately, recycling has some limitations due to the complex composition of the materials, often combined with more polymers or contaminated by other additional materials. Sorting and previous separation of such waste might not be profitable from both economic and energetic points of view. In those cases, mechanical recycling can be more expensive and more energy-intensive than manufacturing new plastics from scratch [13]. When that occurs, the next preferred method might be chemical recycling with energy recovery, consisting in reprocessing of PW to extract liquid or gaseous fuels trough gasification or pyrolysis; the fuel obtained have similar characteristic to Natural Gas (NG) or petrochemical fuel. However, since not all the plastics are suitable for such applications, the incineration with energy recovery is the last option, as landfilling should be avoided entirely.

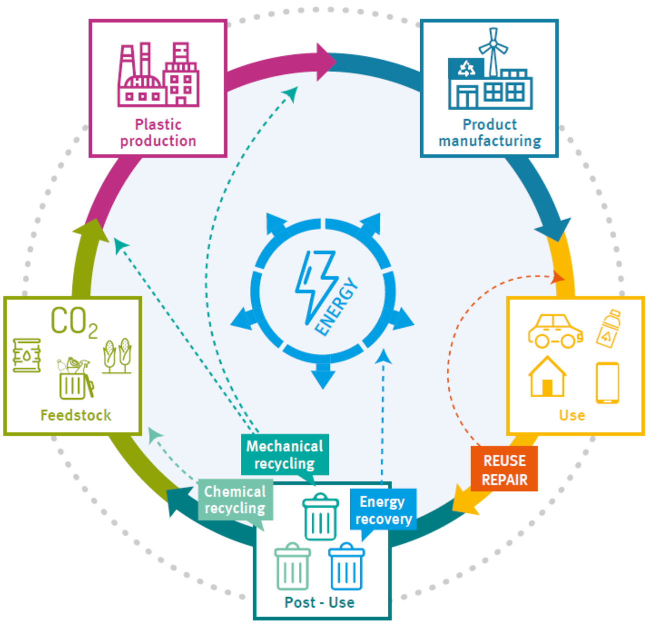

Figure 5 - Circular Economy Flow [2]

2.3. From plastic waste to energy

In the previous section, the PW issue and problems related to its management have been summarized, and the insights suggest that it is clear that the problem is far from a definitive solution.

Media are currently trying to raise awareness to reduce and reuse plastics, especially for single-use tools, such as bags, trays, plates, and glasses. New technologies are being continuously developed, like manufacturing organic-based plastic, which can be collected in organic waste and composted. The governments are also implementing policies to minimize landfilling and its consequent release of GHG, predominantly methane, in the atmosphere. Therefore, when the PW produced cannot be recycled, thermal degradation with energy recovery becomes the last process to avoid the waste to be landfilled. However, the complexity of the recycling processes has made the recycling rates pretty low, so far. Figure 6 Illustrates the destiny of plastics materials after having been used, highlighting the treatments required to make the after-use value chain sustainable, exploiting all the possible value from PW.

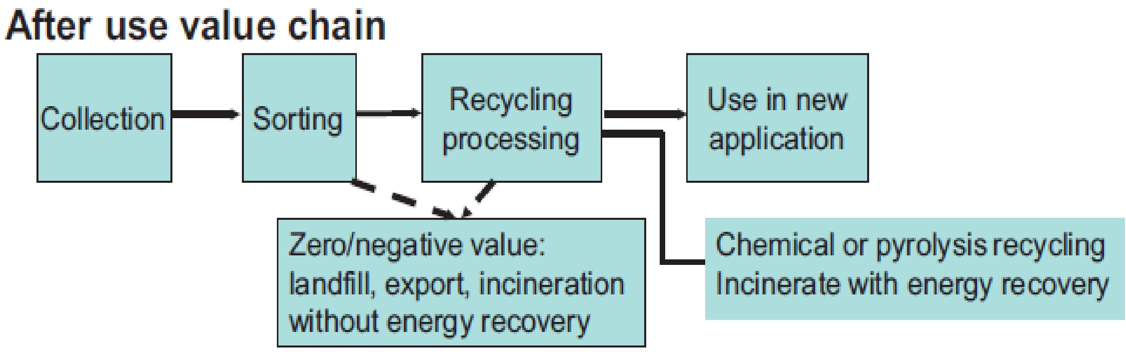

Figure 6 - Plastic value chain and complexity [10]

In this perspective, Energy Recovery from PW is often a preferred solution. Materials coming from a collection or post-industrial waste do not need complicated preliminary treatments; indeed, for incineration, the PW is used as a fuel as it comes from the end of use [28]. Advanced Waste-to-Energy (WtE) plants fall within the recovery class as they exploit the energy content of non-reusable, non-recyclable waste, thereby reducing the demand for landfill, which is the least preferred option due to tremendous environmental impacts (methane emissions, potential groundwater pollution among all).

When referring to WtE from Municipal Solid Waste (MSW), but the same goes for PW, there are three leading technologies: gasification, pyrolysis, and incineration. This section contains a brief overview of all of them and a comparison based on literature review and online research. Unfortunately, all three technologies' costs and performances vary enormously according to many factors such as PW types, taxes, policies, equipment types, and externalities [29]. More specific data, especially regarding financial aspects and emissions rates, must be investigated by analysing existing projects, but these data are not public; a special request to the owner Companies should be formalized.

Gasification, pyrolysis, and incineration are similar since the primary concept is the thermal degradation of PW by burning, and the product yielded is used for energetic applications. From a purely environmental perspective, incineration is considered the less preferable process for end-of-life PW [28]. In contrast, both GP are collocated just one level above (Figure 7) in the waste hierarchy, as they are considered among chemical recycling techniques with energy recovery [10]. On the other hand, incineration is the most well-known and mature technology; although as of now all of these three processes are considered at a high stage of maturity, incineration is the most spread and applied worldwide [30], as researches and development (especially for the cleaning of the exhaust gases) have been increasing its appeal during the years. Its implementation started at the beginning of the last century, and its economic viability is the most stable. Moreover, Incinerators are intensely monitored, and legislation is strict but precise, unlike other technologies of which the low grade of implementation leads to misunderstanding in regulations. Indeed, from a purely technical perspective, all three technologies are well known and mature, but their deployment on an industrial scale varies for each one of them.

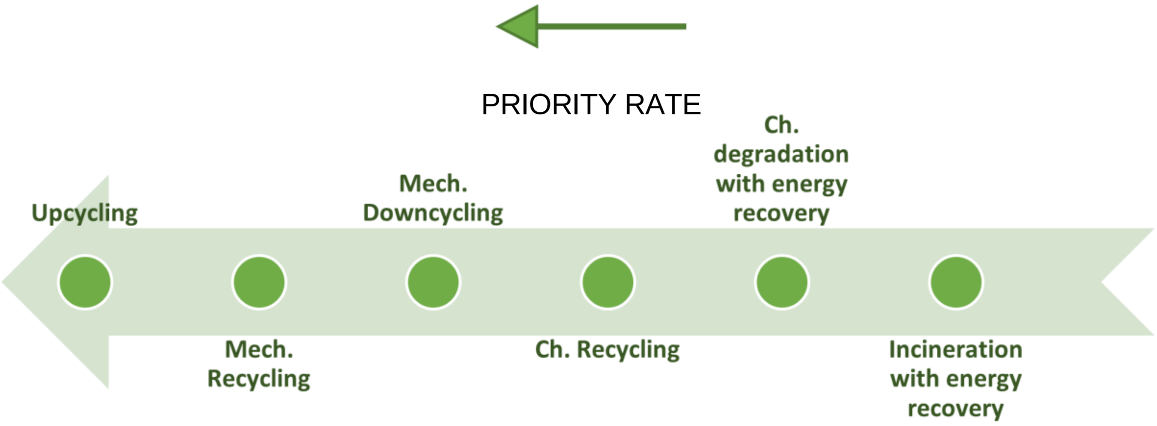

Figure 7 - PWM hierarchy [10], [19], [31]

There are two more significant differences, the first related to the product obtained by each process, the second to the operating temperatures [32]. In any case, the net calorific value of plastic is relatively high [33], and, therefore, it is considered very attractive for thermal processing to produce heat and electricity as the final stage [34]. Moreover, all three processes can be applied for PW, but the feedstock can vary among MSW, biomass, and organic waste.

2.3.1. Gasification

Gasification of PW is the thermal process in which waste is processed into a synthetic gas that can be used for electricity and heat production. The final products (syngas) can be used to create other valuable fuels such as methane, methanol and others, or it can be burnt directly to generate power as a substitute for NG [33]. The thermochemical process occurs in a temperature range of 700-1100°C. The most common types of gasification reactors are bubbling fluidized bed (BFB), circulating fluidized bed (CFB), and plasma gasifiers.
The final product depends on the type of the reactor, the quality of the feedstock, and the process used; however, it is possible, and most of the times necessary, to implement the plant with additional equipment for cleaning steps to improve the purity of the gas, even if that leads to higher investment and operational costs [33].
The performance of different gasification technologies configurations varies according to how the feedstock is processed [29]. Both optimizations of production efficiency and minimization

of costs are possible by matching the type of feedstock with the most appropriate reactor. However, it is to be kept in mind that a gasification plant's flue gas equipment must be the same as an incinerator, together with the regular measurements of toxic substances emissions [11].
Moreover, some technologies require energy input (NG, electricity…) to reach the desired operating temperature within the gasifier [35]. That is to be taken into account for the economic, energetic, and environmental balance of the facility. Another relevant drawback about gasification installations is related to bureaucratic obstacles. Administrative requirements are stricter if the gasification plant is intended for energy recovery than for chemical recycling [11], and the related legislative costs and permits are being found to make a gasification plant unprofitable. These burdens are making gasification less attractive from an economic point of view than both incineration and pyrolysis, as many additional auxiliary components are either mandatory or strictly necessary. Gasification of waste is proven, as well as its technological level for application to PW. However, it is not spread on an industrial scale in the EU and in the United States (US) (source: CEWEP consultancy); in Japan, instead, gasification plants exist for treatment of MSW, commercial and industrial waste, and Refused Derived Fuel (RDF). In particular, there are 122 waste slagging gasification plants processing around 7 million tons of waste per year [36].

2.3.2. Pyrolysis

Pyrolysis is a well-known process, and its maturity is quite proven when referring to biomass or organic waste. However, pyrolysis of PW is an emerging technology for the production of liquid fuels after the thermal degradation of plastics (or any other MSW) feedstock. It has been observed that the synthesized fuel has similar properties to the petro-diesel one [29]. One significant advantage of pyrolysis of PW is that the selection of the feedstock is very flexible; unlike the mechanical recycling treatment, for example, many more plastic materials are adapted to be treated with this thermal degradation process [34]. Some more advantages of the pyrolysis process are the flexibility of installation of the equipment, no necessity of previous waste separation, and minimum environmental issues [35]. The liquid yield rate obtainable from the pyrolysis process can reach 80%; the process of fast pyrolysis, that is the one that occurs at temperatures just below 500°C (unlike indirect pyrolysis that occurs at 350° - 450°C), takes to better economic benefits than other thermochemical conversion processes [37]. However, the process seems to be highly energy-intensive, as it is still being debated if the input energy needed is more than the energy content of the fuel produced. Moreover, the analysis of oil produced by distillation of plastic waste has shown that the obtained fuels are more suitable for compression ignition engines, the performances of the engines are slightly improved, and the emission level is in the standard [29]. Therefore, a combination of a diesel engine with an alternator is possible for electric power generation. Suitability of polymers for liquid fuel production is taken from Chandran et al. [29] and shown in Figure 8:

Types of plastics	Feedstock for liquid fuel	Descriptions
Polyethylene (PE) Polypropylene (PP) Polystyrene (PS) Polymethyl methacrylate (PMMA)	Suitable Suitable Suitable Suitable	These plastic contain relatively high ratio of hydrogen to carbon and also produce liquid with an acceptable calorific value with relatively clean exhaust gases
Polyvinyl chloride (PVC)	Not suitable	This plastic contains chlorine; it produces corrosive flue gases on combustion
Polyethylene terephthalate (PET)	Not suitable, presence of terephthalic acid and benzoic acid	These plastics contain oxygen
Phenol resin (PF)	Not suitable	
Polyoxymethylene	Not suitable	
Polyurethane (PUR)	Not suitable	This plastic contains nitrogen and sulfur that causes SOx and NOx emission from diesel engine combustion
Acrylonitrile—butadiene—styrene copolymer (ABS)	Suitable, but needs further processing to be suitable	Nitrogen and cyanide presence in oil affects diesel engines combustion

Figure 8 - Suitability of plastics for liquid hydrocarbon production [29]

The parameter to take into account for suitability of a certain material for pyrolysis process is the carbon to hydrogen ratio in the original composition, the more uniform is this ratio the more suitable is the feedstock. That is the reason why PVC is not adapt for fuel production, whereas PP and PE present an excellent inclination for this type of conversion [29]. Regardless its promising prospect for sustainability, for treating PW not applicable to mechanical recycling, and for increasing overall recycling rate [38], pyrolysis of PW has not yet reached an industrial maturity globally (source: CEWEP consultancy).

2.3.3. Incineration

Incineration is the direct combustion of PW; in other words, the waste itself is used as a fuel. It is possible to burn the most heterogeneous PW by incineration, and its total mass will be reduced up to 90%. However, productions of harmful smokes and toxic ash, such as dioxin, as well as the even less popularity of the technology ("not in my backyard"), make incineration

to be the less attractive WtE treatment and the last one in the PWM hierarchy [10] [28] [32]. Therefore, the main drawback is undoubtedly related to the Flue Gas emissions and the by-products of incineration. Even if fly ash and bottom ash are in mass percentage less than a quarter than the ones formed by the combustion of coal, the content of heavy metals derived from additives (Cd, Hg, As, Cl, and so forth.) is much higher. Nevertheless, about 98% of the content of pollutants of flue gas can be downed in a traditional incineration plant's additional component, such as electrostatic separator or bag filters. Additional equipment is strictly needed also for temperature control, emissions rate control, and gas treatment.
However, most advanced technologies have demonstrated to guarantee a dramatic efficiency in Flue Gas Cleaning (FGC) and Air Pollution Control (APC) for exhaust gases in WtE applications. Some plants owners claim that they emit in the atmosphere some gases of which the pollutants content makes the quality of the air better than the surrounding one [36]. Furthermore, emissions have been dramatically decreased during the recent years. As an example, dioxin emission from WtE plants in Germany have been reduced from 400 g to less than 0.5 g in 1990s decade, whereas the quantity of waste incinerated is more than doubled in that period [39]. Arena et al., carried out a Life-Cycle Assessment (LCA) study to evaluate the environmental burdens related to MSW treated in both a moving grate combustor (incinerator) and a vertical shaft gasifier; the results shown that both the technologies are environmentally sustainable, but the moving grate revealed a better impact on the emissions in air [40].
Currently, incineration plants in Europe can provide electricity to 18 million people and heat to 15.2 million people, thanks to the 90 million tons annually treated in WtE facilities (source: consultancy with CEWEP). A rough potential of incinerator state-of-art incineration facilities can be quantified in 30% of gross electrical efficiency, with around 0.6÷0.8 MWh_{el} of power generation per ton of MSW treated [41].

2.3.4. Remarks

From an environmental point of view, both GP are considered cleaner than incineration. Technically speaking, GP have a significant advantage that the by-products of these processes are reusable, and for what PW concerns, the high temperature of both GP provokes the total breakdown of its molecules in a new compound (syngas or liquid fuel). In particular, in gasification, the syngas produced is cleaned up quickly so that the residence time is not enough to let dioxin formed [28]. Dioxin is one of the most dangerous environmental pollution compounds, and it is a by-product of the incineration process. The lower harmfulness of GP than incineration, in terms of atmospheric pollution, is being highlighted in recent times by several LCA studies [42] [43].
Kourkoumpas et al. [43] showed that the incineration of RDF is less harmful, in terms of GHG emissions, that direct incineration of MSW. As might be expected, it is also demonstrated that

higher pre-separation of paper and plastics, lower Global Warming Potential (GWP) impact. More specifically, it has been observed almost linear relation between the recovery rate and the total environmental impact. All these results are based on two scenarios in which the ultimate treatment of MSW is considered for the same flow waste and the same electrical efficiency of the WtE power plant. It is also claimed that the energy input used for the WtE plant is covered by the electricity produced [42].

On the other hand, even though GP technology can be considered well-proven and mature, its implementation in WtE Power plants is still scarce. Before 2017, there were no large-scale operational GP power plants in Europe, and the few ones existing, mainly in Japan and the USA, require specific waste streams, high initial capital costs. Its economic profitability mainly depends on the market value of the fuel produced [35].

3. Case study description

The purpose of this thesis project is to assess a preliminary techno-economic and environmental evaluation for the upgrading of an existing thermal power plant. The plant's current working performance ensures the total cover of the local community's heat needs, plus a small supply of electricity to the local grid.

The heating plant is located in the Česká Lípa district, in the Liberec Region, the northern part of the Czech Republic, close to Germany and Poland's boundaries. The distance from Prague is approximately 100 km. Currently, the plant's architecture includes two steam boilers for heat generation, with a total installed rated power output of 15.24 MWh_{th}. The fuel used is a combination between low-sulfur lignite (bought from Polish coal mines) and biomass. The plant is directly connected to the local District Heating (DH) system by a pipeline length of 16.93 km. A back-pressure steam turbine is installed with a rated power of 0.295 MW_e, ensuring the electricity needed to run the plant itself and a small supply in the local power system.

The plant owner intends to completely renovate the facility, ensuring the supply of heat to the final consumers, mainly to local households. The upgrade will consist of converting this conventional heating plant to a WtE power plant, with a double effect. On the one hand, the plant will secure energy supply to the local community; on the other hand, it will represent an effective way to manage the waste produced in the nearby factories that would otherwise end up in landfills. Several manufacturing factories in the vicinity of the plant provoke the daily production of hundreds of kg of homogeneous and unrecyclable PW. Therefore, the WtE plant in question will get one more cash inflow channel given by the gate fee, and in the meantime, the facility will ensure the management of solid PW.

3.1. Scope of the project

This section contains the selection of the technologies that are considered to be the most suitable for this thesis project. The choices derive from a literature review and information obtained by the company owner of the plant. Particular emphasis will be dedicated to the combustion component and the Air Pollution Control (APC) and Flue Gas Cleaning (FGC) systems. The technical aspects for the remaining components of the plant will be analysed and reported only at a primary level. In particular, the design performances and sizing of the boiler, including super-heater, evaporator and economizer, and the combination steam turbine + electrical generator are out of the scope of this thesis.

Economic and environmental concerns are prioritized because this project is at a very preliminary stage. Before dealing with the thermodynamic and technical aspects, the company intends to carry on economic analysis to assess the project's financial potential. Moreover, the company has shown great interest in fostering decarbonization, making the plant attractive from an ecological perspective.

3.1.1. Incineration

The plant's specific area is suitable for such installation since it is located outside the city and the portion of the land where the plant is located, whose owner is the same as the plant, is much larger than the plant itself. It has been debated if the new power plant, after the upgrade, should be based either on gasifier technology or incineration. Pyrolysis installation has been discarded from the beginning, as its economic profitability is still low, and its implementation is only at a pilot stage. After preliminary consultancy meetings, it seems that the project will follow the direction of an incinerator. It is mainly because the project is not to be intended as a pilot model for future works, but currently, this plant is the only source of heat supply for the community. Therefore, reliable technology is needed to keep the supply needed, and incineration is more proven to maintain a stable baseload.

3.1.2. Heat demand

DH supplier provided the monthly heat generation of the power plant for 2019, as it is reported in Table 3.

Table 3 - 2019 heat generation of the heating plant [Local DH]

	Jan	Feb	Mar	Apr	May	Jun
MWh_{th}	3 660.101	3 341.19	2 481.67	1 598.94	1 686.68	790.22
GJ_{th}	13 176.40	12 028.29	8 934.02	5 756.18	6 072.05	2 844.81
	Jul	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
MWh_{th}	970.88	668.08	1 187.96	1 873.43	2 522.37	3 097.17
GJ_{th}	3 495.16	2 405.08	4 276.64	6 744.34	9 080.54	11 149.81

Which leads to a total production of approximately **85 963.31 GJ_{th},** which would satisfy the local heat demand. At full capacity, the heat generation of the power plant should be as listed in Table 4.

Table 4 – Theoretical heat generation at full capacity

	Jan	Feb	Mar	Apr	May	Jun
MWh_{th}	11 338.56	10 241.28	11 338.56	10 972.80	11 338.56	10 972.80
GJ_{th}	40 818.82	36 868.61	40 818.82	39 502.08	40 818.82	39 502.08
	Jul	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
MWh_{th}	11 338.56	11 338.56	10 972.80	11 338.56	10 972.80	11 338.56
GJ_{th}	40 818.82	40 818.82	39 502.08	40 818.82	39 502.08	40 818.82

That would lead to a (theoretical) total production of **480 608.640** GJ_{th} in 2019, considering the current rated power output equal to 15.24 MWh_{th}, operating 24/7 at full capacity. Thanks to the heat production data provided by the DH supplier, it is possible to estimate the capacity factor (CF) of the plant just by dividing the actual power generated by the rated power. The results are summarized in Table 5.

Table 5 - Estimation of CF per month

Month	Jan	Feb	Mar	Apr	May	Jun
CF	0.32	0.33	0.22	0.15	0.15	0.07
Operating hours	240.17	219.24	162.84	104.92	110.67	51.85
Month	Jul	Aug	Sep	Oct	Nov	Dec
CF	0.09	0.06	0.11	0.17	0.23	0.27
Operating hours	63.71	43.84	77.95	122.93	165.51	203.23

It is possible to appreciate how the predicted heat generated by the plant with such a rate is not comparable with the useful heat sold. Especially for what summer period concerns, it is clear that heat needs drop, unlike the winter months, where the heat demand is expected to be higher.

On the whole year basis (if there is a need to consider), the average CF is found to be equal to 0.196. The CF calculated for every month of 2019 is shown in Figure 9.

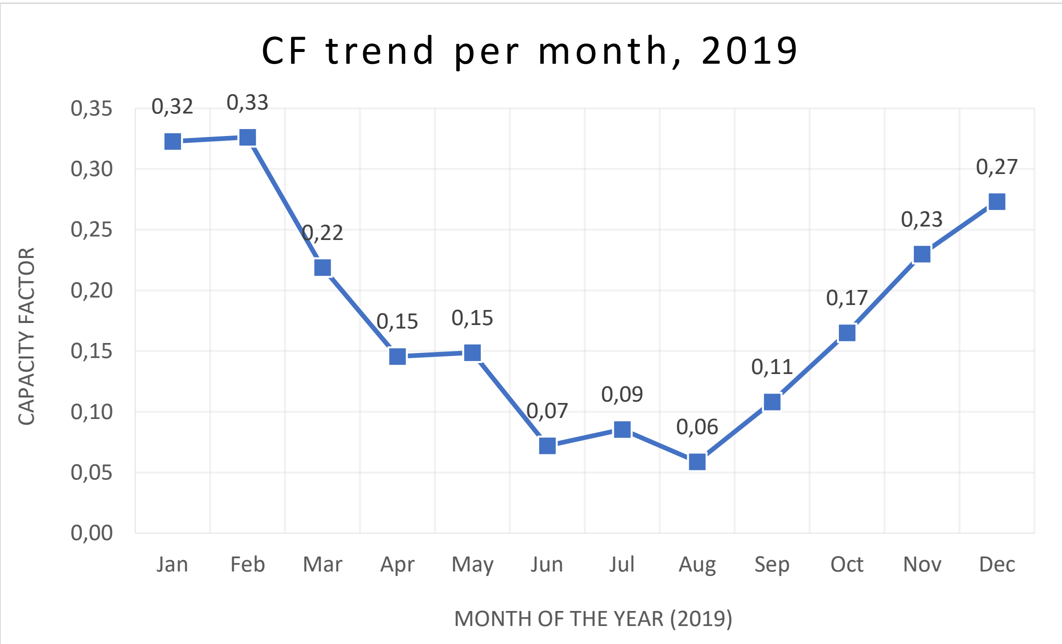

Figure 9 - Estimation of CF monthly

As mentioned in section 3 and reminded before in this section, the heat generation of the power plant in 2019, shown in Table 3, is sufficient to satisfy the needs of the community, and therefore the production shown in Table 3 should be maintained. The curve of the heat demand is shown in Figure 10.

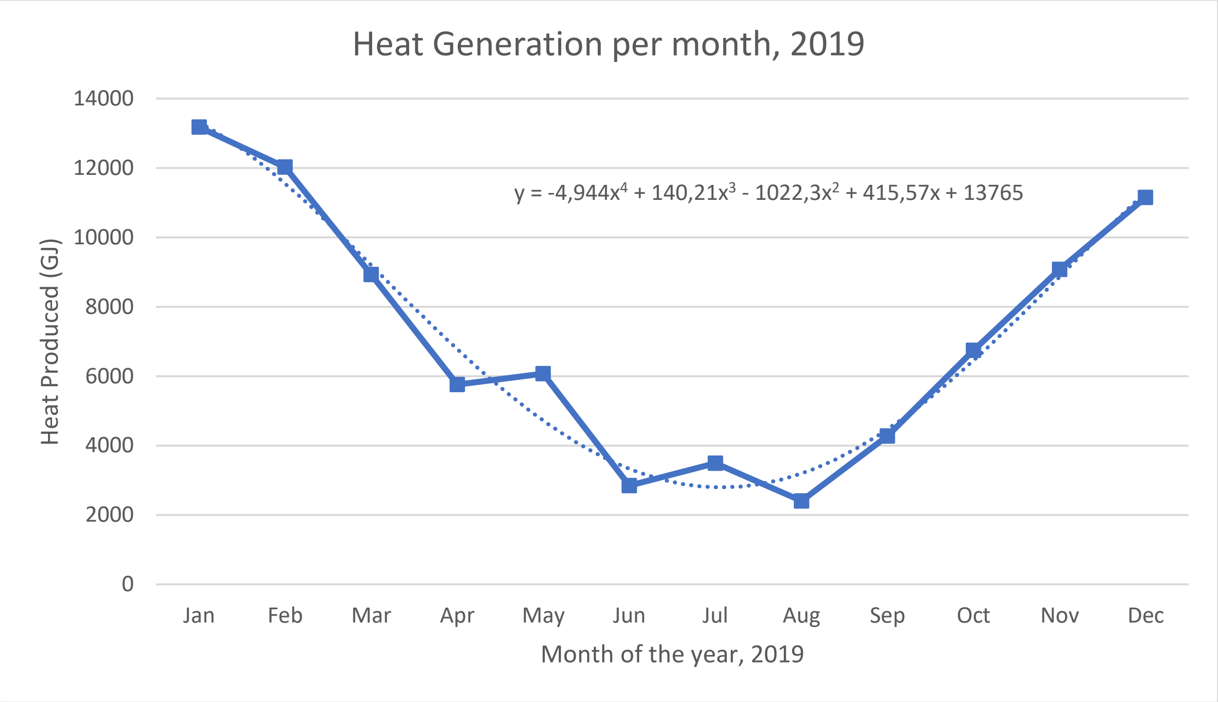

Figure 10 - 2019 heat generation and trend line

A trend function approximating the 2019 production is calculated in order to have clear guidance for what the future production of the plant is supposed to be.

4. Methodology

The scope of this section is to estimate the Low Heating Value (LHV) for the PW that will be used as feedstock; subsequently, a combustion chamber for such a feedstock will be proposed, according to a literature review, the best available techniques (BAT) for waste incineration (WI), and an analysis of various WtE power plants all across Europe. Finally, a FGC System will be proposed in order to fulfill the EU regulations and to help the company to increase the public acceptance of this facility.

4.1. LHV of the fuel

One of the most crucial factors that may affect the performances of a thermal power plant and the estimation of energy produced and, consequently, of the reliability of the plant and the future sales is the LHV of the fuel. LHV [MJ/kg] is defined as the amount of energy released when it is completely burnt in adequate oxygen amount. There are two ways of expressing the energy content of a fuel, the Lower Heating Value and the Higher Heating Value (HHV). The difference between HHV and LHV is the vaporization energy of water. In the HHV, water is in the fluid state, whereas in the LHV, water is in the gas state. HHV = LHV + (Heat required for evaporation of water) [44]. In this section, the LHV of the fuel expected to be combusted in the plant, namely PW deriving from industrial activities, and mainly from the automotive sector, will be estimated. Since there is no specific information yet about the type of PW to be treated, its LHV will be calculated according to the findings deriving from the review of the specific industrial sector. Hence, the value will be calculated based on the scientific literature review; afterward, it will be adjusted according to the knowledge and the assumptions considered reliable by the candidate. The final result will be a value of the LHV as far as possible in line with the project's real expectations.

4.2. Feedstock

PW is generally divided into post-consumer and post-industrial waste. Although the former generates a higher waste content and its treatment is the most challenging [16], this project will focus on the latter, namely plastic waste generated by industrial applications. Moreover, inside the perspective of a circular economy, post-industrial waste finds less space, as, for it, the hierarchy is more difficult to be followed.

In this project's specific case, the amount of PW will be retrieved from the nearby factories, which produce and manufacture plastics components of vehicles, and therefore generating a high daily quantity of waste that is difficult to recycle and that would otherwise be intended for landfill.

Plastic usage in the automotive sector has been presented in section 2.1.3. LHV for every polymer used, with the related percentage of utilization, is reported in Table 6 below:

Table 6 - Estimation of LHV of PW from the automotive sector

Polymer	Acronym	LHV [MJ/kg]	Percentage in Composition (mass basis)	Source
Polypropylene	**PP**	43.95	32%	[45] [28] [46]
Polyurethane	**PU**	25.6	17%	[47]
Polyvinyl Chloride	**PVC**	19.27	16%	[46]
Polyamides	**PA**	32	12%	[28]
Acrylonitrile-butadiene-styrene copolymer	**ABS**	N/A	7%*	-
Polyethylene	**PE**	46	5%*	[28]
Polycarbonate	**PC**	N/A	4%*	-
Polyethylene terephthalate	**PET**	23.24	1%*	[28] [46]
Polystyrene	**PS**	36.15	1%*	[28] [46]
Polyoxymethylene	**POM**	N/A	1%*	-
Poly(methyl-methacrylate)	**PMMA**	25	1%*	[45]
*estimated according to sources consulted				

When more than one source was available, the average value of those reported was considered. The composition of the polymers indicated with an asterisk (Table 6) has been estimated based on the literature review carried out. Polymers indicated with N/A did not show any reference to their heating values, and therefore they have been considered not suitable for incineration. Final LHV is estimated according to the weighted average of every single LHV multiplied by the relative fraction. Finally, a correction factor of 0.75 is considered to the LHV found due to the composition of the plastic composites, as mentioned before, often contaminated with other materials that would lower the calorific value. In conclusion, the following LHV has been calculated:

$$LHV = 21.36\ \frac{MJ}{kg}$$

It is worth to mention that this LHV calculated is in line with the findings from scientific sources consulted that provide an average calorific value for PW from commercial and industrial sectors [48]. Hence, this specific value will be considered, sensitized by $\pm 10\%$, for the expectations about the heat and power generation of the incineration plant object of the project.

4.3. Environmental impact

4.3.1. Current EU legislation

In this section, it will be reported a summarize of the EU legislation in force about the air emission limits set from industrial applications. Currently, the **DIRECTIVE 2010/75/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 24 November 2010 on industrial emissions (integrated pollution prevention and control)** is the legal reference. The installation of the subject of this thesis project falls within the applications of the Directive 2010/75/EU as, according to Art.3, par.41, item 1, it is defined as waste co-incineration plant "*any stationary or mobile technical unit whose main purpose is the generation of energy or production of material products and which uses waste as a regular or additional fuel or in which waste is thermally treated for the purpose of disposal through the incineration by oxidation of waste as well as other thermal treatment processes, such as pyrolysis, gasification or plasma process, if the substances resulting from the treatment are subsequently incinerated*" [49]. Therefore, Chapter IV (Artt. 42 - 55) of the directive mentioned above contains the rules and the obligations to comply with about the commissioning, the operational performances, and the pollution measures and control. In this chapter, emissions limits will be reported, together with some insights from the reference document about the BAT conclusions, of which the implementation guarantees that almost certainly the emission standards to be kept.

It should be noticed that the **COMMISSION IMPLEMENTING DECISION (EU) 2019/2010 of 12 November 2019 establishing the best available techniques (BAT) conclusions, under Directive 2010/75/EU of the European Parliament and of the Council, for waste incineration** "*represents a document purely indicative*", as the techniques listed and described in that document are "*neither prescriptive nor exhaustive, and other techniques may be used that ensure at least an equivalent level of environmental protection as indicated in Directive 2010/75/EU*" [50]. In the next paragraph, air emission limits from both the official Documents from EU Parliament and Council will be summarized; afterward, it will be described the methods and the technologies for the abatement of the emissions of the polluting substances with the implementation of FGC equipment, resultant from a scientific literature review. The last paragraph includes comments, considerations, and a proposed layout for the FGC system equipment.

4.3.2. Air emissions limit values

Emissions into the air from waste and waste co-incineration plants shall not exceed the emission limit values set out in Table 7, Table 8 and Table 9, as well as the next considerations for dioxin, furans, and CO. The values of the concentration of the pollutants shall be measured at the point of outflow of the flue gas from the stack. The stack shall be designed with a height not to affect the impact of the soil and to ensure a reasonable impact on the human health [50] [51].

All emission limit values shall be measured at T=273,15 K; P= 101,3 KPa:

Table 7 - C – Daily average emission limit values for the polluting substances (mg/Nm3) [49]

Polluting substance	C
Total Dust	10
TOC	10
HCl	10
HF	1
SO_2	50
NO_X	400

Table 8 - C – Half-hourly average emission limit values for the polluting substances (mg/Nm3) [49]

Polluting substance	C
Total Dust	30
TOC	20
HCl	60
HF	4
SO_2	200
NO_x	400

Table 9 – C - Average emission limit values (mg/nm3) for the following heavy metals over a sampling period of a minimum of 30 minutes and a maximum of 8 hours [49]

<table>
<tr><th>Polluting substance</th><th>C</th></tr>
<tr><td>Cd</td><td>Total: 0,05</td></tr>
<tr><td>Tl</td><td>0,05</td></tr>
<tr><td>Hg</td><td rowspan="5">Total: 0,5</td></tr>
<tr><td>Sb</td></tr>
<tr><td>As</td></tr>
<tr><td>Pb</td></tr>
<tr><td>Cr</td></tr>
</table>

Co	
Cu	
Mn	
Ni	
V	

- Emission limit for dioxin and furans (ng/Nm3) = **0,1**
- Emission limit values (mg/Nm3) for carbon monoxide (CO) in the waste gases:
  (a) **50** as daily average value;
  (b) **100** as half-hourly average value;
  (c) **150** as 10-minute average value.

The following measurements relating to air polluting substances shall be carried out [49]:

- Continuous measurements of the following substances: NO_x, CO, total dust, TOC, HCl, HF, SO_2.
- Continuous measurements of the following process operation parameters: temperature near the inner wall or at another representative point of the combustion chamber as authorized by the competent authority, concentration of oxygen, pressure, temperature, and water vapour content of the waste gas.
- At least two measurements per year of heavy metals and dioxins and furans; one measurement at least every three months shall, however, be carried out for the first 12 months of operation.

The statement "*continuous measurements"* refers to the average value, respectively on a 30-minutes period when half-hourly average is requested, and a 24 hours period when daily average daily period, of the valid values measured. This kind of measurement requires an automatic system, installed on-site permanently [50].

5. Economic analysis

In this section, the methods needed to perform a preliminary analysis of the financial resources is presented. The economic feasibility of the incineration plant will be assessed by comparing the financial charges due to initial investment and operation and maintenance (O&M) costs on the one hand, and the revenue derived from allowance to manage waste (gate fee) and sale of heat and electricity, on the other. Moreover, the optimal size of the plant is to be determined, depending on the waste flow rate (tons per day) available. Most common sizes are 250, 500, 1000, 2000 tons/Day [28].
When conducting the economic analysis of an incineration power plant, one of the most crucial pots is the externalities to be evaluated. Negative externalities usually are incineration tax, atmospheric pollution, population density, and distance between the urban centre and the plant, whereas the external benefits include the power generation technology substituted (nuclear, NG, coal, and lignite) and the recovery method, the latter is better achieved in Combined Heat and Power (CHP) plants. Anyway, a reliable monetization of both positive and negative externalities is a challenging task [28].

5.1. Methodology for economic evaluation

This section presents a preliminary economic evaluation based on data obtained from a comprehensive literature review and specifications about WtE plants similar to the one under analysis. This methodology derives from the fact that getting data about capital and O&M cost is too complicated on a theoretical basis, and this kind of information is most of the time reserved by the owner of the facility. Therefore, one reliable method to obtain comparable data for assessing a financial analysis for this project thesis is using empirical formulas, which derive from analysing similar case studies.
Specifically, it should be considered and compared data for every one of the components that will assemble the Plant in its whole (combustion chamber, steam turbine, electrical generator, and so forth), of which accurate and reliable costs are impossible to obtain without consulting a specialized company. Moreover, when focusing on PW incineration only, data are scarce, and therefore the considerations are limited to WtE plants that are treating MSW. The estimations will be calculated according to some empirical formulas, either found in some papers or elaborated after having reprocessed other sources of data. The final results are intended to be a general starting point for decision making about investment and cost-benefit analysis. At the end of each section, there will be presented comments and considerations to the results. The literature sources investigated do not show a particular coherency in the order of magnitude of the formulas or data proposed, and, therefore, sometimes it has been necessary to reprocess some data. Therefore, the final formulas for estimating the economic parameters desired will be adapted as a function of the installed capacity of the plant indicated

in ktons per year, and expressed in the following form:

$$\boldsymbol{X} = A * \boldsymbol{C}^{B} \quad (1)$$

where:

- $\boldsymbol{X}$ is the economic parameter to be determined (in mln €)
- $\boldsymbol{C}$ is the operating capacity of the plant (in ktons/year)
- A and B are two empirical constants.

5.1.1. Capital Expenditures

Capital Expenditures (CapEx), also named capital costs, are defined as the financial resources allocated by a company to undertake new projects or investments or, as in this case, for the upgrading of existing commercial activities. Within the scope of this project, CapEx can be considered as the initial investment, including costs about the purchase of the equipment, labour costs, site preparation, and building. Capital costs depend, first of all, on the type of technology chosen for the project (Moving grate, Fluidized bad etc.) [52], [53]. A report by Horizon2020 Initiative states that the investment cost for installing a WtE power plant varies from 550 €/ton to 800 €/ton [54]. Chaliki et al. [55] evaluated this range from 600 €/ton to 900 €/ton. More data are reported by WSP, that in 2013 published *"A Review of State-of-the-Art Waste-to-Energy Technologies"*, in which some values for the expected capital cost for the installation of a WtE plant are estimated. However, the desired format for estimating the investment cost of the project is the one shown in Equation 1, to better identify how the investment is affected by the designed capacity. Haghi et al. [31], in a case study for a techno-economic assessment of MSW incineration plant, proposed the equation 2:

$$Inv_{0,1} = 2.35 * C^{0.7753} \quad (2)$$

Where Inv_0 represents the capital cost of the project (in mln USD/$), and C indicates the rated capacity of the plant (in ktons/year). From now on, all the other data obtained from the sources investigated will be reprocessed in order to obtain an equation in the same form as for equations 1 and 2.

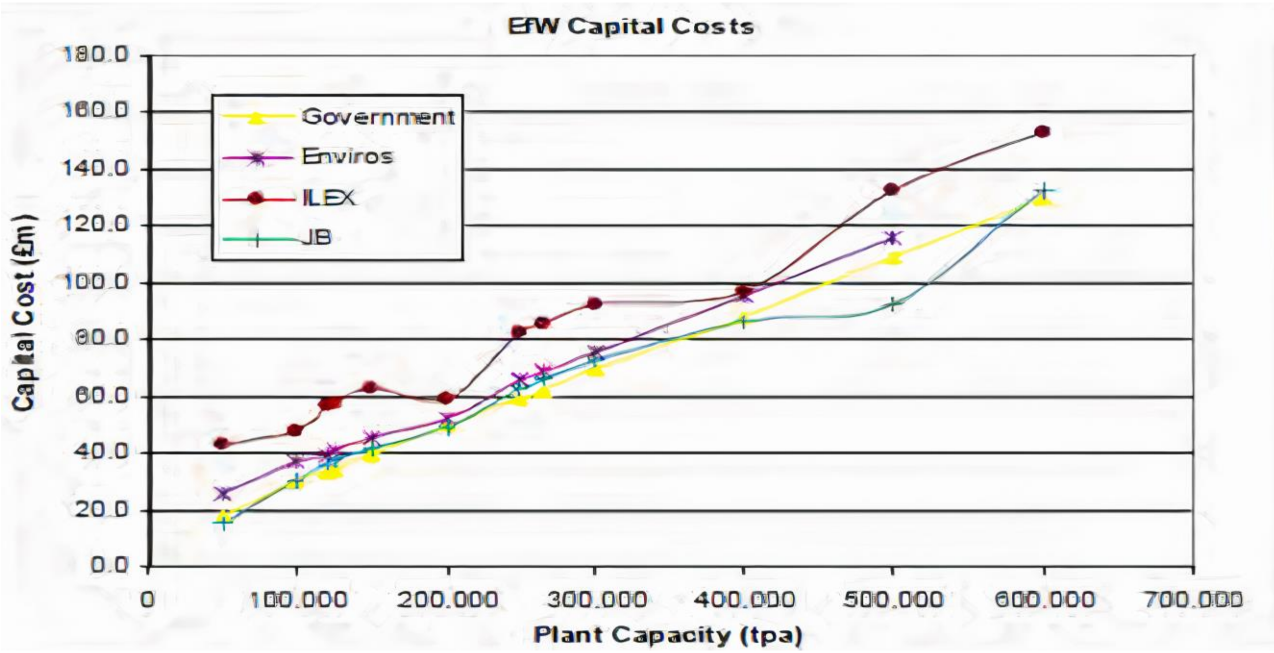

Figure 11 - WtE capital costs vs. plant capacity [36]

Figure 12 is taken from the WSP report [36], in which the authors compared four estimates of the investment in Pound Sterling (GBP/£) required for build a WtE incineration plant, each one of them based on four different parameters from four consultancies (Government, Enviros, ILEX, JB). Data was extracted from Figure 11, and the values are listed in Table 10. According to the exchange rate provided by Google Currency Converter Tool, a conversion factor of 1 £ = 1.09 € has been applied.

Table 10 – Values extracted from [36]

	Investment cost (mln €)		
Plant Capacity (ktons/y)	JB	Enviros	ILEX
43.75	17.44	17.44	29.07
100	31.97	31.97	40.69
118.75	34.88	37.79	43.60
125	36.33	39.24	44.18
150	40.69	43.60	49.41
200	52.32	55.23	58.13
250	63.95	66.85	72.67
268.75	66.85	72.67	75.57
300	72.67	78.48	81.39
396.875	95.92	95.92	104.64
500	116.27	98.83	124.99

The data have been reprocessed in order to homogenize the order of magnitude, as in the equations 1 and 2. The relative plotting on a graph for these series is shown in Figure 12. It can be observed that the data belonging to the parameters “Government” (Figure 11) are excluded, the reason is explained in the next session.

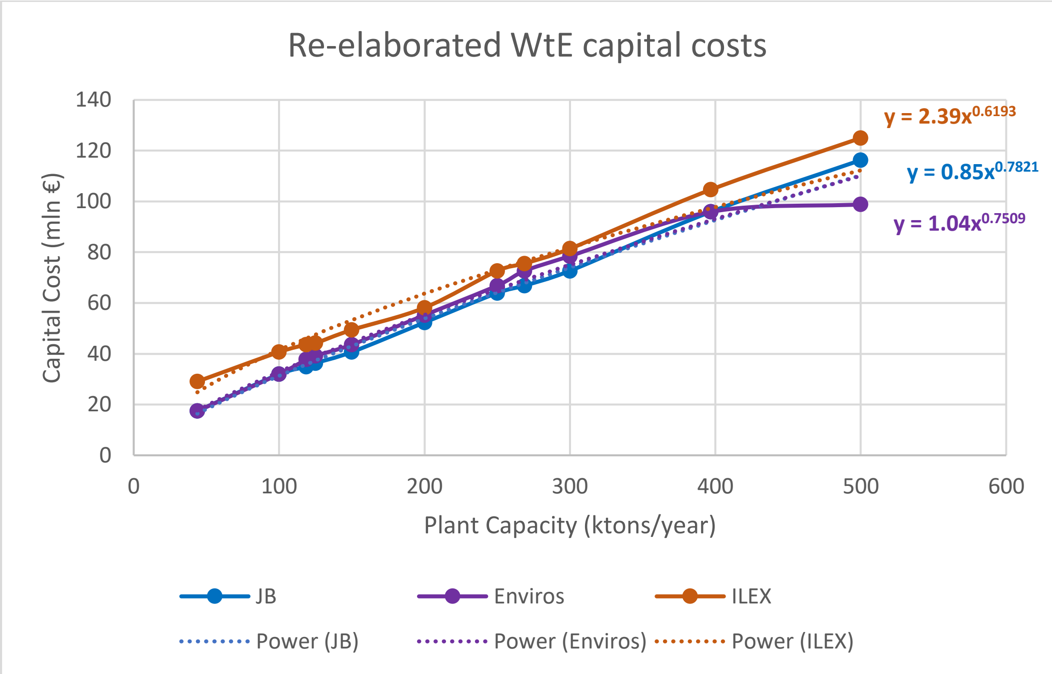

Figure 12 - WtE capital costs (mln €) vs. plant capacity (ktons/y) (adapted from [36])
(*converted by GBP using a conversion factor equal to 1 £ = 1.09 € [Google Currency Converter Tool])

At this point, Excel allows to plot the related trend line for each one of the curves resulted in order to have an equation describing the variation of the expected capital cost with the installed capacity. It is possible to draw on the graph the related trend line of the curves in the form desired (“power”) and to view the related equation on the graph itself. The equations obtained are:

$$Inv_{0,2} = 0.85 * C^{0,7821} \qquad (3)$$

$$Inv_{0,3} = 1.04 * C^{0.7509} \qquad (4)$$

$$Inv_{0,4} = 2.39 * C^{0,6193} \qquad (5)$$

One more equation will derive by reprocessing the data illustrated in Figure 13, that shows the inversely proportional relationship between the size of the plant and the capital cost in Canadian Dollars (CAD) per unit of capacity installed, measured in treated tons of waste per hour.

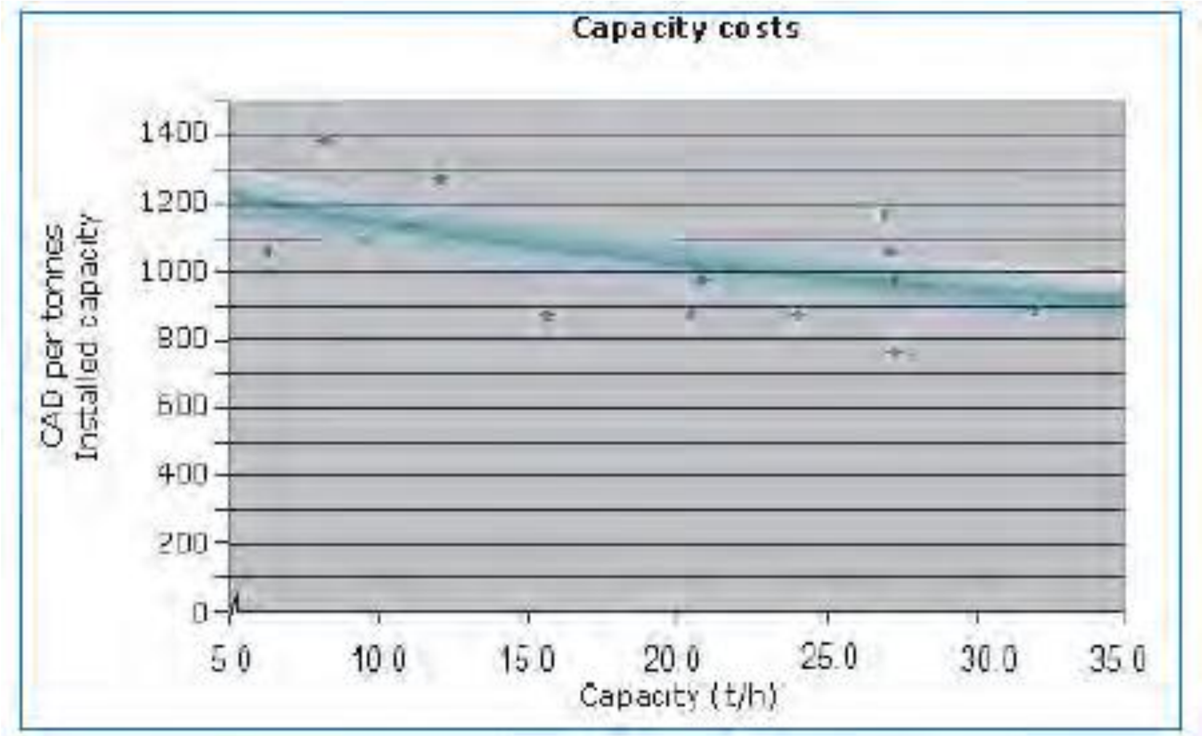

Figure 13 - Comparison of capital costs (CAN$) for WtE facilities per installed capacity (Source: WSP)
(*converted by Canadian Dollars using a conversion factor equal to 1 CAD = 0.65 € ([Google Currency Converter Tool])

The methodology to estimate the specific values of the points of the graph in Figure 13 is the same as in the previous part. The value obtained are, by the way expressed in CAD for the y-axis, and in tons/h for the x-axis. At this point, multiplying the values on the x-axis by 8000 h - average operating hours per year in a WtE plant [36] – it is obtained the plant capacity in ktons/year. Afterward, by multiplying the unit price (y-axis) by the corresponding annual capacity just obtained, it is obtained the gross investment in mln CAD. The last step is converting CAD in € utilizing the conversion factor 1 CAD = 0.65 € [Google Currency Converter Tool].

After reprocessing the data in Figure 13 it can be depicted as in Figure 14.

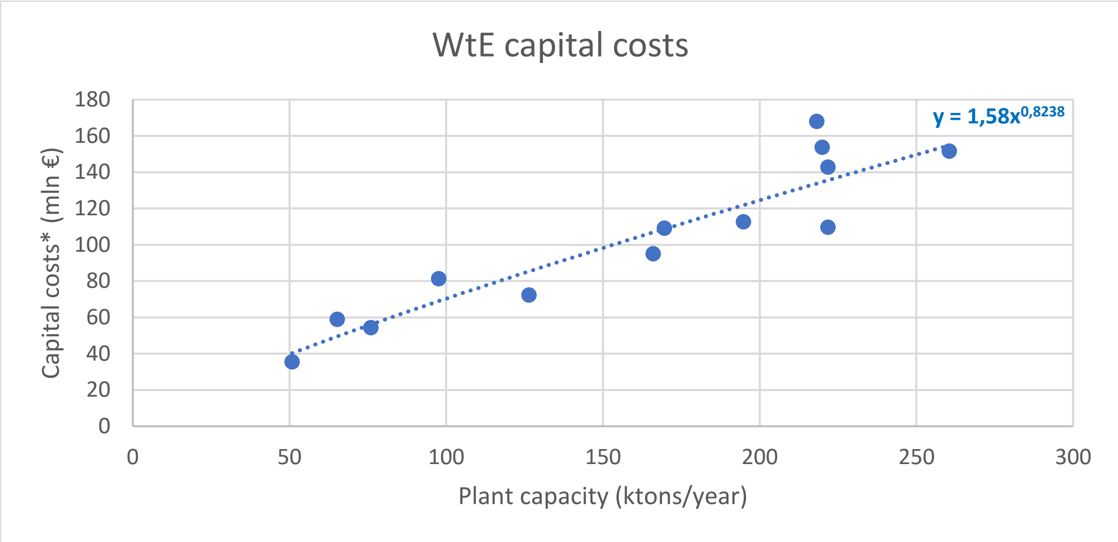

Figure 14 - WtE capital costs (mln €) vs. plant capacity (ktons/y) (adapted from [36])
(*converted by Canadian Dollars using a conversion factor equal to 1 € = 0.65 CAD [Google Currency Converter Tool])

From which is obtained the equation 6:

$$Inv_{0,5} = 1.58 * C^{0.8238} \qquad (6)$$

At this point, five correlations are obtained (Eqs. 2-6), relating two of the most critical parameters for an economical assessment. By mean of those and adjusting the plant capacity according to the technical requirements, five different values of Inv_0 per each designed plant size will be obtained. They are considered to be enough to perform a preliminary sensitivity analysis of how much would be the financial resources needed to start the project.
In the end, only converting € to Czech Korunas (CZK) will provide the final results.

5.1.2. Operating Expenditures

Operating Expenditures (OpEx), also named operating costs, are defined as the expenses that regularly incurs in business activity. They include all those costs related to making the activity keep running, scheduled with a regular frequency. OpEx for an incineration power plant includes maintenance, energy costs, wages, purchase of resources, and so on [52], [53].
As it is highlighted by different sources consulted, the capacity of the Plant is the parameter that will mostly influence the result. OpEx is usually indicated on an annual basis, therefore as €/y or mln €/y.
In this section, five equations for estimating the OpEx are elaborated. It is worth to mention that the process to obtain the five correlations is the same as for CapEx as described in the previous section. It means that the first correlation for OpEx derives from the same source used to obtain the correlation for CapEx after reprocessing data and so on until obtaining the

same correlations.

Horizon2020 states that the range of operational costs of a WtE power plant goes from 35 to 80 €/ton [54]. Haghi et al. [31] based on some researches and case studies, predicted a formula for estimating the operational costs as well:

$$Op_1 = 0.07 * C^{0.8594} \qquad (7)$$

Where Op represents the OpEx of the facility (in mln $), and C indicates the rated capacity of the Plant (in ktons/year).

Equation 7 is written with the same form and order of magnitude of Equation 1, therefore the next four equations are obtained in that form as well, as for the CapEx.

Figure 15 shows the operating unit cost, that is the cost per ton of rated capacity, for WtE plants. It can be observed that the parameters are the same, with one exception, “Government”, that was excluded from CapEx equations.

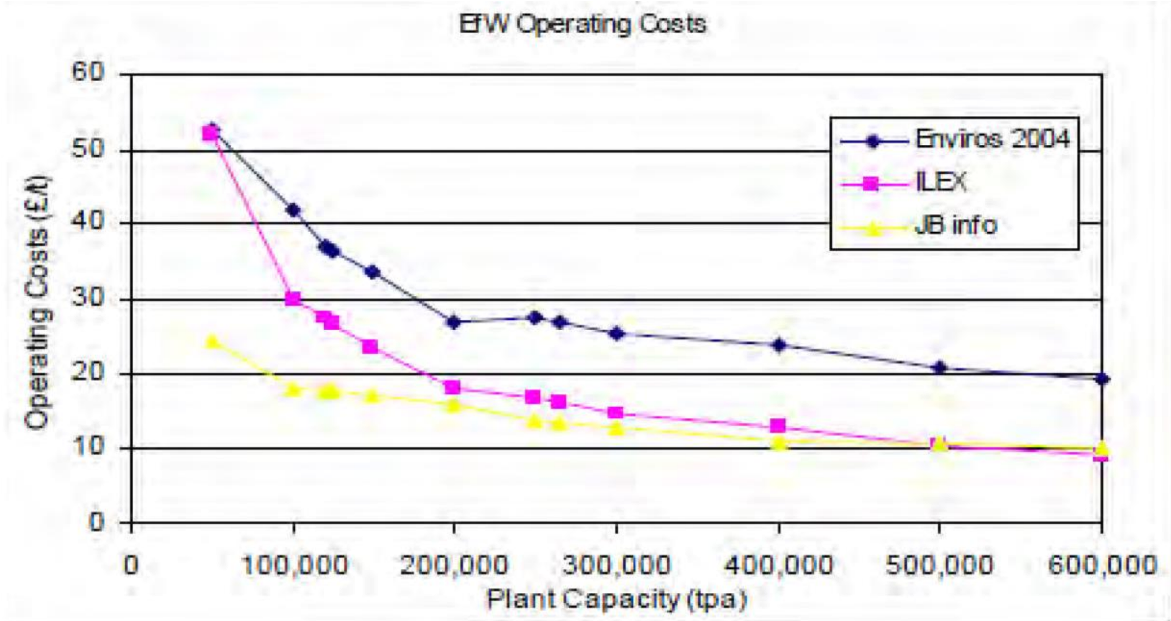

Figure 15 - WtE operating cost [36]

In this case, the methodology to obtain the values of the point has been the same as for the ones in Figure 11, whereas the conversion from unit price to total price has been calculated as for the Equation 7. Finally, the value obtained have been converted to €, inserted in an Excel sheet and plotted on a graph, to obtain the related trend lines equations in the desired form, exactly as it has been done for CapEx. The results for OpEx are plotted in Figure 16.

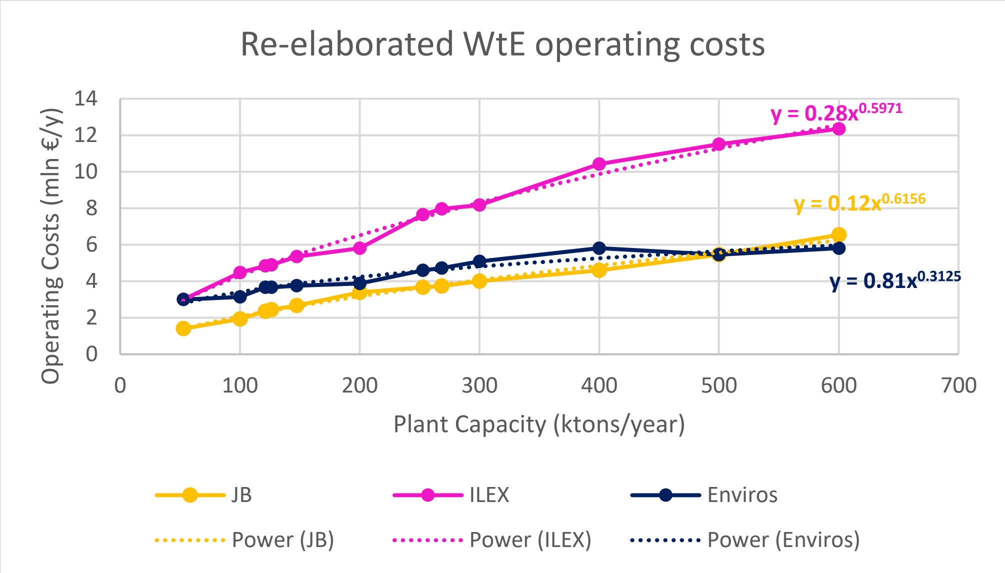

Figure 16 - WtE operational costs (mln €) vs. plant capacity (ktons/y) (adapted from [36])
(*converted by GBP using a conversion factor equal to 1 £ = 1.09 € [Google Currency Converter Tool])

From Figure 16 it is possible to obtain three correlations that are equations 8-10:

$$Op_2 = 0.12 * C^{0.6156} \qquad (8)$$

$$Op_3 = 0.28 * C^{0.5971} \qquad (9)$$

$$Op_4 = 0.81 * C^{0.3125} \qquad (10)$$

For the last equation, as in section 5.1.1 it is possible to analyse the further data provided by the WSP report and reprocess them to obtain a correlation. Figure 17 is taken directly from the WSP report.

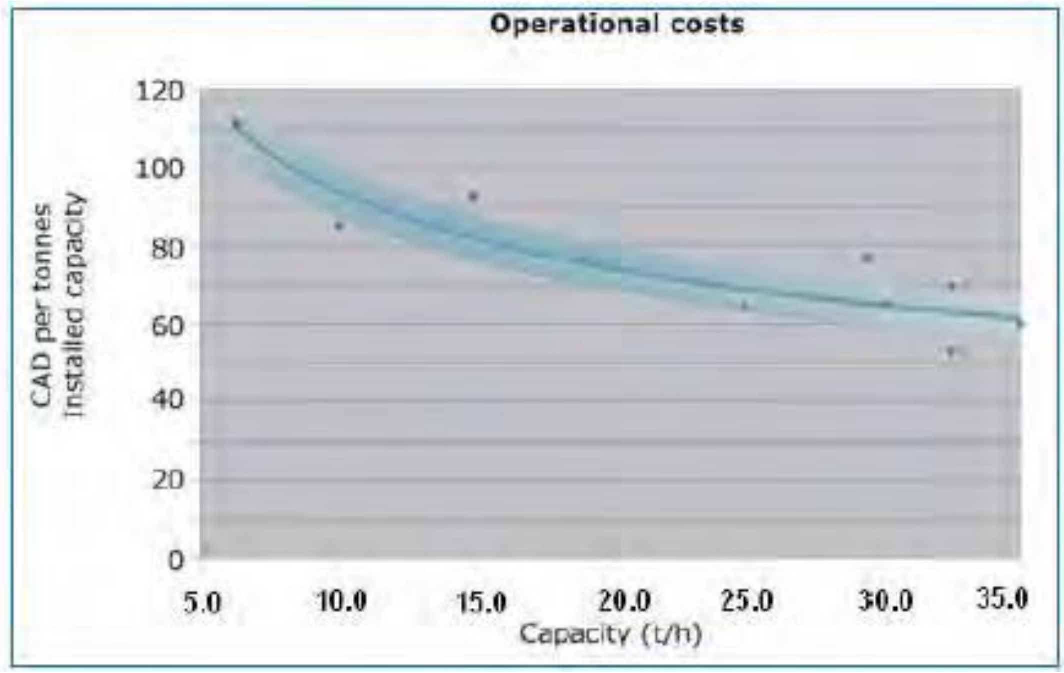

Figure 17 – Comparison of operational costs (CAD) for WtE facilities per installed capacity [36]

Despite the low quality of the picture and the different measurement units, this graph has been analysed and reprocessed by the writer and the result is shown in Figure 18.

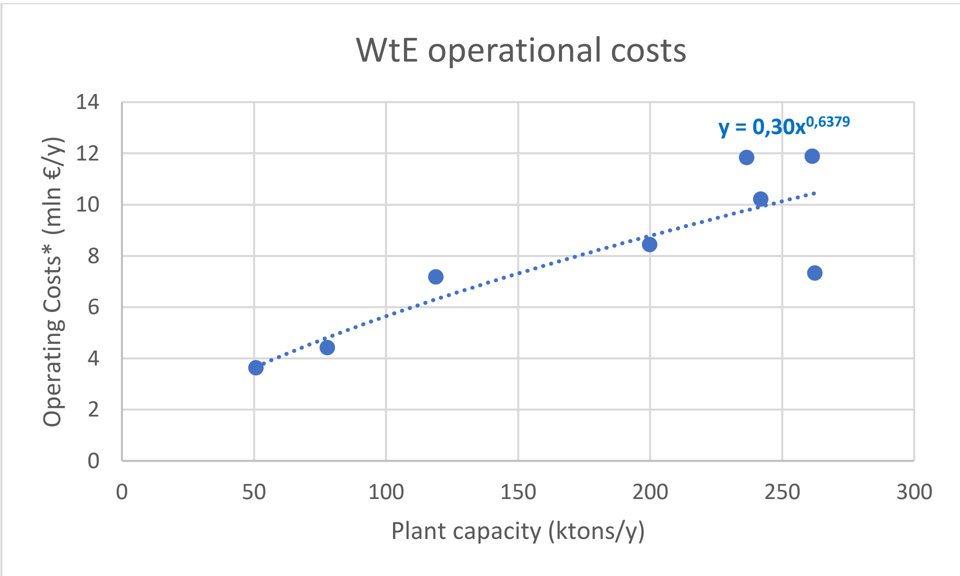

Figure 18 - Comparison of operational costs for WtE facilities per installed capacity (adapted from [36])
(*converted by Canadian Dollars using a conversion factor equal to 1 CAD = 0.65 €[Google Currency Converter Tool])

By plotting the trend line, it is possible to obtain the equation 11:

$$Op_5 = 0.30 * C^{0.6379} \qquad (11)$$

At this point, five correlations (Eqs 7-11) for OpEx are obtained. These equations will be used in sections 6.7 for estimating CapEx and OpEx for this project, and in sections 6.9 and 6.10 for the discussions about the economic results obtained.

5.2. Net present value and internal rate of return

The methodology for calculating net present value (NPV) and internal rate of return (IRR) is taken by author/s et al., [56]. Here it is briefly explained, and its application with Excel will be presented in 6.9. Before introducing the concept of NPV and IRR, some references to basics of energy economics are necessary.
The annual energy output of a power plant can be calculated according to equation 12:

$$Q = P \cdot \mathrm{CF} \cdot 8760 = P \cdot \hbar \qquad (12)$$

Considering that 8760 is the number of hours in one year and then, multiplying by the CF, the number of operating hours is given.
Indicating with p_{en} the price per unit of energy sold the expected annual income from energy sales (for any year t) is given by:

$$R_t = p_{en,t} \cdot \mathrm{Q} \qquad (13)$$

Besides the incomes, there are the costs to be considered. First of all, the initial investment Inv_0 in the initial period t_0, but also the variable costs per year, for example, because of wages, maintenance, and variable cost of energy; we indicate these costs with C_{var}.
Therefore, the cash flows incomes after the initial investment are given by the profit:

$$P_t = \left(p_{en,t} - C_{var,t}\right) \cdot Q_t \qquad (14)$$

At this point, we can introduce the concept of NPV, that is the profit of a project not only considering the usual quantities such as initial investment, expected revenue, and fixed and variable costs, but indeed, the NPV represents the resulting quantity by actualizing these internal values and spreading in the whole lifetime of the project, considering a specific interest rate i per each year:

$$NPV = -Inv_0 + \sum_{t=1}^{T} \frac{\left(p_{en,t} - C_{var,t}\right) \cdot Q_t}{(i+1)^t} \qquad (15)$$

Where the term $(i+1)^t$ is referred to as a discount factor, meaning that cash flows occurring later in the time have a reduced value at present. In other words, NPV is a financial function that is calculated for an investment, and it represents the present value of the investment minus the amount of money that it costs to but in.
In practice, one easy and fast way to calculate the NPV is with Microsoft Excel; the latter offers a preset function for this called NPV. In order to be able to calculate the NPV by using the Excel function, the initial investment Inv_0, the net cash flows per each year of the operational lifetime of the project, and the interest rate i are required to be known.

6. Results

6.1. Waste Pre-treatment: collection, sorting, and process

A typical WtE plant operational scheme is shown in Figure 19.

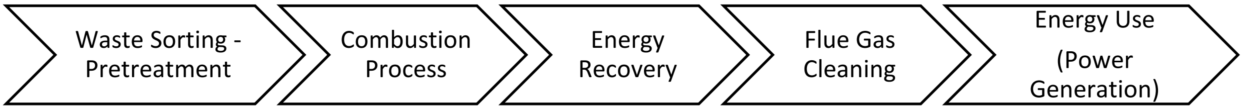

Figure 19 - Main Stages of a typical WtE power plant [57]

As mentioned in chapter 3, the collection of the PW will derive from the transportation of industrial PW from the surrounding factories. The specific distance between the location of the plant and these factories is unknown, therefore, it is considered not to be included in the analysis, as both the power plant and the facilities that generate the waste are situated in the same rural-industrial area in a province of Northern Czech Republic. It is also assumed that there will not be any need for sorting the feedstock, as it is coming from the industrial application of specific products manufacturing (mainly automotive parts), and therefore it will be homogeneous in plastic composition and regularly supplied. The only concern that may arise is about the pre-treatment, as a first shredding might be necessary in order to feed the combustion chamber with grinded solid fuel of smaller and homogeneous dimensions. However, as the specific composition of the waste is still unknown (unlike its nature), this process cannot be included in the scope, and its analysis is postponed to future works.

6.2. Combustion process

Incineration units are divided according to various methods, for example, with respect to the feedstock, the operation, and the final product required [48]. When referring to Solid Waste, it can be thermally treated in three ways: grate incinerator, rotary kilns, and fluidized beds [36]. The choice of application for this project is a grate incinerator combustor, as it is the widest applied for direct incineration of solid waste, with a range of applications especially in Europe, where around 90% of incineration WtE plants use this type of technology [30]. Rotary kilns are usually applied for any type of waste, but they require a higher CapEx and OpEx due to their high-temperature operation and therefore are preferred for medical and hazardous waste [48] [36]; on the other hand, fluidized beds are usually applied for the incineration of properly divided wastes, such as RDF or sewage sludge [48].

For what incinerator grates concerns, they consist of a moving grate located at the bottom of the combustion chamber, where the waste is fed from the collection room using a mechanical crane. Afterward, the combustion of the waste takes place, by supplying air from the bottom of the grate, and the movement of its rods ensures a homogeneous distribution in the combustion chamber. A number of grates are applied in practice, such as forward reciprocating, reverse reciprocating, roller system, and horizontal pattern [57]. Moving grates can be classified according to the relative movement of the grates that transport the waste and how the hot flue gas is sent to the boiler. The design decision of the grate depends mainly on the type of feedstock and the field of application. A classification is shown in Figure 20.

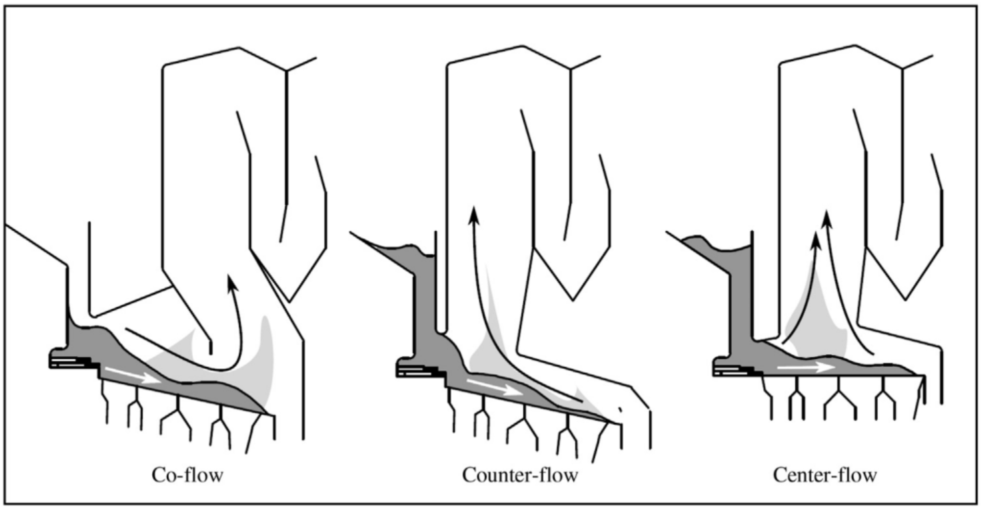

Figure 20 - Classification of furnace types according to the flow gases and feedstock waste [48]

The co-flow incineration chamber is the most suitable for this application, since its best feasibility, rather than the others, for high LHV waste (> 15 MJ/kg) [30] [2]. The PW can be burnt at a temperature of 850°C, for at least 2 seconds after the last injection of the combustion air. A secondary injection of air is possible, and sometimes required, to ensure complete combustion and increase the efficiency of the process [36]. Lastly, a cooling system is beneficial for controlling the metallic rods temperatures and improving their lifespan. Generally, air-cooled grates are used for cooling down the grate [35], but in this case, water cooling is proposed due to the high LHV of the waste treated. Its application is more complicated, but it ensures a better control to maximise the efficiency of the combustion, that will take to less waste needed and consequent reduction of pollutants in the flue gas [36].

[2] In fact, non-sorted LHV of MSW is commonly around 7-12 MJ/kg; this difference is due to the high organic, moisture, and ash content of unsorted MSW [35].

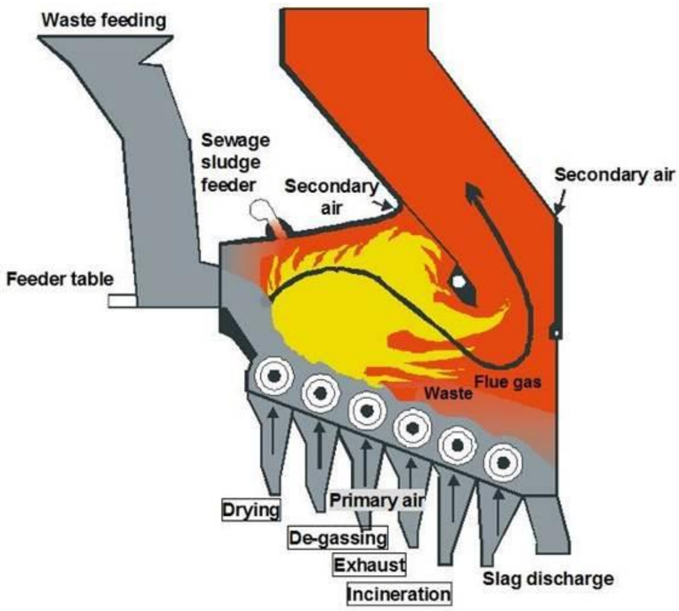

Figure 21 - Example of moving grate co-flow combustion chamber [30]

6.3. Energy recovery

The moving grate is enclosed by walls composed of tubes in which pressurized water flows, to capture the heat; this is the first energy recovery process. The walls will be layered with refractory ceramic that is resistant to corrosion phenomena [58]. The hot flue gas generated by the combustion of the waste exits the combustion chamber passes through the boiler, and economizer and superheater to maximize the heat capture from the combustion.

After the combustion stage, the produced hot flue gas will exit the furnace at 850°C, the optimal temperature for WtE application to avoid problems of corrosion and erosion [36]. Inside the boiler, the hot flue gas will be cooled down and the heat will be transferred to circulating water for the production of steam. According to the use of energy that one wants to make, the boiler can be designed for power generation, heat generation, or combined plant.

In this project, a CHP application is proposed. This choice aims to maximize the overall efficiency of the plant and take the full advantage of the connections of the power plant, which allows injecting heat in the form of steam into the DH systems and power in the form of electricity into the power systems.

6.4. Power generation

In this section, energy generation in the form of heat and electricity will be estimated. Calculations will be carried out according to the most common values for incinerators found in literature, and to propose a system that will comply with the heat energy demand shown in 3.1.2.

6.4.1. Heat generation

The boiler thermal efficiency, calculated as the energy input value from the waste and the heat output contained in the steam, is around 85% [59] [48] [30]. LHV has been estimated in section 4.1 , LHV = 21.36 MJ/kg. In order to comply with an acceptable value of energy produced and sold, a good starting point is to rate the plant installed capacity at 30 000 tons/year. This value is relatively small for WtE applications, but afterward it will be shown why it is an optimal value for the economic aspect. Therefore:

$$Q_{th} = 21.36\ \frac{MJ}{kg} \cdot 30\,000\ \frac{tons}{years} \cdot 0{,}85 = 535\,500\ GJ_{th}$$

Well above the estimated annual heating demand **85 963.31 GJ$_{th}$.**
Considering that only a part of this value will be sold, whereas most of the heat will be either condensed in the steam turbine or cooled down for recirculation in the boiler, it can be assumed to sell to the DH system **95 000 GJ$_{th}$.**

6.4.2. Electricity generation

Part of the steam that will be condensed and used for power generation. Most advanced WtE units can achieve a gross electric efficiency of 30% [36] [41], and in 2.3.3 it has been said that around 0.6 to 0.8 useful MWh$_{el}$ can be generated by burning 1 ton of MSW, whereas the typical LHV of MSW is around 8 to 12 MJ/kg [55] [41].
However, in this section, the assumptions will be based on a gross electrical efficiency of 0.25, and from injecting to the grid a value around 40% of the electricity generated[3]. In fact, part of the electricity will be used to run the plant, and other losses are predicted.
Therefore, utilizing the conversion factor 1 MWh = 3,6 GJ, we obtain:

$$Q_{el} = 21.36\ \frac{MJ}{kg} \cdot 30\,000\ \frac{tons}{years} \cdot 0.25 \cdot 0.4 \cong\ 17\,800\ \ MWh_{el}$$

6.5. Economics

In sections 5.1.1 and 5.1.2 CapEx and OpEx have been defined, showing how they are two of

[3] The author states that this info derives from a consultant meeting with the company, and therefore it is assumed to be reliable for the purpose of the project

the most crucial parameters to be well defined to perform an economic assessment. According to the methodology elaborated, five equations have been obtained to estimate both CapEx and OpEx, which would provide five different results per each Plant's capacity that will be proposed. Equations 2-11 elaborated in sections 5.1.1 and 5.1.2 are summarized in Table 11. As mentioned before, it is beneficial to remind that every line for CapEx is comparable with the related for OpEx, since each one of the two derives from investigating the same source.

Table 11 - Summary of the equations elaborated in section 5.1

CapEx		OpEx	
$Inv_{0,1} = 2.35 * C^{0.7753}$	(2)	$Op_1 = 0.08 * C^{0.8594}$	(7)
$Inv_{0,2} = 0.85 * C^{0,7821}$	(3)	$Op_2 = 0.12 * C^{0.6156}$	(8)
$Inv_{0,3} = 1.04 * C^{0.7509}$	(4)	$Op_3 = 0.28 * C^{0.5971}$	(9)
$Inv_{0,4} = 2.39 * C^{0,6193}$	(5)	$Op_4 = 0.81 * C^{0.3125}$	(10)
$Inv_{0,5} = 1.58 * C^{0.8238}$	(6)	$Op_5 = 0.30 * C^{0.6379}$	(11)

In conclusion, it is shown a graph in which it is possible to appreciate the qualitatively different trend of CapEx vs. unit price and capacity for the sake of completeness. The results are shown in Figure 22.

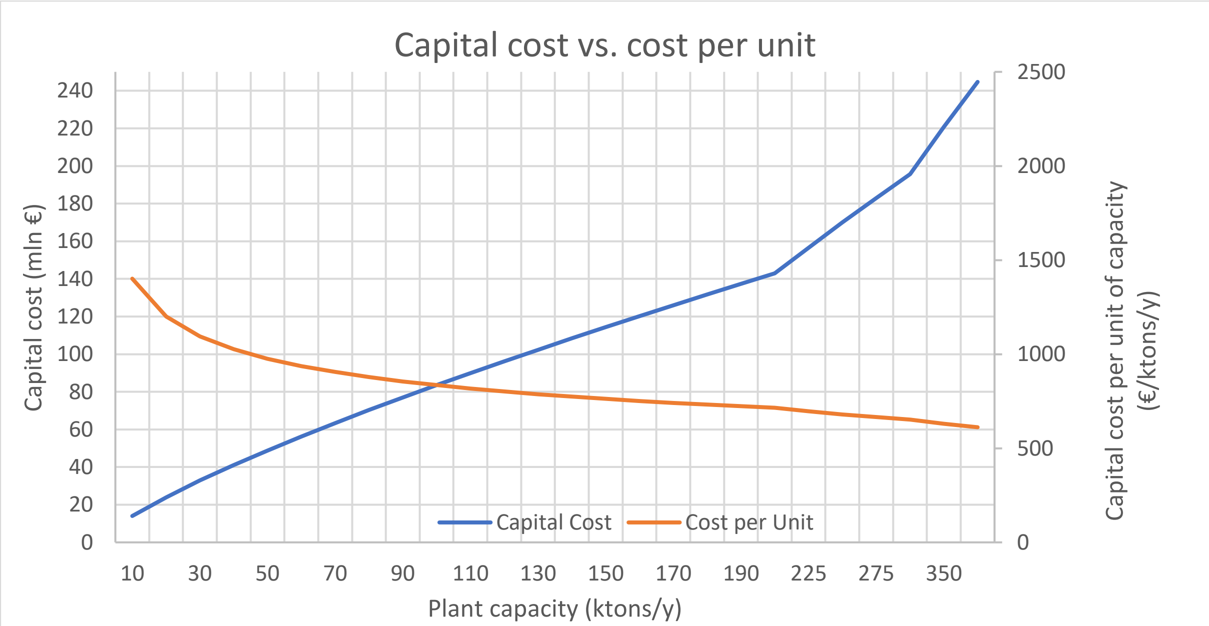

Figure 22 - WtE investment cost vs. cost per unit of capacity

6.6. Cash inflows

6.6.1. Introduction

The upgrade of the power plant will have a double effect on the balance of the facility. So far, low sulfur lignite has been imported from Poland; the price for the purchase and the transportation of the solid fossil fuel are unknown, but it is possible to assume that they are dramatically affecting the current OpEx of the plant. As of now, heat is sold to the DH and a small amount of electricity to the national grid. Therefore, the only relevant revenue derives from the selling of the heat, with the fuel affecting in negative the economic performances. Switching to the WtE type will dramatically overturn this issue.

6.6.2. Gate fee

For nonrecyclable plastic, like for MSW, the producer pays the treatment facility in order to get rid of the waste. This is called a **gate fee**, namely money to be paid at the gate to the incinerator.

It has not been easy finding values in literature, as many factors can influence this tax, and it can vary according to the Country, the type of waste, the type of treatment, and so forth.

Moreover, only the most reliable sources of which the quality was considered significant have been selected, and the values are included in Table 12.

Table 12 - Values of gate fees found

#	Original Price/ton	CZK
1	87 £ [60]	2 610
2	98.5 £ [61]	2 955
3	83 € [62]	2 241
4	70-100 € [63]	2 295

The conversion rate used to switch from foreign currency to CZK is (Google Currency Converter Tool) up to date October 2020:

1 £ ≈ 30 CZK

1 € ≈ 27 CZK

It should be pointed out that gate fees are very floating and variable according to the location, the type of treatment, and the producers. Usually, landfill gate fees are lower than WtE gate fees, but in that case, a further tax is charged to the landfill operator. In this case, no further takes will be charged to the plant operator, as a valuable treatment is intended for the waste.

It is also beneficial to report that all of the gate fees listed in Table 12 are slightly higher than the amount identified by the company, which cannot be spread for reasons of reservations. In any case, the gate fee will not only open one more cash flow, eliminating the bulky purchase of lignite, but we will see that it will be the most significant in-flow channel of the facility.

6.6.3. Energy

6.6.3.1. Heat

A high pressure (HP) boiler will provide space and hot water heating through the DH system. So far, heat supply represented the only channel of revenue from this plant, therefore the price indicated by the company is highly reliable. However, the company has strictly required not to spread this information; indeed, an investigation has been required in order to confirm the expected price. Some available online sources have been consulted [64] [65] [66], and the unit price for heat to be sold to the district heating fluctuates between 17:23 €/GJ. Therefore, a value of **20 €/GJ**, corresponding to **540 CZK/GJ,** will be utilized in this thesis project. This value is absolutely in line with the expectation unit price of the company.

6.6.3.2. Electricity

When electricity is purchased by the local electricity trader from the generator, the so-called electricity wholesale price is the reference for the cost. Usually, the Levelized Cost of Electricity (LCOE) is estimated according to the primary source of energy, the type of generation, transmission and distribution fees, losses, and taxes [56]. In this case, a specific estimation of the LCOE is considered to be out of the scope of this project. The reason is that, as in the case of the unit price for heat, a starting value was provided by the company, with the requirement of an inquiry to be confirmed or denied. The sources investigated [67] [68] have provided a unit price of 39:41 €/MWh_{el}. In particular, according to ICIS [69], this price is expected to rise until 60 €/MWh_{el} in 2030. For coherence with the economics calculations and to keep the wholesale price as indicated by the company, a value of **40 €/MWh_{el}** will be utilized in this report.

6.7. CapEx and OpEx

In section 5.1 it has been elaborated a series of equations for predicting the financial expenses of the project realization. It was shown that by increasing the size of a WtE power plant, the cost per unit of ton installed decrease (Figure 22). A typical breakdown for the capital costs of build up a WtE plant is listed in Table 13. The third column of Table 13 reflects the expectations of the author about how every single category can change according to the assumptions and the proposals of this project. Combustion equipment and FGC system are predicted to take a major percentage of the CapEx, which will be compensated by cancelling the costs for approvals, acquisition of land and other expenditures related to the last row. It is reminded that the constraints related to the aspects contained in the last row of have already been solved earlier in the project timeline.

Table 13 - Typical cost build-up of WtE plants [36] and expectations

Component	% of CapEx	% expected
Combustion Equipment	40	40
Power Generation equipment	10	10
Flue Gas Cleaning System	15	25
Building and civil works	25	25
Others (permission, grid connection, site purchasing, etc.)	10	0

It is therefore reminded that the beginning of this thesis project takes place in a stage when the upgrading of the plant already took the direction of incineration, and that decision derived from obtaining the initial authorization of building also in the area surrounding the existing plant. Table 14 summarizes the OpEx for a power plant. These are considered to be in line with the predictions of the work of this project.

Table 14 - Typical operational costs of WtE plants [36]

Activity	% OpEx
Labour and administration	30
Maintenance	30
Utilities and supplies	20
Residues management and disposals	20

Therefore, CapEx and OpEx have been calculated according to the equations of Table 11, and the results are shown in Figure 23. These values will be used for the financial analysis in the next section.

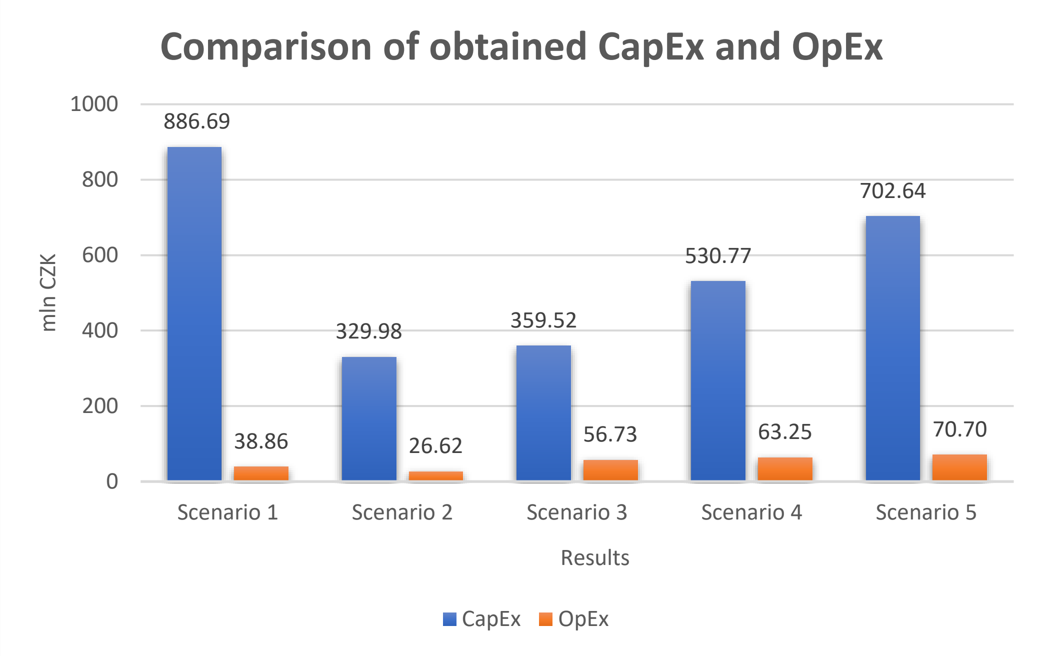

Figure 23 - Obtained values of CapEx and OpEx

6.8. Expected revenue

Table 15 summarizes the estimation of revenue calculated in this section. Results are shown in € and CZK, for a major comprehensibility. The last column of Table 15 contains the expected annual revenue from each channel, calculated by multiplying the expected amount of energy sold (6.4) by the unit price of it (6.6.3). Table 16 contains the total annual revenue estimated, calculated according to the gate fees found in the literature. The calculations are based on an estimated lifespan of 30 years and 8 000 operational hours per year [58] [35] [36].

Table 15 - Expected annual revenue from the plant's operations

Gate fee	1	CZK/ton	2 610	78.3	mln CZK
		€/ton	96.57	2.89	mln €
	2	CZK/ton	2 955	88.65	mln CZK
		€/ton	109.335	3.28	mln €
	3	CZK/ton	2 241	67.23	mln CZK
		€/ton	83	2.49	mln €
	4	CZK/ton	2 295	68.85	mln CZK
		€/ton	85	2.55	mln €
Heat		CZK/GJ	540	51.3	mln CZK
		€/GJ	20	1.9	mln €

ETSEIB

Electricity		CZK/MWh	1 080	19.23 mln CZK
		€/MWh	40	0.7 mln €

Table 16 - Variation of total annual revenue with respect to the gate fee

Gate fee #1	176.85	mln CZK
	6.55	mln €
Gate fee #2	187.20	mln CZK
	6.93	mln €
Gate fee #3	165.78	mln CZK
	6.14	mln €
Gate fee #4	167.40	mln CZK
	6.20	mln €

6.9. NPV and IRR

NPV and IRR have been presented in 5.2. In this section, the methodology for their calculation is explained, together with the related application on Microsoft Excel spreadsheet. First of all, the economic inputs are necessary to assess expenditures and incomes. For the expenditures, namely, the costs related to the investment and operational and maintenance, 5 different scenarios are proposed, according to the equations summarized in Table 11 and the results shown in Figure 23. It is worth to remind that those five equations for both CapEx and OpEx derive each one from the same source, therefore there are applicable one by one to create five different scenarios of cash outflow. For what the cash inflow concerns, the expected revenue derived by the energy sales is the same for all of the scenarios, as estimated in 6.8. The situation is different for the gate fees, as they represent the most profitable channel of revenue, and for this reason, each scenario has been split into 4 sub-scenarios with respect to each revenue by gate fee estimated. Finally, an interest rate of 4.5% [56] is considered.

The methodology consists of assessing the investment cost for year 0, and the expected revenue compensates operational and maintenance costs from year 1. Present Value (PV) cash inflow and outflow are calculating according to the equation:

$$PV_t = \frac{\left(p_{en,t} - C_{var,t}\right) \cdot Q_t}{(i+1)^t}$$

Where $p_{en,t} \cdot Q_t$ is the cash inflow for the year t, and $C_{var,t} \cdot Q_t$ the cash outflow. Afterward, the cumulative cash inflow and outflows are calculated with Excel (Running Total Function), and cumulative PVs are obtained for both cash inflow and cash outflow. At this point, it is possible to apply the NPV function to the results obtained. The TIR.COST function will provide the IRR. For finding the payback period, it is possible to create a new line with the difference between the total cumulative cash outflow and the total cumulative cash inflow per each year; when that difference provides a positive number, that is assumed to be the first year when some money will be made, and therefore the payback period. An example of the template sheet is provided in appendix A, while the results are summarized below.

Table 17 - Economic evaluation of Scenario 1 with respect to the gate fee

Scenario 1	NPV	IRR	Payback period
Gate Fee #1	907.41 mln CZK	12.01%	11 years
Gate Fee #2	1 076.00 mln CZK	13.26%	10 years
Gate Fee #3	727.09 mln CZK	10.63%	12 years
Gate Fee #4	753.48 mln CZK	10.84%	12 years

Table 18 - Economic evaluation of Scenario 2 with respect to the gate fee

Scenario 2	NPV	IRR	Payback period
Gate Fee #1	1 663.51 mln CZK	37.09%	3 years
Gate Fee #2	1 832.10 mln CZK	40.23%	3 years
Gate Fee #3	1 483.19 mln CZK	33.72%	4 years
Gate Fee #4	1 509.58 mln CZK	34.22%	4 years

Table 19 - Economic evaluation of Scenario 3 with respect to the gate fee

Scenario 3	NPV	IRR	Payback period
Gate Fee #1	1 143.61 mln CZK	25.64%	5 years
Gate Fee #2	1 312.20 mln CZK	28.53%	4 years
Gate Fee #3	963.29 mln CZK	22.54%	6 years
Gate Fee #4	989.67 mln CZK	22.99%	5 years

Table 20 - Economic evaluation of Scenario 4 with respect to the gate fee

Scenario 4	NPV	IRR	Payback period
Gate Fee #1	866.08 mln CZK	15.96%	8 years
Gate Fee #2	1 034.66 mln CZK	17.98%	7 years
Gate Fee #3	685.76 mln CZK	13.78%	9 years
Gate Fee #4	712.15 mln CZK	14.01%	9 years

Table 21 - Economic evaluation of Scenario 5 with respect to the gate fee

Scenario 5	NPV	IRR	Payback period
Gate Fee #1	572.84 mln CZK	10.60%	12 years
Gate Fee #2	741.42 mln CZK	12.22%	11 years
Gate Fee #3	392.52 mln CZK	8.81%	15 years
Gate Fee #4	418.91 mln CZK	9.08%	14 years

Taking into account the results obtained, some discrepancies are observed. First of all, scenarios 2 and 3 will be discarded from further analysis. This is because, despite the results derives from an accurate method but with inputs of which the origin is aleatory and uncertain, some discrepancies with reliable results were expected. Usually, the IRR for projects like this range from 10% to 20%, and the payback period is estimated in not less than 7-8 years. It was confirmed by the company owners' and therefore, scenarios 1, 4, and 5 will be considered from now on for further engineering economics.

6.10. Sensitivity analysis

In this section, a sensitivity analysis will be performed. The objective is to show which factor will have more influence on the NPV of the project when it varies from $\pm$10%. The inputs that will be considered for this economical sensitivity analysis are the ones estimated previously in sections 4.1, 6.6.2, 6.6.3, 6.7, namely:

- **LHV** = 21.36 MJ/KG
- **Gate fee**
- **Wholesale electricity price** = 1080 CZK/MWh
- **Heat unit price** = 540 CZK/GJ

- **CapEx** (for scenario 1, 4, and 5)
- **OpEx** (for scenario 1, 4, and 5)

About the gate fee, a different methodology is applied since four different specific values have already been found in the literature. Therefore, it has been decided to apply the variation of $\pm$10% to the arithmetic mean (GF_m) of those, and the obtained values stay within the minimum and the maximum of the gate fee values presented in 6.6.2 according to the values listed in Table 22:

Table 22 - Recalculation of the gate fee for the sensitivity analysis

Originals		Recalculated	
min (#3)	2 241 CZK/ton	$GF_m \cdot 0.9$	2 273 CZK/ton
		GF_m	2 525 CZK/ton
MAX (#2)	2 955 CZK/ton	$GF_m \cdot 1.1$	2 778 CZK/ton

The results of the sensitivity analysis carried out for scenarios 1, 4, and 5, with a variation of the variables of +10%, have been elaborated using MS Excel. The tornado plots in Figure 24, Figure 25, and Figure 26 summarize the outcomes for these three scenarios. A first observation is that the proportions with the variation of the NPVs in the different scenarios are the same for each sensitivity analysis. This is due to the fact that the variable inputs are kept constant; with the exception of CapEx and OpEx, as their input values are not linear for the scenarios considered, and, in fact, their influence is not proportional, like the other variables. In particular, OpEx is affects most on the NPV in both scenarios 4 and 5, while in scenario 1, CapEx is the economic parameter that influences most the profitability of the project.

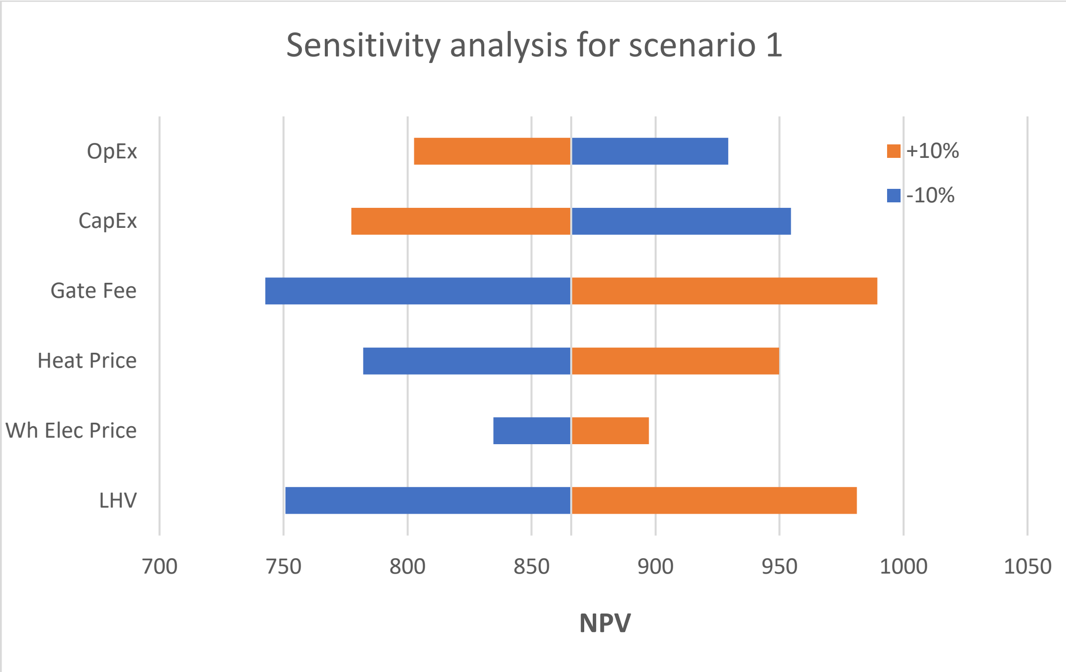

Figure 24 - Sensitivity analysis for scenario 1

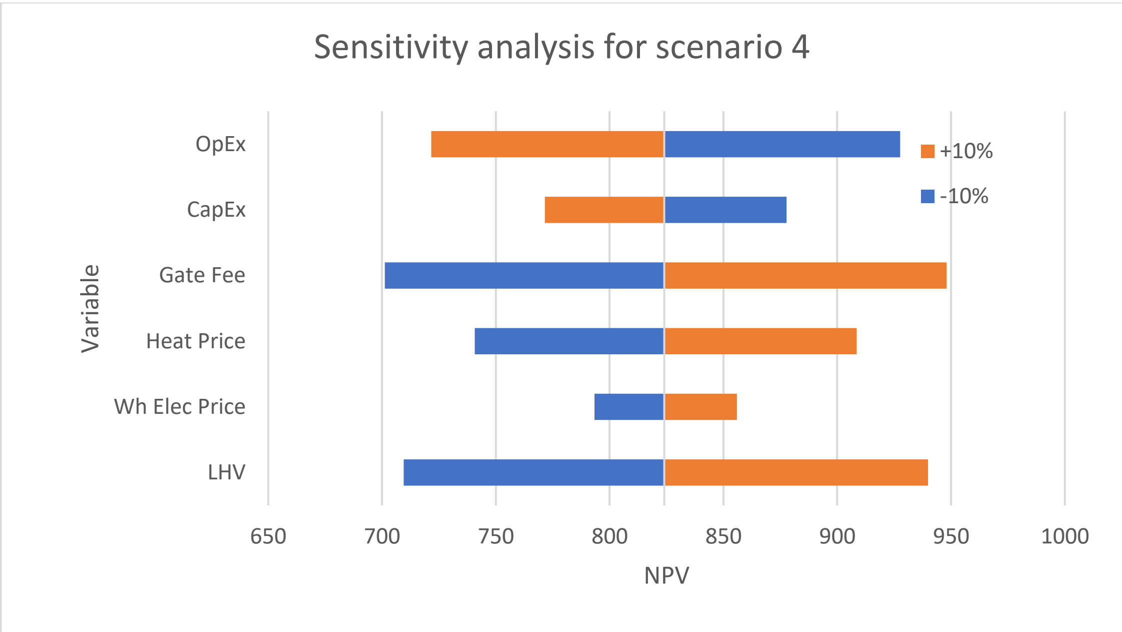

Figure 25 - Sensitivity analysis for scenario 4

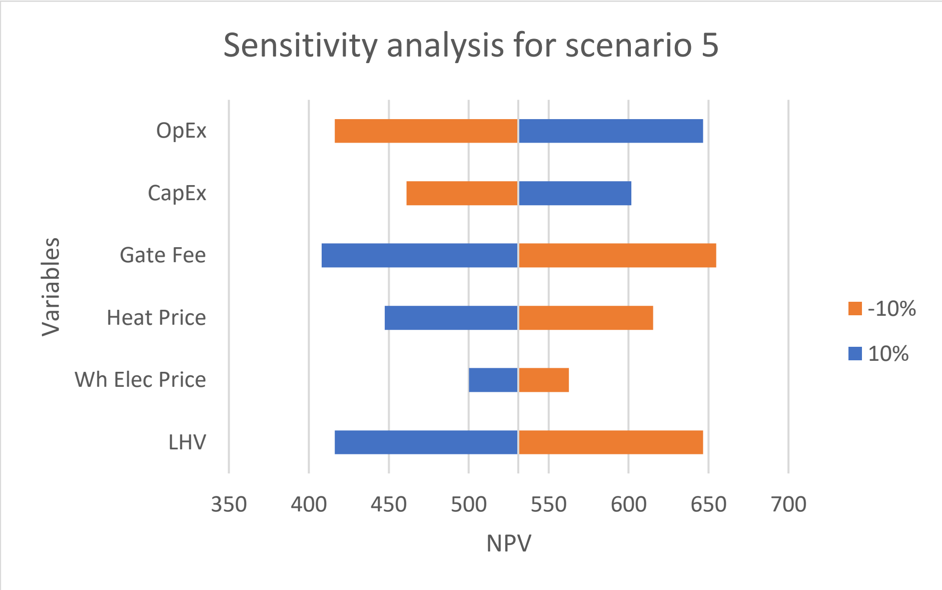

Figure 26 - Sensitivity analysis for scenario 5

6.10.1. Discussion

It is possible to appreciate from the tornado graphs (Figures 24, 25, and 26) that LHV and gate fee are the variables that would affect the most the NPV. However, this result should be contextualized in terms of the variation of LHV will influence heat and electricity production. The power plant is connected to the local power system, therefore, every excess of electricity that will not be used to run the operations of the plant will be sold back to the grid, generating revenue. As for heat production concerns, there is, first of all, to consider losses in the grid, even though, in this case, they can be assumed to be marginal (only 16.93 km of the pipeline). Indeed, the main reason for getting such different values is that most of the heat produced will be recovered and cooled, and only a small part of it will be sold, as it represents an amount much higher than the current needs so that it cannot be sold to any third party. Therefore, the LHV cannot be considered the most critical parameter, at least from an economic point of view. As expected, the Gate Fee is the cash flow channel of which the variation will influence the NPV more than any other else. The price for the Gate Fee assumed in this work derive from the consultation of scientific sources available in literatire and might not be entirely reliable, as the local context in the Czech Republic could impose a cheaper or higher cost. In the future, further research and comparison with specialized institutions should be arranged, as well as concrete agreements with the PW producers with the aim to propose a gate fee that will be beneficial from the two parts. An optimal agreement on the value of the gate fee will lead to a double-win for the owner of the plant, the waste generators, the environment, and the local community. In conclusion, due also to its randomness to define a specific value, the study assesses that the gate fee is the most delicate parameters for a project like this.

6.11. Cleaning system

6.11.1. Techniques for abatement of pollutants and flue gas cleaning

In this section, it will be proposed a set of installations to comply with the emission limit standards and to reduce at minimum the environmental impact related to PW incineration.
First, there will be presented technologies to boost the overall performance of an incineration plant that are valid in every thermal power plant working process.
Afterward, it will be selected among the existing technologies, the ones that are suitable in order to mitigate the negative effect in the atmosphere of gas emissions from burning plastics. The prevision for the most harmful substances by burning plastics derives from a literature review of the topic. The techniques proposed have been thoroughly investigated in the literature, and they are reflected in the Commission Implementing Decision (EU) 2019/2010 about the conclusion of best available techniques for waste incineration.
The high energy content of PW is attractive for conversion to energy applications; however, it is due to the presence of hydrocarbon in the composition of the polymers [70]. Adequate APC by the implementation of advanced FGC System is a must in WtE power plants.
The principal substances generated from the incineration of PW are [48] [70] [28] [71] [72]: Particulate (**dust**), **dioxins** and **furans**, **NOx**, **CO**, Heavy Metals - mainly Mercury (**Hg**), Cadmium (**Cd**), Lead (**Pb**).

6.11.1.1. Primary Techniques

Before mentioning how APC and FGC have to be selected, it is worthy to recall some primary techniques that allow a reduction of NOx formation already when the combustion is occurring.

- **Flue gas recirculation**: by letting the flue gas recirculate, the fresh air needed for the combustion will lower, with consequent reduction of the excess air rate. Therefore, less air is needed for the combustion, and less Nitrogen from the air will be injected [36]. This will mitigate the formation of NOx in the flue gas composition. [36] This technique also boosts the effectiveness of the Flue Gas Cleaning systems, as less flue gas will have to be treated, with consequent reduction of size and energy consumption of the Air Pollution Control Equipment [50].
- **Advanced combustion control system:** the utilization of a computer-based automatic system for the control will boost the efficiency of the combustion, leading to greater burning of the waste. As a consequence, less air will be needed for the combustion process [36].

6.11.1.2. Secondary Techniques – APC and FGC

- **Dust removal - FABRIC FILTER**

A fabric filter particulate removal is nothing but a series of filter bags (Figure 27) in which the dust gets captured. The flue gas that exits the top of the device is free from dust particles, as they have been deposited outside the bags when the gas had entered them, at the bottom [36]. The fabric filters are found to be the most effective of the particulate removals, namely, cyclones and electrostatic precipitator (ESP), as its cleaning efficiency is the highest, and they have the further advantage of providing a surface for the reactions, avoiding the formation of acid gases. In fact, they should be installed at the back of the downstream of the scrubber.

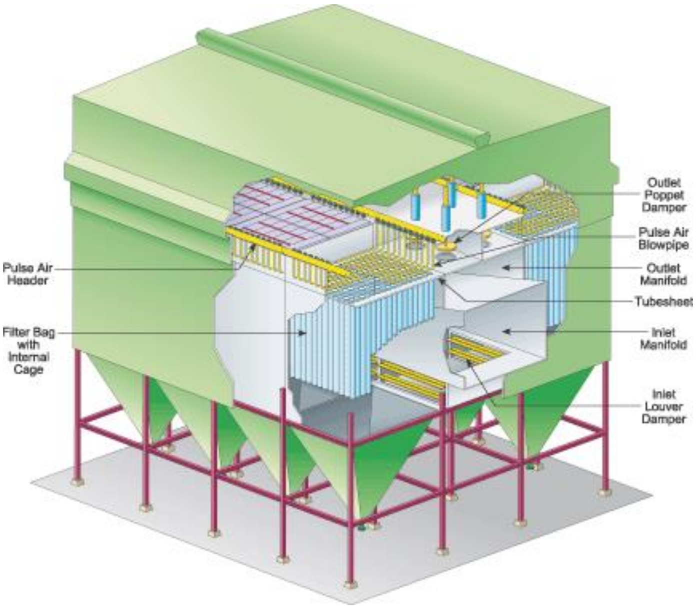

Figure 27 - Typical bag fabric filter [36]

- **Acid gases (HCl, HF, and SOx) removal - DRY SCRUBBER**

The cleaning of acid gases occurs by means of alkaline reagents, which react with the flue gas [30]. Dry scrubbers (Figure 28) are usually used in combination with a fabric filter, that provides the surface where the reaction occurs. This reaction consists of using hydrated lime or sodium carbonate (the former is preferred for the dry process) as a reagent to absorb acid gases [70]. Besides the advantage of being combined with the fabric filter, dry scrubbers produce a dry by-product that is easier to be managed than the liquid by-product from the wet scrubber [36].

Figure 28 - Typical dry scrubber [36]

- **Heavy Metal and dioxin/furan Removal - DRY SORBENT INJECTION**

The technique consists of the injection and dispersion in the flue gas stream of an adsorbent powder [50]. Solid compounds such as volatile heavy metals (mercury, cadmium, lead) and dioxin/furans remaining in the flue gas stream cannot be solved in water. Therefore, their concentration is minimized by injecting activated carbon [36]. This material has an exceptionally high specific surface area and is very effective at adsorbing such compounds. Activated carbon is co-injected in a dry scrubber, and afterward the carbon and adsorbed compounds are captured by the fabric filter [73].

- **De-NOX – SELECTIVE CATALYTIC REACTOR**

Flue gas recirculation as a means to reduce the air supply and reduce the amount of NOx has already been presented previously. One more way could be to inject pure oxygen into the combustion chamber [70]. In any case, these primary techniques are surely useful for NOx control, but they are not enough. Further processes should be applied.
The most popular method is by the application of either urea or ammonia (Figure 29), which will react with the NOx contained in the flue gas to produce pure nitrogen and water [30], trough the reactions:
$4\ NO + 4\ NH_3 + O_2 \rightarrow 4\ N_2 + 6\ H_2O$

$2\ NO_2 + 4\ NH_3 + O_2 \rightarrow 3\ N_2 + 6\ H_2O$

This requires the installation of one more element in the whole APC system, namely a selective reactor [73]. Selective reactors are divided into catalytic (SCR) and non-catalytic (SNCR). The choice of this project SCR. The difference stands in the reaction temperature and the presence or not of a catalyst to boost the reaction at a lower temperature of operation [74] [73] [30]. In this context, the choice falls on the SCR system. SCRs are found to have a higher efficiency of NOx removal than SCNRs. Moreover, thanks to the catalyst, they require lower temperature to work, even though this boost on performance and the manufacture of a catalyst leads to higher investment costs. Usually, SCRs are located at the back-end of the flue gas cleaning system, as the catalyst might be sensitive to other pollutants that need to be previously removed.

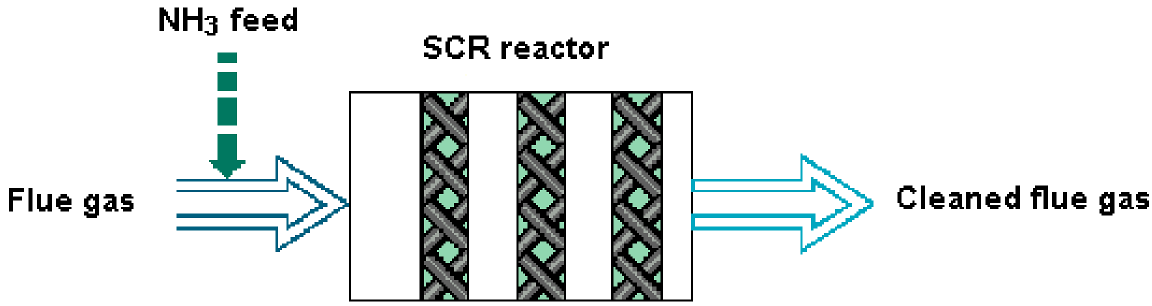

Figure 29 - Selective catalytic reactor working principle [30]

In summary, these are the components selected, on a primary stage, for the gas cleaning and the APC of the WtE power plant object of this work. However, a rearrangement of the technology's selection cannot be excluded. In particular, discussions more likely to arise are in relation to the high capital costs of such a system, as well as about a higher dust efficiency requirement, which would lead to the further addition of a cyclone or an ESP, as it happens in many WtE existing plants [36].

6.11.2. Final Remarks

In this section, the major environmental issues related to the operation of a WtE power plant have been presented. A list of the emission limits set by the EU has been reported. It is beneficial to remind that DIR EU/2010/75 represents a rule of thumb for incineration, but higher (or lower) limits may be required by the State Member or the local entity in charge of giving the authorization. In any case, arising problems related to air quality make the environmental impact the most important factor when designing a power plant. In this thesis work, due to lack of specific data, especially about the costs and the specific composition of the PW treated, it has not been possible to carry out a comprehensive environmental cost-benefit analysis. In any case, the above-mentioned techniques guarantee, most of the time, that the emission limits will be respected. APC equipment proposed in the previous paragraph are the ones that could assure the maximum flue gas cleaning efficiency, and their installations should prescind from economic concerns. Moreover, it should be kept in mind that lately, State Members and European Union are providing subsidies and additional funding to the plant owner, in case of advanced systems proposed [36]. Therefore, the combination proposed in the previous section is assumed to be the most effective both for performances and to apply for funding by the EU. It is worth to mention that all the techniques designed for FGC and APC are reflected in the contents of the BAT guidelines for waste incineration issued by the European Commission [50].

It is beneficial to remind that Art. 24 of Directive 2010/75 EU states that the information about air (and water) emission should be regularly published, and that all this info must be publicly available [49]. This info will be revised, and the emission values shall be expressed as percentage of the related limits indicated in the Directive 2010/75 EU. As an example about how the measured emissions shall be shown openly to the public, the average measured data of the last week of September 2020 of the WtE plant in Acerra (Italy) is reported in Figure 30.

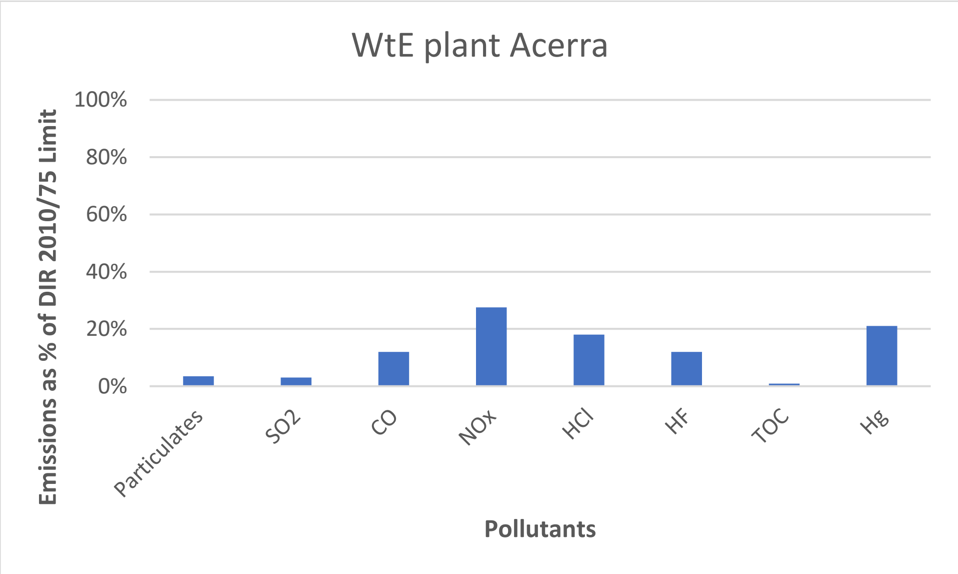

Figure 30 – Average daily measured emission of last week of Sep 2020 of WtE plant of Acerra [75]

7. Conclusions

In this work, the feasibility for the upgrading of a WtE plant has been analysed. According to the methodology and basing on the info collected, in part from consultancy with the company owner of the plant and mostly from literature review, the insights of this work indicate that the project is promising. An operational capacity of 30 000 tons of PW per year has been proposed in order to satisfy the local heat demand and get two important cash inflow channels from selling of electricity and the gate fee. The sensitivity analysis conducted on the three scenarios finally proposed (scenario 1, 4 and 5) showed that the gate fee is the parameter that will affect the most the NPV of the project. In future, meeting with the waste producers and the local authority are necessary in order to assess a specific value of the gate fee per ton of waste generated. This will help the economic analysis to move further, and any modifications can be adjusted. However, the preliminary economic analysis carried out demonstrates the profitability of the project, and, therefore, further assessments can be conducted. In conclusion, from an economic point of view, according to the outcomes of this thesis work the project deserves to move on.
A proper FGC system has been proposed with the aim not only to comply with the current EU legislation, but also to make the plant as more sustainable as possible. The FGC components proposed have already proven, in other plants, to depurate the exhaust flue gas as most efficiently as possible. The proposal of a FGC as designed in this project will help the company to get external funding or financial concessions that will reduce the impact of the capital costs. The upgraded power plant will not have a great impact on the local area, as it will replace an existing one, and, indeed, will be an effective way to manage the amount of waste regularly generated by the factories around. Some aspects are still to be defined, in particular, from a technical point of view, but this will come in the next stage of the project.

7.1. Further proposals

In this project, many technical issues have been considered out of scope due to the very early stage of the project timeline. Anyway, an effective way to boost the plant performance could be splitting the combustion component in two or three separated grates, called line of incineration. This method will allow a major homogeneity of the waste burnt and an easier combustion control [30], with consequent improving on the combustion performances and on the quality of the flue gas. Moreover, it will decrease the issues related to the maintenance or eventual failure of the pant, as one line per time can be shut down while the others are working. This will allow a scheduled alternated maintenance of the combustion system with a reduction of the issues related to shut down the plant, and a possible increase of the operating hours.

Secondly, one of the main concern about the installation of a WtE plant is the common

believing that it will emit dirty gases in the air causing toxic pollution (not in my backyard!). Nevertheless, as of now, the existing technologies have demonstrated that the flue gas exiting the chimney from a WtE installation is clean and treated, and it definitely complies with the emission limits imposed by the authorities, the social acceptance of a waste management facility is often rejected by the community [76]. In this perspective, a sponsoring campaign is necessary to raise public awareness that PWM is a terrible concern globally, and that WtE can be an effective solution to deal with that.
Anyway, one more possible way to increase the popularity of the plant is by embellishing the external from an architectural point of view. This is the case, for example, of the Maishima incineration plant in Osaka, Japan.

Figure 31 - The Maishima incineration plant in Osaka [36]

One last proposal for enhancing the overall effectiveness of the project is related to the external fuel supply. Since NG is needed as external supply for the combustion of the fuel, and the plant is not connected to the gas grid, two NG tank are predicted to be installed near the plant. The effect on the operational costs has been considered in this work and the profitability is still promising. However, that would represent a further cash outflow channel, and the exploitation of a limited energy fuel like the NG. A possible solution to deal with this issue could be to extend the scope of the new plant with the installation of a gasifier. Gasification + incineration examples have not been found in literature, but the combination of the two could be an effective way to make the plant independent on NG external purchasing. Moreover, it would create a unique layout that can represent a pilot for further similar projects. the main obstacle to this proposal is the cheap price of NG and the consequent increase on CapEx that can make the owner go in the direction of an incinerator only. However, the author states that a preliminary analysis for this combination could be interesting.

8. Acknowledgements

This Thesis's Project has been realized within the Innoenergy Master's School Program SELECT – Environomical Pathways for Sustainable Energy Systems. The first thanks go to all the Innoenergy staff, professors and students, for having guided me and shared the experiences in this amazing two-year journey.
A special thanks to Prof. César Alberto Valderrama for the dedicated academic supervising of this thesis' project, and for having been always present for any further help in giving info, problem solving and motivating.

Last but not least, thanks to Ing. Zuzana Hernandez, the technical supervisor of this work , for having given me the opportunity of carrying out this internship in MVV Energie Czech a.s., a company that demonstrate to have futuristic approach and global vision for future projects in the field of sustainable energy. Thanks also to the Director Branislav Posuch for having accepted this collaboration with the student author of this thesis.

ETSEIB

9. References

[1] O. Horodytska, A. Cabanes e A. Fullana, «Plastic Waste Management: Current Status and Weaknesses,» in *The Handbook of Environmental Chemistry*, Springer, Berlin, Heidelberg, 2020.

[2] PlasticsEurope, "Plastics – the Facts 2018," 11 2018. [Online]. Available: https://www.plasticseurope.org/application/files/6315/4510/9658/Plastics_the_facts_2018_AF_web.pdf. [Accessed 15 March 2020].

[3] L. Lebreton and A. Andrady, "Future scenarios of global plastic waste generation and disposal," *Palgrave Communications,* vol. 5, no. 6, pp. 1-11, 2019.

[4] "The Nobel Prize in Chemistry 1953," NobelPrize.org, 2020. [Online]. Available: https://www.nobelprize.org/prizes/chemistry/1953/staudinger/facts/.

[5] R. Crawford, Plastics Engineering, III ed., Oxford: Butterworth-Heinmann, 1998.

[6] "Plastics by the Numbers," 2020. [Online]. Available: https://learn.eartheasy.com/articles/plastics-by-the-numbers/. [Accessed 19 March 2020].

[7] M. Johnson-Groh, "Below the Great Pacific Garbage Patch: More Garbage," *Eos,* vol. 101, 2020.

[8] A. Guina, "An Explorer Just Made the Deepest Ever Manned Sea Dive — and He Found a Plastic Bag," *Time,* May 2019.

[9] Green World Warriors, "Whale shark eating plastic in asia - Green World Warriors," 2020. [Online]. Available: https://greenworldwarriors.com/2018/11/21/whale-shark-eating-plastic-in-asia/.

[10] EASAC, "Packaging plastics in the circular economy," German National Academy of Sciences Leopoldina 2020, Jägerberg, 2020.

[11] A. Villanueva and P. Eder, "End-of-waste criteria for waste plastic for conversion," Publications Office of the European Union, Luxembourg, 2014.

[12] European Commission, "Waste prevention and management - Environment - European Commission," [Online]. Available: https://ec.europa.eu/environment/green-growth/waste-prevention-and-management/index_en.htm.

[13] Plastic ZERO Public Private Cooperations for avoiding plastics as a waste, "Action 4.1: Market conditions for plastic recycling," LIFE10 ENV/DK/098, 2013.

[14] A. Mirjalili, B. Dong, P. Pena, C. S. Ozkan and M. Ozkan, "Upcycling of polyethylene terephthalate plastic waste to microporous carbon structure for energy storage," *Energy Storage,* no. e201, 02 August 2020.

[15] T. M. Letcher, "Introduction to plastic waste and recycling," in *Plastic Waste and Recycling*, Amsterdam, Elsevier Inc, 2020, pp. 3-11.

[16] M. L. Mastellone, "A feasibility assessment of an integrated plastic waste system adopting," *Resources, Conservation & Recycling: X,* vol. 4, p. 100017, 2019.

[17] R. Geyer, J. R. Jambeck and K. L. Law, "Production, use, and fate of all plastics ever made," *Science Advances,* vol. 3, no. 7, 2017.

[18] "Plastic Material Recycling Information on Plastixportal," 2020. [Online]. Available: https://www.plastixportal.co.za/recycling_of_plastics.html. [Accessed April 2020].

[19] R. Geyer, "Production, use, and fate of synthetic polymers," in *Plastic Waste and Recycling*, Elsevier, 2020, pp. 13-30.

[20] L. Miller, K. Soulliere, S. Sawyer-Beaulieu, S. Tseng and E. Tam, "Challenges and Alternatives to Plastics Recycling in the Automotive Sector," *Materials,* vol. 7, no. 8, pp. 5883-5902, 2014.

[21] J. W. McAuley, "Global Sustainability and Key Needs in Future Automotive Design," *Environmental Science & Technology,* vol. 37, no. 23, pp. 5414-5416, 2003.

[22] SPI - The Plastics Industry Trade Association, "Automotive Recycling – Devalued is now Revalued.," 2016. [Online]. Available: https://www.plasticsindustry.org/sites/default/files/2016-03256-SPI-PMW-Auto-Recycle-web.pdf. [Accessed June 2020].

[23] "13 High Performance Plastics Used in the Automotive Industry - Craftech Industries - High-Performance Plastics," [Online]. Available: https://www.craftechind.com/13-high-performance-plastics-used-in-the-automotive-industry/.

[24] EuRIC - The European Recycling Industries' Confederation, "EuRIC call for recycled plastic content in cars," 2020.

[25] M. Riedl, "Top 7 Thermoplastics in Automotive Manufacturing," 2020. [Online]. Available: https://ta-netzsch.com/top-7-thermoplastics-in-automotive-manufacturing.

[26] P. Groewegen and F. den Hond, “Product waste in the automotive industry: technology and environmental management,” *Business Strategy and the Environment,* vol. 2, no. 1, pp. 1-12, 1993.

[27] A. Doyle, “Volvo Cars aims for 25% recycled plastics in cars from 2025,” Reuters, 18 June 2018. [Online]. Available: https://www.reuters.com/article/us-volvo-plastics/volvo-sets-goal-of-25-percent-recycled-plastics-in-cars-from-2025-idUSKBN1JE07I.

[28] M. Modesti, *Incenerimento con recupero di energia: TERMOVALORIZZAZIONE,* P. M. Modesti, Ed., Università di Padova, 2018-2019.

[29] M. Chandran, S. Tamilkolundu and C. Murugesan, “Conversion of Plastic Waste to Fuel,” in *Plastic Waste and Recycling*, Amsterdam, Academic Press, 2020, pp. 385-399.

[30] F. Neuwahl, G. Cusano, J. Gomez Benavides and S. R. S. Holbrook, “Best Available Techniques (BAT) for Waste Incineration,” Publications Office of the European Union, Luxembourg, 2019.

[31] E. Haghi and F. Tehrani Bazdidi, “Techno-economic assessment of municipal solid waste incineration plant-case study of Tehran, Iran,” in *Proceedings of The First Sustainable Development conference of Engineering Systems in Energy, water and Environment*, Tehran, 2015.

[32] Waste to Energy Systems, “Why is Gasification better than Incineration? - Waste to Energy Systems,” [Online]. Available: https://www.wastetoenergysystems.com/why-is-gasification-better-than-incineration/.

[33] Gershman and Brickner, “Gasification of Non-Recycled Plastics From Municipal Solid Waste In the United States,” GBB Solid Waste Management Consultants, McLean VA, USA, 2013.

[34] M. Pohjakallio and T. Vuorinen, “Chemical routes for recycling - dissolving, catalytic, and thermochemical technologies,” in *Plastic Waste and Recycling*, Academic Press, 2020, pp. 369-379.

[35] D. Mutz, D. Hengevoss, C. Hugi and T. Gross, “Waste-to-Energy Options in Municipal Solid Waste Management A Guide for Decision Makers in Developing and Emerging Countries,” Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, Bonn, 2017.

[36] WSP, “Review of State-of-the-Art Waste-to-Energy Technologies,” London, 2013.

[37] J. Wróblewska-Krepsztul and T. Rydzkowski, “Pyrolysis and incineration in polymer waste management system,” *Journal of Mechanical and Energy Engineering,* vol. 3, no. 4, pp. 337-342, 2020.

[38] Q. M. Oasmaa A, H. Pihkola, I. Deviatkin, J. Mannila, A. Tenhunen, H. Minkkinen, P. M and J. Laine-Ylijoki, "Pyrolysis of Plastic Waste: Opportunities and Challenges," *Journal of Analytical and Applied Pyrolysis,* 2020.

[39] Confederation of European Waste-to-Energy Plants, "What is wase to energy?," CEWEP, 2020. [Online]. Available: https://www.cewep.eu/what-is-waste-to-energy/.

[40] U. Arena and F. D. G. F. Ardolino, "A life cycle assessment of environmental performances of two combustion- and gasification-based waste-to-energy technologies," *Waste Management,* no. 41, pp. 60-74, 2015.

[41] Royal HaskoningDHV, "Municipal Solid Waste Diversion and Beneficiation Opportunities at Nelson Mnadela Bay Municipality," KwaZulu Natal (South Africa), 2014.

[42] A. Demetrious and E. Crossin, "Life cycle assessment of paper and plastic packaging waste in landfill, incineration, and gasification-pyrolysis," *Journal of Material Cycles and Waste Management,* vol. 21, no. 4, pp. 850-860, 2019.

[43] D.-S. Kourkoumpas, S. Karellas, S. Kouloumoundras, G. Koufodimos, P. Grammelis and E. Kakaras, "Comparison of Waste-to-Energy Processes by Means of Life Cycle Analysis Principles regarding the Global Warming Potential Impact: Applied Case Studies in Greece, France and Germany," *Waste and Biomass Valorization,* vol. 6, no. 4, pp. 605-621, 2015.

[44] A. Raja, A. P. Srivastava and M. Dwivedi, Power Plant Engineering, New Delhi: New Age International (P) Ltd., Publishers, 2006.

[45] M. Ioelovich, "Energy Potential of Natural, Synthetic Polymers and Waste Materials - A Review," *Academic Journal of Polymer Science,* vol. 1, no. 1, 2018.

[46] D. A. Tsiamis and C. M. J., "Determining Accurate Heating Values of Non-Recycled Plastics (NRP)," Earth Engineering Center | City College, New York City, 2016.

[47] R. Zevenhoven, "Treatment and disposal of polyurethane wastes: options for recovery and recycling," Helsinki University of Technology, 2004.

[48] S. Al-Salem, "Energy Production from Plastic Solid Waste (PSW)," in *Plastics to Energy*, William Andrew, 2019, pp. 45-64.

[49] The European Parliament and Council, "DIRECTIVE 2010/75/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 24 November 2010 on industrial emissions (integrated pollution prevention and control)," *Official Journal of theEuropean Union,* pp. 17-119, 17 12 2010.

[50] The European Commission, "COMMISSION IMPLEMENTING DECISION (EU) 2019/2010 of 12 November 2019 establishing the best available techniques (BAT) conclusions, under Directive 2010/75/EU of the European Parliament and of the Council, for waste incineration," *Official Journal of the European Union,* pp. 55-92, 2019.

[51] T. E. P. a. Council, "DIRECTIVE 2010/75/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 24 November 2010 on industrial emissions (integrated pollution prevention and control)," *Official Journal of theEuropean Union,* pp. 17-119, 17 12 2010.

[52] U.S. Energy Information Administration, "Generating Unit Annual Capital and Life Extension Costs Analysis," EIA, 2019.

[53] MWH, "Sustainable Energy Handbook - Simplified Financial Model," Sustainable Energy for All.

[54] J.-J. Dohogne, Waste Management Costs & Financing, Horizon2020, 2014.

[55] P. Chaliki, C. S. Psomopoulos and N. J. Themelis, "WTE plants installed in European cities: a review of success stories," *Management of Environmental Quality: An International Journal,* vol. 27, no. 5, pp. 606-620, 2016.

[56] P. Zweifel, A. Praktiknjo and G. Erdmann, Energy Economics, Berlin, Heidelberg: Springer, 2017.

[57] S. Kumar and S. Ankaram, "Wate-to-Energy Model/Tool Presentaion," in *Current Developments in Biotechnology and Bioengineering*, Elsevier, 2019, pp. 239-259.

[58] P. Breeze, "Traditional Waste Combustion Technologies," in *Energy from Waste*, Academic Press, 2018, pp. 49-64.

[59] L. R. Radovic and H. H. Schobert, Energy and fuels in society, New York: McGraw-Hill, 1997.

[60] "WRAP Gate Fees 2018 Report Map | WRAP UK," 2020. [Online]. Available: http://www.wrap.org.uk/collections-and-reprocessing/recovered-materials-markets/reports/gate-fee-reports/2018-report-map.

[61] "Landfill tax and landfill rates, RDF and energy from waste," 2020. [Online]. Available: https://www.letsrecycle.com/prices/efw-landfill-rdf-2/.

[62] D. Hogg, "Costs for municipal waste management in the EU," Eunomia Research & Consulting, Bristol, 2002.

[63] S. Speck, The use of economic instruments in Nordic and Baltic environmental policy, 2001-2005, Copenhagen: Nordic Council of Ministers, 2006.

[64] Gronergy, “The competitiveness of district heating compared to individual heating,” Green Energy Association, 2018.

[65] ETSAP - Energy Technology Systems Analysis Programme, “District Heating,” IEA ETSAP, 2013.

[66] S. Werner, “European District Heating Price Series,” Energyforsk AB, 2016.

[67] OTE, “Key Information for wholesale electricity price,” Prague, 2019.

[68] E. Mazegue Pavelková and I. Živělová, “Pricing Electric Power in the Czech Republic and in selected Countries,” *ACTA UNIVERSITATIS AGRICULTURAE ET SILVICULTURAE MENDELIANAE BRUNENSIS,* vol. 64, no. 114, pp. 1001-1011, 2016.

[69] ICIS Editorial, “ICIS POWER HORIZON: Czech and Slovak power prices will move in accord through 2030,” [Online]. Available: https://www.icis.com/explore/resources/news/2019/07/01/10385901/icis-power-horizon-czech-and-slovak-power-prices-will-move-in-accord-through-2030. [Accessed October 2020].

[70] S. Al-Salem, P. Lettieri and J. Baeyens, “The valorization of plastic solid waste (PSW) by primary to quaternary routes: From re-use to enery and chemicals,” *Progress in Energy and Combustion Sciences,* pp. 104-126, 2009.

[71] A. Nagy and R. Kuti, “The Environmental Impact of Plastic Waste Incineration,” *AARMS,* vol. 15, no. 3, pp. 231-237, 2016.

[72] R. Verma, K. S. Vinoda, M. Papireddy and A. N. Gowda, “Toxic Pollutants from Plastic Waste - A review,” *Procedia Environmental Sciences,* no. 35, pp. 701-708, 2016.

[73] M. Jurczyk, M. Mikus and K. Dziedzic, “FLUE GAS CLEANING IN MUNICIPAL WASTE-TO-ENERGY PLANTS – PART I,” ASSOCIATION INFRASTRUCTURE AND ECOLOGY OF RURAL AREAS, Krakow, 2017.

[74] S. L. P. B. J. Al-Salem, “Recycling and recovery routes of plastic solid waste (PSW): A review,” *Waste Management,* no. 29, pp. 2625-2643, 2009.

[75] a2a, “Qualità dell'aria - valori medi giornalieri,” [Online]. Available: https://www.a2a.eu/it/sostenibilit%C3%A0/acerra-emissioni.

[76] ISWA - The International Solid Waste Association, “The NIMBY "Not In My Back Yard" Reader,” ISWA Working Group on Communication and Social Issues, 2004.

APPENDIX I – Excel Sheets Example

	CAPEX					OPEX					
	Capacity	30	MLN €	mln CZK		Capacity	30	MLN €	mln CZK		
1	2.3507	0.7753	32.84046638	886.6925923	1	0.0774	0.8594	1.439392	38.86357		
2	0.8548	0.7821	12.22140248	329.977867	2	0.1215	0.6156	0.986035	26.62293		
3	1.0356	0.7509	13.31565063	359.5225671	3	0.2757	0.5971	2.100999	56.72698		
4	2.392	0.6193	19.6581375	530.7697124	4	0.8093	0.3125	2.342664	63.25192		
5	1.5838	0.823	26.02382509	702.6432773	5	0.2991	0.6379	2.618617	70.70267		
	Gate Fee										
1	2610					LHV	21.363				
2	2955					eff_b	0.85				
3	2241					eff_el	0.25				
4	2295										
Gate fee	**2525.25**	CZK/ton		Unit Price Heat		**540**	CZK/GJ	Expected Sales		95332.39	GJ
Cost of capital	**4.50%**			Unit Price elec		**1080**	CZK/MWhe			17802.64	Mwhe
INV_0	**702.64**	mln CZK									
Yearly_OPEX	**70.70**	mln CZK									
Inv_unit		CZK		OP Cap	30	tons/year					
Op_unit		CZK		MAX Cap	30	tons/year					

	LHV	531.422	Wh Elec Price	531.422	Heat Price	531.422	Gate Fee	531.422	CapEx	CapEx	531.422	OpEx	OpEx	531.422
90%	19.2267	**416.2492237**	972	**500.10359**	486	**447.567632**	2272.725	**408.02**	632.379	**632.379**	**601.6863256**	63.632	**63.6324**	**646.5888**
100%	21.36	**531.4219979**	1080	**531.4219979**	540	**531.421998**	2525.25	**531.422**	702.643	**702.643**	**531.4219979**	70.703	**70.703**	**531.422**
110%	23.4993	**646.594772**	1188	**562.7404057**	594	**615.276364**	2777.775	**654.8225**	772.908	**772.908**	**461.1576701**	77.773	**77.773**	**416.2552**

Cash Inflows	**Year 0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Gate Fee	0	75.7575	75.7575	75.7575	75.7575	75.7575	75.7575	75.7575	75.7575	75.7575	75.7575	75.7575	75.7575	75.7575	75.7575	75.7575
Heat	0	51.47948925	51.47948925	51.47948925	51.47949	51.4794893	51.47949	51.47949	51.47949	51.47949	51.47948925	51.47949	51.47949	51.47949	51.47949	51.47949
Electricity	0	19.22685381	19.22685381	19.22685381	19.22685	19.2268538	19.22685	19.22685	19.22685	19.22685	19.22685381	19.22685	19.22685	19.22685	19.22685	19.22685
Total	0	146.4638431	146.4638431	146.4638431	146.4638	146.463843	146.4638	146.4638	146.4638	146.4638	146.4638431	146.4638	146.4638	146.4638	146.4638	146.4638
PV cash flow	0.000	140.157	134.121	128.346	122.819	117.530	112.469	107.626	102.991	98.556	94.312	90.251	86.364	82.645	79.087	75.681
Cumul cash fl	**0.000**	**140.157**	**274.278**	**402.624**	**525.443**	**642.973**	**755.442**	**863.068**	**966.059**	**1064.615**	**1158.927**	**1249.178**	**1335.542**	**1418.188**	**1497.274**	**1572.955**
Costs	**Year 0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
INV_0	702.6432773															
Operational		70.70267177	70.70267177	70.70267177	70.70267	70.7026718	70.70267	70.70267	70.70267	70.70267	70.70267177	70.70267	70.70267	70.70267	70.70267	70.70267
PV cash outflow	702.6432773	67.658	64.745	61.957	59.289	56.735	54.292	51.954	49.717	47.576	45.527	43.567	41.691	39.896	38.178	36.534
Totale parziale	**702.6432773**	**770.301**	**835.046**	**897.002**	**956.291**	**1013.026**	**1067.319**	**1119.273**	**1168.990**	**1216.566**	**1262.094**	**1305.660**	**1347.351**	**1387.247**	**1425.424**	**1461.958**
	Manual	Excel														
NPV	531.422	531.42														
IRR	10.197%															
ROI	28.659%	28.659%														
	-702.6432773	75.76117129	75.76117129	75.76117129	75.76117	75.7611713	75.76117	75.76117	75.76117	75.76117	75.76117129	75.76117	75.76117	75.76117	75.76117	75.76117
Payback Period	-702.643	-630.145	-560.768	-494.379	-430.848	-370.053	-311.877	-256.205	-202.931	-151.951	-103.166	-56.483	-11.809	30.941	71.850	110.997

Cash Inflows	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
Gate Fee	75.7575	75.7575	75.7575	75.7575	75.7575	75.7575	75.7575	75.7575	75.7575	75.7575	75.7575	75.7575	75.7575	75.7575	75.7575
Heat	51.47949	51.47949	51.47949	51.47949	51.47949	51.47949	51.47949	51.47949	51.47949	51.47949	51.47949	51.47949	51.47949	51.47949	51.47949
Electricity	19.22685	19.22685	19.22685	19.22685	19.22685	19.22685	19.22685	19.22685	19.22685	19.22685	19.22685	19.22685	19.22685	19.22685	19.22685
Total	146.4638	146.4638	146.4638	146.4638	146.4638	146.4638	146.4638	146.4638	146.4638	146.4638	146.4638	146.4638	146.4638	146.4638	146.4638
PV cash flow	72.422	69.303	66.319	63.463	60.730	58.115	55.612	53.218	50.926	48.733	46.634	44.626	42.705	40.866	39.106
Cumul cash fl	**1645.377**	**1714.680**	**1780.999**	**1844.462**	**1905.192**	**1963.307**	**2018.920**	**2072.137**	**2123.063**	**2171.796**	**2218.431**	**2263.057**	**2305.762**	**2346.627**	**2385.733**
Costs	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
INV_0															
Operational	70.70267	70.70267	70.70267	70.70267	70.70267	70.70267	70.70267	70.70267	70.70267	70.70267	70.70267	70.70267	70.70267	70.70267	70.70267
PV cash outflow	34.960	33.455	32.014	30.636	29.316	28.054	26.846	25.690	24.584	23.525	22.512	21.542	20.615	19.727	18.878
Totale parziale	**1496.918**	**1530.373**	**1562.387**	**1593.023**	**1622.339**	**1650.393**	**1677.239**	**1702.929**	**1727.512**	**1751.037**	**1773.549**	**1795.092**	**1815.706**	**1835.434**	**1854.311**
	75.76117	75.76117	75.76117	75.76117	75.76117	75.76117	75.76117	75.76117	75.76117	75.76117	75.76117	75.76117	75.76117	75.76117	75.76117
Payback Period	148.459	184.307	218.612	251.439	282.853	312.914	341.681	369.209	395.551	420.759	444.882	467.966	490.055	511.194	531.422