Economic assessment of a 40,000 t/y mixed plastic waste pyrolysis plant using direct heat treatment with molten metal: A case study of a plant located in Belgium

Frank Riedewald[1], Yunus Patel[1], Edward Wilson[1] Silvia Santos[2] and Maria Sousa-Gallagher[3]

1. Composite Recycling Ltd, The Rubicon Centre, CIT Campus, Bishopstown, Cork, T12 Y275, Ireland.
2. Alumisel, Polígono A Granxa s/n, Pontevedra, 36400 O Porriño, Spain.
3. Process and Chemical Engineering, School of Engineering, University College Cork, T12 YN60, Ireland; m.desousagallagher@ucc.ie

Abstract

Pyrolysis has been identified as an ideal process to recycle mixed plastic waste (MPW). This study investigates the economics of a 40,000 t/y MPW pyrolysis process, called PlastPyro, located in Belgium, to an accuracy of ±15% i.e. “Definite Estimate”. The process uses molten metal in a direct heat treatment process to pyrolyse the waste. An internal rate of return (IRR) of 20% strongly indicates that a 40,000 t/y PlastPyro plant is financially interesting for private investors. The capital expenditure (CAPEX) is estimated to be €20.1m or €26.1m if the cost of capital is included. The operating expenditures (OPEX) of the plant are estimated €3.4m per year. The sensitivity analysis shows six main variables having major impacts on the financial returns of a PlastPyro plant: (1) the addressable volume and quality of plastic waste, (2) the feedstock costs, (3) the capital and operating expenditures, (4) the revenues from the sale of the produced pyrolysis oil (P-oil), (5) the tipping fees and (6) the potential to co-locate a PlastPyro plant with a waste plastic sorting facility. For example, the 15-year low P-oil revenue price of €210/t results in an IRR of 20%; but on the 6th of March 2020 the P-oil price may have achieved €227/t, resulting in an IRR of 37%. The paper also shows that a reliable supply of MPW is available, and that reliable, accessible markets for the P-oil are available. Finally, cost estimates should state their accuracy and usually factorial cost estimates are not accurate enough to state the IRR.

Keywords: mixed waste plastic, recycling, pyrolysis, molten metal, economic assessment, accuracy of cost estimates, CAPEX, OPEX

1. Introduction

Only 9% of the global plastic waste stream is recycled; the rest is either landfilled, incinerated or accumulates in the environment (Geyer et al., 2017). This low plastic recycling rate is due to a number of factors: (1) Waste plastic bags, polystyrene packaging or coffee cups can only be recycled if the material is available in clean, large quantities; (2) over 95% of plastic recycling is by mechanical recycling, which is suitable for homogeneous and contaminant-free plastic waste only (Punkkinen et al., 2017); (3i) Most plastics polymer chains break down during reprocessing and, as a result, many plastics can only be recycled once or twice (Anonymous, 2017).

A plastic waste stream composed of a single, clean plastic-type often has a commercial value and may be recycled back to virgin plastic. But mixed plastic waste (MPW) is a waste stream composed of different plastics, often various colours and is usually contaminated with foreign objects, turning it into a stream for which a waste collection company has to pay for to landfill or incinerating it as it cannot be recycled (Chruszcz and Reeve, 2018; Punkkinen et al., 2017). In the United Kingdom, MPW consists of various plastics with an average composition of 38.5% polyethylene, 22.5% polypropylene, 15.3% polyethylene terephthalate, 4% polystyrene, 3.5% polyvinylchloride and 16.5% contamination (Chruszcz and Reeve, 2018; Foster, 2008).

For many countries, a convenient outlet for mixed waste plastic used to be China, having in 2016 imported two thirds of the world's plastic waste. However, since January 2018 China stopped the import of all plastic waste (Economist, 2018) not meeting the quality demands of the plastic reprocessing sector i.e. plastic waste containing less than 0.5% foreign materials (Economist, 2018), a requirement which very few plastic waste streams meet. Household plastics waste, for example, typically contains 3.7% contamination (Chruszcz and Reeve, 2018), making it unsuitable for reprocessing without extensive pre-processing. After the Chinese ban, the majority of the plastic waste was diverted to south-east Asia, forcing these countries also to ban the import of plastic waste (FT, 2018). More recently, these countries are returning waste plastic to the exporting countries, as it is contaminated and non-recyclable (FAZ, 2020). In response to the Chinese ban, many municipals in Europe and the US are now sending more plastic waste to landfill or incineration as recycling at home is too expensive (FT, 2018; NYT, 2019).

In the meantime, the regulatory pressure to increase waste plastic recycling is stepping up. In January 2018, the EU Plastics Strategy (Commission, 2018) designated plastic waste recycling as a priority in the Circular Economy Action Plan (Commission, 2015), and on the 10th of May 2019, the EU, along with most other states of the world (the US a notable exception), agreed to reclassify plastic waste as hazardous, significantly reducing the capabilities to legally export plastic waste to the third world (RT, 2019; Treaty, 2019).

Pyrolysis has long been identified as an ideal process to recycle MPW and pure plastics (Aguado et al., 2002; Punkkinen et al., 2017; Sharuddin et al., 2016) and maybe one of the solutions to manage the growing amounts of plastic waste (Czajczynska et al., 2017; EEA, 2019). Pyrolysis is the process of cracking the long-chain plastic macromolecules into smaller ones in the absence of oxygen (Achilias et al., 2007; Aguado et al., 2002; Yan et al., 2015).

The chemistry of plastic pyrolysis is complex as four cracking mechanisms are involved, namely end-chain scission or unzipping, random chain scission, chain stripping, and cross-linking (Panda et al., 2010). As each plastic type has different modes of decomposition (Panda et al., 2010), the three products of plastic pyrolysis are also complex in composition. The gas is a mixture of light organics (methane, propane etc.) (Ciliz et al., 2004; Williams, Elizabeth and Williams, 1997; Williams, Paul and Slaney, 2007) which may be used to produce heat for the process, making it self-sustaining (Haig et al., 2010). The pyrolysis oil (P-oil) is a mixture of hundreds of hydrocarbons (Bhaskar et al., 2003; Ciliz et al., 2004; Dobó et al., 2019; Miandad et al., 2017; Williams, Elizabeth and Williams, 1997; Williams, Paul and Slaney, 2007) and may be upgraded to a transport fuel such as diesel, used as a basic chemical or both (Dobó et al., 2019; Lopez et al., 2017). Finally, the solids are a carbon-rich ash, which may, for instance, be used as a solid fuel (Jamradloedluk and Lertsatitthanakorn, 2014; Williams, Elizabeth A. and Williams, 1997).

The pyrolysis operating temperature is one of the main parameters determining the yield and composition of the pyrolysis products, and its influence has been extensively studied (Al-Salem et al., 2017; Lopez et al., 2017; Panda et al., 2010; Sharuddin et al., 2016; Williams, Elizabeth A. and Williams, 1997; Williams, Paul T. and Slaney, 2007). It was found that higher operating temperatures result in higher gas and char yields while the P-oil yield decreased. The optimum pyrolyzing temperature maximising the P-oil yield, the most valuable product of plastic pyrolysis, ranges from of 400 to 550°C (Al-Salem et al., 2017; Sharuddin et al., 2016; Williams, Elizabeth A. and Williams, 1997).

One advantage of pyrolysis over other plastic recycling processes is that plastic contaminated with food residue can be treated, eliminating an expensive washing step. Moreover, sorting by colours and plastic-type is not necessary (Punkkinen et al., 2017; Sharuddin et al., 2016; Slater and Crichton, 2011). Notably, the financial returns from plastic pyrolysis are higher than the financial returns from chemical depolymerisation or gasification as the capital requirements are lower (Haig et al., 2010).

Few studies assessing the economic performance of an MPW pyrolysis plant are available in the literature and all of these studies lack detail, making it difficult to compare and assess their validity. Westerhout et al. (1998) assessed three different reactors i.e. a bubbling fluidised bed, a circulating fluidised bed and a rotating cone. Another study investigated the economic performance of a plastic waste to fuel pyrolysis plant located in Malaysia (Sahu et al., 2014). A catalytic fluidised bed reactor was simulated using ASPEN, and the economic performance analysed, showing that the plant must have a throughput of at least 120,000 t/y to be economically viable with an investment cost of $58 million. Fivga and Dimitriou (2018) used ASPEN to investigate the economic performance of another fluidised bed reactor with three different throughputs (1,000, 10,000, and 100,000 kg/h). The investment cost of the 100,000 kg/h plant is estimated to amount to £56.7 million. Such a plant would be huge, as 100,000 kg/h equates to a yearly throughput of 800,000 tons, which is a higher throughput than the MPW collected in the UK in 2015 (Chruszcz and Reeve, 2018) making such a plant unrealistic for most circumstances. A recent study (Jiang et al., 2020), again using ASPEN, reports on the economic performance of a molten salt MPW pyrolysis plant, which found that a 16,000 t/y plant achieves an internal rate of return (IRR) of 33%. Larrain et al., (2020), estimated that the minimum throughput of a waste plastic pyrolysis plant must be about 80,000 t/y to achieve an IRR of at least 15% i.e. being economically viable. The preferred throughput is, however, 120,000 t/y to achieve the financial returns which may satisfy investors.

Pyrolysis is advocated by some conservation pressure groups, for example, the Ocean Recovery Alliance, as an environmentally sound plastic waste treatment option (ORA, 2015). Moreover, a life cycle analysis of plastic pyrolysis shows that pyrolysis is a viable alternative over incineration and landfill (Gear et al., 2018). But pyrolysis based on conventional rotary kiln technology has not been a commercial success (Gleis, 2012). The main reason why conventional rotary kilns, or their variations, are uneconomical is that they cannot be scaled up beyond a throughput of 10,000 t/y (Haig et al., 2010; Punkkinen et al., 2017). Instead, two or more rotary kiln reactors must be installed in parallel to achieve commercially attractive throughput requirements (Haig et al., 2010; Punkkinen et al., 2017).

This paper investigates the economics of a future, commercial scale MPW pyrolysis process, named PlastPyro. The I economic analysis aims to determine under which conditions a PlastPyro plant is financially interesting for private investors, as MPW recycling plants will only be built and operated if the financial incentive is large enough. The difficulty of an economic analysis are the many uncertainties when trying to predict future market conditions. Consequently, this paper takes the worst-case approach, i.e., the lower revenue stream, the lower yield and the lower gate fee. This reduces the revenue stream an operator achieves, resulting in a more conservative estimate of the financial returns.

2. The PlastPyro process

The PlastPyro process brings MPW into direct contact with molten zinc, which is held at an operating temperature of 450°C. A reaction time of 10 minutes was chosen as the design parameter for the PlastPyro process for two reasons: (1) Whole tyres pyrolyse within 15 minutes on molten zinc (Rathsack et al., 2015), but plastic should pyrolyse faster; and (2) Zincoxide (ZnO), which is part of the slag floating on the molten zinc, is a catalyst, increasing the plastic pyrolysis reaction rate (Ahmad et al., 2017; Miandad et al., 2016).

The PlastPyro process, is a continuous plastic pyrolysis process, schematically shown in Fig. 1. The MPW is provided in a feeding bin and is transported by a feeding auger into the pyrolysis chamber, i.e., onto molten zinc, which is held at a temperature between 450 and 500°C. On the molten zinc, the MPW pyrolyzes into hydrocarbon vapours, gases and solids. The solids, a carbon rich ash, float on the molten zinc. The vapours and the solids are removed simultaneously from the pyrolysis chamber via a solids/vapour extractor in a hoover-like fashion. The solids are separated from the vapours by a cyclone and exit the system via a rotary valve. A quench may be installed to separate the waxes (longer chain hydrocarbons) and return them to the pyrolysis chamber to be cracked into smaller molecules. The vapours are condensed to P-oil, which is sent to a storage tank. A fan provides the suction force to remove the vapour and solids. The non-condensable gases include methane, propane and other gases. These may be (1) sent to the burner(s) to heat the pyrolysis process, making it self-sustaining, (2) used to generate electricity or (3) both of the previous options. The molten zinc is the heat transfer media only and is not consumed by the process.

The safety of the molten zinc operation of the PlastPyro process is governed by standards (EN, 2000; Riedewald et al., 2015) from the hot-dip galvanising industry (Maaß and Peißker, 2011) while the safety of the remaining process matches those from the chemical industry (Crowl and Louvar, 2011).

2.1. P-oil yield

Depending on the plastic-type, the P-oil yield varies. Pure, single type, uncontaminated mixed plastic waste may have a P-oil yield as high as 90wt% (Sharuddin et al., 2016), whereas Aguado et al. (Aguado et al., 2002) report on yields between 80 and 92wt% for various plastics. But as MPW is of varied composition, the yields are best given as a range: Haig et al., 2010 state that the P-oil yield of MPW pyrolysis is between 67 and 80wt%, the solids yield 2 to 15wt% and the gas yield 8 to10wt%. This study assumes that all the gases are used for internal energy generation and are therefore not available for other uses; for example, electricity generation. This work also assumes that the solids do not offer any commercial value and that they are landfilled. Furthermore, this study takes a low P-oil yield of 65wt% and a high solid yield of 13wt%, making the financial returns more conservative (summarised in Fig. 2).

3. Market analysis

A market analysis on waste plastic pyrolysis was carried out to establish: (1) the addressable MPW volumes, (2) the price for the products of plastic pyrolysis i.e. P-oil and (3) the tipping fees the PlastPyro operator receives for accepting MPW.

3.1. Waste plastics market

In 2011 the EU member states exported nearly half of the plastic waste collected for recycling or 3 million tons to Asia, mostly to China (EEA, 2012). In the UK just over 500,000 tonnes of MPW were collected in 2015 (Chruszcz and Reeve, 2018). Both statistics indicate the scale of the non-recyclable plastic waste in the EU, the UK and indeed worldwide. To make any inroads into MPW treatment, the facility is assumed to have a minimum throughput of 30,000 t/y. This, of course, assumes that the recycling plant is located close to a large city with an efficient municipal plastic waste collection and sorting operation. Therefore, no shortage of mixed, non-recyclable plastics waste is predicted.

On the contrary, the global plastic production currently stands at some 400 million tons per year, and in tandem, plastic waste is predicted to double until 2035 as plastic is such a useful material (EEA, 2019).

3.2. P-oil market

P-oil, the product from a plastic pyrolysis process, has a high economic value (Punkkinen et al., 2017; Sharuddin et al., 2016; Slater and Crichton, 2011). The P-oil could be sold to an oil refinery, a fuel blender, upgraded by the waste plastic pyrolysis operator or others to diesel, wax or other petroleum products. Unfortunately, the P-oil price is difficult to predict over an extended time horizon despite many attempts (Abdollahi and Ebrahimi, 2020; Gkillas et al., 2020; Leng and Li, 2020).

Therefore, for the purpose of this economic study, it is assumed that the P-oil is sold as Fuel Oil No. 6 (US specification) or Heavy Bunker Oil (European specification) to an oil refinery, as the properties of these are similar to P-oil. Such fuels are used in the shipping industry, are of relatively low quality, and, hence, the revenue achievable from such fuels is relatively low. The P-oil may command a higher price, as fuels produced from plastic waste have lower sulphur levels than conventional petroleum fuels, as plastic contains no sulphur. This potentially higher price is ignored as the P-oil market is uncertain and, therefore, it is prudent to assume a lower price.

With the emergence of the US shale oil boom in 2010, the price of crude oil went downwards. This trend reached a bottom in February 2016 when the crude oil price sank to a 15-year low of $28.14/barrel (EIA, 2020). This oil price was so low that some shale oil companies reduced production as their margins became uneconomical (Economist, 2015). At that time, US refineries received $1.2/gallon or €275**/**t for Fuel Oil No. 6 (Calculation, 2020). Assuming a minimum margin of €25/t for the refinery and a transport cost of €40/t (Bains and Robinson, 2012), a P-oil revenue figure of €210/t for the PlastPyro operator was calculated.

Selling the P-oil to an oil refinery should be put into context. For instance, the TOTAL oil refinery in Antwerp, Belgium, has an oil throughput of 57,000 m^3/d (Wikipedia, 2020). Hence, even a 100,000 m^3/y or 280 m^3/d addition of P-oil generated from the pyrolysis of ca, 154,000 t/y of MPW is negligible as an input for most oil refineries.

It may be possible to obtain carbon credits for the P-oil or plastic pyrolysis in general; possibilities not addressed by this study.

3.3. Tipping fee

A waste treatment facility, or the PlastPyro operator, may be paid a fee, the tipping fee, for accepting MPW. Tipping fees in Belgium are between €50 and €80**/**t (CEWEP, 2017). For this economic assessment, a tipping fee of €25/t is assumed that is half of the lower range of the Belgium tipping fee. Such a low tipping fee was used for this assessment as it makes the economic analysis more conservative.

4. Financial assessment

The economics of a PlastPyro plant is assessed by two frequently used financial measures; the net present value (NPV) and the internal rate of return (IRR) (Crundwell, 2008). The NPV of an investment is calculated by adding all cash flows, reduced by the discount rate, to its current value i.e. the NPV is taking the time value of money into account. Should the NPV be positive, the project is expected to create value; should it be negative, it is expected to destroy value. The NPV is defined as:

$$\mathrm{NPV} = \sum_{t=0}^{n} \frac{\mathrm{CF}_t}{(1+k)^t} \qquad (1)$$

with CF_t the cash flow in year t, n the time frame and k the discount rate.

The IRR is defined as the discount rate k at which the NPV turns zero or mathematically:

$$\mathrm{NPV} = 0 = \sum_{t=0}^{n} \frac{\mathrm{CF}_t}{(1+\mathrm{IRR})^t} \quad (2)$$

The IRR gives an indication of the relative return of an investment without taking the scale of the project into account (Crundwell, 2008). In general, larger infrastructure projects such as a waste plastic pyrolysis plants are considered profitable by private investors if the IRR exceeds 15% (Riedewald, 2020a). Privately operated waste companies require an IRR of 15% for new technologies and 10% for established ones (Riedewald, 2020b). In special circumstances, the IRRs of waste management plants may be lower than 15% and still considered investable. In one municipal waste incinerator project, with discount rates as low as 3.3%, the IRR was just 6.9%, while on another project with EU funding an IRR of 7.6% was sufficient for private investment (CSIL, Various Years). But these are financially secure, and long-term government supported investments. For the purposes of this financial evaluation study, a desired minimum IRR of 20% is assumed. The reason for setting a more challenging IRR target value of 20% is that financial uncertainties on the revenue stream exist. The evaluation period of the IRR is 10 years (same as the bank loan period).

The location of the plant is assumed to be in Belgium, close to Antwerp. This location has a relatively high-cost base, but is also close to major areas of population with heavy industry minimising transportation costs for both waste materials and products. It is further assumed that all considerations made in the market analysis chapter for the UK also apply for Belgium. Furthermore, it is assumed that the PlastPyro operator has a 10-year contract with a waste sorting facility, which ensures a continuous and reliable supply of waste plastics. Moreover, it is assumed that state financial support is not available; that the uptime of the plant is 85% equating to 7,500 hours per year which includes a 2-week annual plant shutdown. All prices were estimated or obtained in January or February 2020. An inflation rate of 3%, an interest rate of 5% and a discount rate of 10% was applied. Finally, the plant life is 20 years. All of these assumptions are summarised in Table 1.

The financial performance of a 40,000 t/y PlastPyro plant over a period of eleven years, including a one-year construction phase is presented in Table 2. The capital expenditure is estimated to be €20.2m or €26.1m if the cost of capital is included. An IRR of 20% (10 years) and an NPV of €1.59m strongly indicate that a 40,000 t/y PlastPyro plant is financially interesting for private investors.

In the following sections, details of the project financials such as capital expenditure, operating expenditure, revenue and taxes are discussed in more detail.

4.1. Capital expenditure

The capital expenditure (CAPEX) of a 40,000 t/y PlastPyro plant may be estimated by various methods depending on the desired accuracy and the available information. Aiming at an accuracy of ±15% places this estimate according to Table 3 between "Preliminary Estimate" and "Definite Estimate". To achieve a ±15% accuracy, factorial estimating techniques by, for instance, the VDI standard 2225 (VDI, 1997) or given in (Couper et al., 2010; Holland and Wilkinson, 2007; Peters et al., 2004; Sinnott, 2005) are not accurate enough. More detailed information is required, demanding a higher level of engineering: P&IDs, layout drawings, and detailed piping and instrumentation costs are necessary (AACE, 2005).

Commercial quotations for the major pieces of equipment were obtained based on engineering specifications, which also established the technical feasibility of the PlastPyro plant. For smaller pieces of equipment such as pumps, historical prices were used. The tankfarm, equipped with two 100 m^3 above ground, 304 stainless steel P-oil storage tanks according to EN 12285-2, includes pipes, instrumentation, pumps etc. and was quoted as a complete package. Table 4 gives a breakdown of the CAPEX per plant area, the instrumentation & control and utilities.

The molten zinc pyrolysis reactor was sized as follows: a reactor with a molten zinc area of 22 m length and 2 m width has an estimated MPW throughput of 42,000 t/y based on a 10-minute reaction time. The molten zinc depth is 1.5 m allowing space for the burners. These reactor dimensions were used for the cost estimate although a throughput of only 40,000 t/y is specified and hence a smaller reactor could have been used. The reactor is filled with 69 m^3 of zinc at a cost of €740,520. According to hot-dip galvanising plant manufactures (Vendor, 2020), the maximum dimension of a molten zinc kettle is 25 m long, 3.5 m wide and 4 m deep. Therefore, the size chosen is well within the maximum size of a molten zinc kettle.

The layout of the PlastPyro plant is relatively compact and small with the pyrolysis chamber requiring the largest footprint. The pyrolysis chamber, cyclone, quench reactor and condensers are very close to each other, minimising pipe runs. The installation cost of the equipment was estimated by comparing it with similar plants and checking those costs with references (Page, 1999a; Page, 1999b). The civil costs associated with the installation of the weighbridge, tankfarm and other equipment was also based on similar plants and checked with references (Page, 1999a; Page, 1999b). A material take-off for piping (diameter, length, specification) and instruments (temperature, pressure, level, control, etc.) was performed. The prices for the supply, installation and testing of the piping were provided by a mechanical contractor. Insulation and heat tracing, if applicable, is also included. Instrumentation and electrical costs were based on historical prices from other plants.

A warehouse large enough to store two days' worth of plastic waste is included at a cost of €2.9m. This warehouse also includes offices, a canteen and other facilities.

The engineering design, management, procurement and commissioning cost of the plant is estimated to be 15% of the CAPEX. The engineering effort for the first plant is estimated at a higher percentage, as it is the first of its kind requiring more engineering input, whereas the engineering for subsequent plants may be set at 9% CAPEX. A contingency of 8% CAPEX (excluding engineering costs) is included as suggested by Peters et al. (Peters et al., 2004). This contingency is an allowance for uncertainties, as estimating is not an exact science. Acts of God, such as earthquakes or work stoppages, are not covered by this contingency. A €150,000 bond for site remediation is also included in the CAPEX. Such a bond is not unusual, ringfencing capital for returning the site to its former condition should the company go bankrupt.

The CAPEX is not spent equally across the three-year design and commissioning phases of the plant. Instead, the CAPEX spending schedule is 20% in year 1, 50% in year 2 (including purchase of long-lead items, for example, the pyrolysis plant, quench and condensers) and 30% in year 3. The design and project management CAPEX is spent at a rate of 2.5 to 5% each month throughout the project.

4.2. Operating expenditure

The operating expenditures (OPEX) of the plant are anticipated to be €3.4m per year. These costs consist of direct (operating materials or consumables, salaries, maintenance, etc.), indirect (depreciation, taxes, etc.), and general costs (administration, permits, travel, insurance, etc.) and are summarised in Table 5.

The annual maintenance costs (AMC) is estimated as typical for chemical plants (Peters et al., 2004). The AMC of the material handling part of the plant is estimated 4.0% of CAPEX, due to the high number of moving parts; the AMC of the utilities plant at 1.5% of CAPEX, the civil at 0.1% of CAPEX, whereas the AMC for the remaining plant is estimated at 3% of CAPEX. The yearly maintenance cost is an estimated €244,700.

The consumables (nitrogen, compressed air, water, etc.) are estimated to amount to €98,918/y. The electrical demand of the plant is estimated by the electrical loading (fan and pump motors, lights etc.) of the plant, at a cost of €0.13/kWh (Commission, 2019) or €35,400/y. Natural gas is required for start-up and holding the plant at the operating temperature if the plant is idle for a defined period, estimated to amount to €15,000/y at a unit cost of €0.04/kWh (Utility, 2020). Compressed air is estimated to be used at a rate of 20 m^3/h at a cost of €0.03/m^3 (Utility, 2020) or €4,500/y. Nitrogen is consumed at a rate of 30 m^3/h at an estimated running cost for the PSA (pressure swing adsorption) plant of €0.07/m^3 (Utility, 2020) amounting to €15,750/y. Also included are zinc losses, estimated to amount to €1,300/y or 0.1 kg/h. The zinc losses are associated with evaporation and are grossly overstated. Ideally, the waste plastic is delivered dry or water free to the plant as water is a nuisance for the pyrolysis process. Water is expensive to evaporate, condense, remove from the P-oil and to treat to emission limits. Overall a cost of €27,000/y is allowed for waste usage and offsite wastewater treatment.

The ash from the plastic pyrolysis is landfilled. In Belgium, the upper range of the landfill fee is €80/t (CEWEP, 2017). Adding transport costs of €50/t (solids) to that brings the cost of landfilling the ash to €130/t or €676,000/y.

Twentynine personnel, at a cost of €1.57m per year, are employed to operate the plant, although a four-shift operating is more common (Moore-Ede et al., 2019). A five-shift working schedule was used for this study as it is best for flexibility, but it is also more expensive, providing a more significant financial challenge for the economics of a PlastPyro plant. The number of operating personals per shift was estimated based on the operation of the plant, whereas the number of administrative and management personnel was based on similar chemical plants. The personnel cost varies between €50,000/y and €90,000/y depending on duties; summarised in Table 5 (average industrial wage in Belgium: €60,000/y (Eurostat, 2018)).

The OPEX also includes: (1) The insurance cost of the plant is estimated at 1% of the fixed CAPEX i.e. excluding engineering and the warehouse cost (Peters et al., 2004) or €15,000/y. (2) Molten zinc corrodes stainless steel making regular kettle replacement necessary (Maaß and Peißker, 2011). A five-year kettle replacement frequency at a cost of €150,000 is assumed. (3) Rent for the site is €360,000/y, whereas rates, office expenses, heating, telecom, professional fees, permits and other expenses amount to €118,000/y. (4) Finally, an annual licence fee of €200,000 payable to the owner of the PlastPyro technology is included.

4.3. Revenue and depreciation

A 40,000 t/y PlastPyro plant generates revenues of €6.26m per year, with the P-oil providing 84.5% of the revenue and the tipping fees 15.5%.

The equipment is depreciated depending on their expected life-span on a straight-line basis, either 5, 10 or 20 years.

4.4. Throughput and market potential

The worldwide market, based on studies (ACC, 2014), maybe about 100 PlastRec plants with MPW throughputs ranging from 30,000 to 120,000 t/y. The UK would require about 5 plants, France 5, Italy 5, etc. resulting in about 30 plants in Europe and another 30 in the US.

5. Sensitivity analysis

A sensitivity analysis was performed to determine the most relevant factors influencing the financial returns. The parameters affecting the IRR of the plant were varied as follows:

Revenue: (1) P-oil: As the P-oil revenue contributes 84.5% to the overall revenue of the plant, any variation in its sales price or yield will significantly influence the financial returns of the plant. On the 6th of March 2020, the Brent oil price was $52.02/barrel, equating to a P-oil sales price of €227/t, resulting in an IRR of 37%. Clearly, using the lowest oil price of the last 15 years grossly underestimates the financial returns of the plant. Should the P-oil yield be 60% rather than 65%, the IRR reduces to 4%; likewise, a P-oil yield increase by 5% increases the IRR to 36%. Indeed, the better the quality or contamination free the plastic waste is, the better the financial returns of the plant. (2) Tipping fee: An increase in the tipping fee from €25 to €40/t – a value still €10 off the lower range of the Belgian tipping fee (CEWEP, 2017) – will result in an IRR increase from 20 to 45%. Therefore, any tipping fee increase would be beneficial for the financial returns of the plant and would likely incentivise private investment into plastic recycling as well as making the financial returns more stable as the tipping fee is not influenced by market forces.

CAPEX: Increasing the CAPEX by +10% results in an IRR decrease from 21 to 8%, demonstrating that CAPEX spending has a significant influence on the financial returns. Moreover, it also shows that CAPEX spending must be tightly controlled.

OPEX: Increasing the OPEX by +20% reduces the IRR by sixteen percentage points. Consequently, an operator must tightly control the operating costs (salaries, business expenditures, etc.). A simple way to decrease the OPEX is to run the plant on a 4 rather than a 5-shift operation increasing the IRR to 27%.

Financial: The influence of financial parameters on the IRR must not be underestimated. For example, reducing the interest rate from 5 to 4% increases the IRR from 20 to 27%.

Throughput: Increasing the plant capacity to 50,000 t/y results in an increase of the IRR to 59%, although both CAPEX and OPEX were increased by 10% to account for the larger throughput.

Co-location: The PlastPyro plant may be co-located with a municipal plastic waste sorting facility. In such a case, the IRR increases to 32%. The sorting facility would feed straight into the PlastPyro plant, negating the need for a dedicated warehouse, weighbridge and various material handling operations. Moreover, personnel efficiencies may be realised. For example, the senior management already exists for the plastic waste facility, as does the engineering personnel.

Combinations of the measures above may also be possible, for example, a 4-shift operation and co-locating the plant with a municipal waste sorting facility. But such combinations were not investigated by this study.
In summary, the IRR of a 40,000 t/y PlastPyro plant is most sensitive to variations in the sale price of the P-oil, tipping fees, CAPEX, OPEX, and the interest rate charged.

6. Discussion

From the financial analysis of a 40,000 t/y or larger MPW PlastPyro plant, it can be concluded that such a plant is economic as it achieves an IRR of over 20% with meagre oil prices. Moreover, a reliable, ample supply of MPW is available as are reliable, accessible markets for the P-oil.

A real PlastPyro plant, however, will have different financial returns than the returns of the theoretical facility presented in this study. This is, as the revenue values used in this paper were based on estimated 15-year low prices for the P-oil and other assumed financials rather than on agreed commercial terms. Therefore, once the location for a plant is agreed, more detailed studies are required to firm up on the cost estimate, as the plant location has a significant influence on the financial returns. Moreover, commercial agreements must be put in place to accurately predict the financial returns of an MPW recycling plant.

From an environmental and financial perspective, PlastPyro plants with throughputs exceeding 40,000 t/y may be desirable. The amount of MPW available would justify larger throughputs. For instance, in the UK alone, 500,000 tonnes of MPW were collected in 2016 (Chruszcz and Reeve, 2018). From a financial perspective, larger plants are also desirable, having higher IRRs due to increased economies of scale. Such large throughput plants are possible with a PlastPyro reactor as it can be made even larger than assumed in this paper, allowing higher throughputs. But MPW transport distances will become increasingly challenging with higher throughput plants as the transport cost of bringing the MPW from distances further away increases.

Likewise, smaller plants with throughputs of 30,000 t/y or less may also be desirable. Moreover, they may be economic depending on commercial agreements, plant location and other parameters. However, should such a plant operate with low throughput reactors, the economic performance may be limited. Punkkinen et al. (2017) lists a number of reactors having MPW throughputs of 7,000 – 21,000 t/y. Plants operating with such low throughput reactors would have to operate with three or more reactors in parallel to achieve economies of scale i.e. 30 - 40,000 t/y. But the CAPEX of facilities with multiple reactors operating in parallel would be higher compared to a PlastPyro plant with just one reactor. As a result, the economics of a PlastPyro plant with one reactor is better than plants with multiple lower throughput reactors.

This study is accurate to ±15%, making it the most accurate economic study of an MPW pyrolysis plant available in the literature. With such an accuracy, the predicted IRR of 20% can be stated with a high degree of confidence. Moreover, in light of this study, comments can be made on other studies assessing the financial performance of various full-scale MPW pyrolysis plants.

Larrain et al. (2020) used equipment and infrastructure costs provided by a waste treatment company, which should give a high level of confidence in their cost estimate. But due to confidentially issues, no details are disclosed; in fact, not even the type of pyrolysis reactor is disclosed. Therefore, it is not clear how the cost estimate was put together, nor is its accuracy stated by the authors. Consequently, no meaningful comments can be made on Larrain et al. (2020).

All the other economic studies by Westerhout et al. (1998), Sahu et al. (2014); Fivga and Dimitriou (2018), and Jiang et al. (2020) use the factored cost estimate method. According to the Association for the Advancement of Cost Engineering (AACE) (AACE, 2005), the factored cost estimate method has the lowest level of accuracy (Table 3). Only Westerhout at al. (1998) acknowledge the limitations of the factored cost estimate, stating that it is accurate to ±40%, which is in line with the classifications given in Table 3. Moreover, they applied the factored cost estimate as intended by comparing three different reactor types with the same throughput to find the one with the highest financial returns; that is, they were concept screening.

Sahu et al. (2014), Fivga and Dimitriou (2018) and Jiang et al. (2020), on the other hand, all omit to state the accuracy of their cost estimates and therefore these studies may give a false impression of accuracy. Fivga and Dimitriou (2018) may also have exceeded the validity of the factorial method. They estimated the economic performances of MPW pyrolysis plant with throughputs of 1,000, 10,000 and 100,000 kg/h with factorial methods. It is likely that the plant throughput variation is too large, because the validity of the factored cost scaling method may be breaking down. Scaling from a 1,000 to a 100,000 t/y plant using factored methods may work mathematically, but expecting a good cost accuracy is questionable to say the least, as the scaleup factor is in the order of 100. Moreover, a 100,000 t/h plant throughput exceeds the MPW available in the UK. Therefore, a 100,000 t/h MPW recycling plant would be excessively large and unrealistic.

Jiang et al. (2020) estimated the economics of a 16,000 t/y molten salt MPW pyrolysis plant and concluded that such a plant achieves an IRR of 33%; an excellent financial return. This high IRR can, however, be explained by the unquestioned use of a revenue value of €780/t for the waxes, which was taken from Fivga and Dimitriou (2018). Such a revenue value is 3.5 times higher than the P-oil revenue value of this study, which explains an IRR of 33% for a low throughput plant of just 16,000 t/y. Putting it another way: using €750/t for the P-oil revenue for this study results in an IRR of 420%, which would be a fantastic financial return compared to the typical values of 10-25% for waste to energy or similar waste plants (CSIL, Various Years; Hadidi et al., 2017). Consequently, the P-oil revenue value of €750/t used by Jiang et al. (2020) is not realistic, and the IRR is too high.

Clearly, accurate cost estimates require more effort than factored estimates. Factored cost estimates may be convenient as they are fast and easy to do, but should only be used for project screening i.e. comparing one option with another.

7. Conclusion

From the economic analysis, it can be concluded that a PlastPyro plant is economic from a throughput of 40,000 t/y onwards. Plants with a higher throughput will result in improved financials, due to increased economies of scale.

The economic analysis presented in this paper is a theoretical analysis, and future work must establish the financial returns that can be achieved. Moreover, the yields may be increased in the future by optimising the operating parameters, which may also result in improved economic and ecologic performances.

For other waste plastics, for example, aluminium laminated food packaging, tyres, wind turbine blades or carbon fibre materials, similar economic analyses following the principles presented here for waste plastics may be generated.

8. Acknowledgements

This project has received funding from the Geological Survey Ireland and ERA-MIN 2 (the European Union's Horizon 2020 Research and Innovation Programme) grant agreement No. 730238.

5. References

AACE (2005) Recommended Practice No. 18R-97; Cost Estimate Classification System - as Applied in Engineering, Procurement, and Construction for the Process Industries; TCM Framework: 7.3 – Cost Estimating and Budgeting.

Abdollahi, H. and Ebrahimi, S.B. (2020) A new hybrid model for forecasting Brent crude oil price. Energy 200, 117520. https://doi.org/10.1016/j.energy.2020.117520.

ACC (2014) American Chemistry Council, "Economic Impact of Plastics-to-Oil Facilities in the U.S.", estimates that the US could support as many as 600 plastic to oil facilities (depending on the production characteristics and size of the facility), https://plastics.americanchemistry.com/Economic-Impact-of-Advanced-Plastics-Recycling-and-Recovery-Facilities-in-the-United-States.pdf; accessed 7th February 2020.

Achilias, D.S., Roupakias, C., Megalokonomos, P., Lappas, A.A. and Antonakou, E.V. (2007) Chemical recycling of plastic wastes made from polyethylene (LDPE and HDPE) and polypropylene (PP). Journal of Hazardous Materials 149(3), 536-542. https://doi.org/10.1016/j.jhazmat.2007.06.076.

Al-Salem, S.M., Antelava, A., Constantinou, A. and G. Manos, A.D. (2017) A review on thermal and catalytic pyrolysis of plastic solid waste (PSW). Journal of Environmental Management 197, 177-198. https://doi.org/10.1016/j.jenvman.2017.03.084.

Aguado, R., Olazar, M., José, M.J.S., Gaisán, B. and Bilbao, J. (2002) Wax Formation in the Pyrolysis of Polyolefins in a Conical Spouted Bed Reactor. Energy & Fuels 16(6), 1429-1437.

Ahmad, I., Khan, M.I., Khan, H., Ishaq, M., Khan, R., Gul, K. and Ahmad, W. (2017) Pyrolysis of HDPE into fuel like products: Evaluating catalytic performance of plain and metal oxides impregnated waste brick kiln dust. Journal of Analytical and Applied Pyrolysis 124, 195-203. https://doi.org/10.1016/j.jaap.2017.02.005.

Anonymous (2017) Recycling symbols & what they mean? A handy reference guide, https://www.citybin.com/wp-content/uploads/2017/11/TCBC_AGuideToRecyclingSymbols.pdf, accessed 24th February 2020.

Bains, M. and Robinson, L. (2012) Recovery of laminated packaging from black bag waste, Wrap, http://www.wrap.org.uk/sites/files/wrap/Recovery%20of%20laminated%20packaging%20from%20black%20bag%20waste.pdf, accessed 5th February 2020.

Bhaskar, T., Uddin, A., Murai, K., Kaneko, J., Kenji Hamano, Kusaba, T., Muto, A. and Sakata, Y. (2003) Comparison of thermal degradation products from real municipal waste plastic and model mixed plastics. Journal of Analytical and

Applied Pyrolysis 70(2), 579-587. https://doi.org/10.1016/S0165-2370(03)00027-5.

Calculation (2020) Feb. 2020 Refiner prices to end-users, No. 6 Residual Fuel Oil, Feb. 2020: $1.53/gallon = $0.61/litre = €0.363/litre = €346/t; Feb. 2016: $1.21/gallon = $0.32/litre = €0.289/litre = €275/t; with: 1$ = €0.9, 1 gallon = 3.785 litre, density P-oil = 950 kg/m^3.

CEWEP (2017) Landfill costs in Europe, https://www.cewep.eu/wp-content/uploads/2017/12/Landfill-taxes-and-bans-overview.pdf, accessed 20th February 2020.

Chruszcz, A. and Reeve, S. (2018) WRAP, Banbury, Composition of plastic waste collected via kerbside, prepared by Resource Futures, http://www.wrap.org.uk/sites/files/wrap/Composition%20of%20Plastic%20Waste%20Collected%20via%20Kerbside%20v2.pdf, accessed 15th February 2020.

Ciliz, N.K., Ekinci, E. and Snape, C.E. (2004) Pyrolysis of virgin and waste polypropylene and its mixtures with waste polyethylene and polystyrene. Waste Management 24(2), 173-181. https://doi.org/10.1016/j.wasman.2003.06.002.

Commission (2015) Circular Economy Strategy, European Commission, Date of Roadmap: 04/2015, http://ec.europa.eu/environment/circular-economy/index_en.htm, accessed 6th February 2020.

Commission (2018) EU Plastics Strategy, https://ec.europa.eu/commission/news/eu-plastics-strategy-2018-nov-20_en, accessed 5th February 2020.

Commission (2019) Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Energy prices and costs in Europe, Brussels, 9th January 2019, https://ec.europa.eu/energy/sites/ener/files/documents/epc_report_final.pdf, accessed 30th January 2020.

Couper, J.R., Penney, W.R., Fair, J.R. and Walas, S.M. (2010) Chemical Process Equipment Selection and Design, Butterworth-Heinemann, Boston.

Crowl, D.A. and Louvar, J.F. (2011) Chemical process safety: fundamentals with applications, 3rd edition, Pearson Education, Boston.

Crundwell, F.K. (2008) Finance for Engineers, Evaluation and Funding of Capital Projects, Springer, London.

CSIL (Various) Centre for Industrial Studies, Milan; (1) Urban Solid Waste Management in Galicia (2) Integrated Solid Waste Management in Northern Lisbon; prepared for: European Commission, Directorate-General, Policy Development Evaluation, https://ec.europa.eu/regional_policy/sources/docgener/evaluation/pdf/projects/valorsul_lisbon.pdf, accessed 3rd January 2020.

Czajczynska, D., Anguilano, L., Ghazal, H., Krzyzynska, R., Reynolds, A.J., Spencer, N. and Jouhara, H. (2017) Potential of pyrolysis processes in the waste management sector. Thermal Science and Engineering Progress 3, 171–197. https://doi.org/10.1016/j.egypro.2017.07.275.

Dobó, Z., Jakab, Z., Nagy, G., Koós, T., Szemmelveisz, K. and Muránszky, G. (2019) Transportation fuel from plastic wastes: Production, purification and SI engine tests. Energy 189, 116353. https://doi.org/10.1016/j.energy.2019.116353.

Economist (2015) The Oil Industry - After OPEC, The Economist, 14th May 2015.

Economist (2018) A Chinese ban on rubbish imports is shaking up the global junk trade, Special Report, The Economist, 29th Sept. 2018.

EEA (2012) European Environmental Agency, Exports of waste plastics and selected waste metals from EU Member States, 1999-2011, https://www.eea.europa.eu/, accessed 11th February 2020.

EEA (2019) Resource efficiency and waste, The plastic waste trade in the circular economy, European Environment Agency (EEA), https://www.eea.europa.eu/themes/waste/resource-efficiency/the-plastic-waste-trade-in, accessed 15th February 2020.

EIA (2020) Europe Brent Spot crude oil price, U.S. Energy Information Administration, eia, https://www.eia.gov/dnav/pet/hist/rbrteD.htm, accessed 18th March 2020.

EN (2000) EN 746-1: 2000, Industrial thermoprocessing equipment Part 1: Common safety requirements for industrial thermoprocessing equipment; and: EN 746-4: 1997, Industrial thermoprocessing equipment.

Eurostat (2018) Wages and labour costs, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Estimated_hourly_labour_costs,_2018_(EUR).png, accessed 5th February 2020.

FAZ (2020) Malaysia schickt illegal importierten Plastikműll zurűck, Frankfurter Allgemeine Zeitung, 20th January 2020.

Fivga, A. and Dimitriou, I. (2018) Pyrolysis of plastic waste for production of heavy fuel substitute: A techno-economic assessment. Energy 149, 865-874. https://doi.org/10.1016/j.energy.2018.02.094.

Foster, S. (2008) Wrap: Domestic Mixed Plastics Packaging Waste Management Options, http://www.wrap.org.uk/sites/files/wrap/Mixed%20Plastic%20Final%20Report.pdf, last accessed 21st June 2020, Wrap.

FT (2018) Why the world's recycling system stopped working, Financial Times, 25th October 2018.

Gear, M., Sadhukhan, J., Thorpe, R., Clift, R., Seville, J. and Keast, M. (2018) A life cycle assessment data analysis toolkit for the design of novel processes – A case study for a thermal cracking process for mixed plastic waste. Journal of Cleaner Production 180, 735-747. https://doi.org/10.1016/j.jclepro.2018.01.015.

Geyer, R., Jambeck, J.R. and Law, K.L. (2017) Global production, use, and fate of all plastics. Science Advances 3. https://advances.sciencemag.org/content/3/7/e1700782.

Gkillas, K., Gupta, R. and Pierdzioch, C. (2020) Forecasting realized oil-price volatility: The role of financial stress and asymmetric loss. Journal of International Money and Finance 104, 102137. https://doi.org/10.1016/j.jimonfin.2020.102137.

Gleis, M. (2012) Vivis TK Verlag, Gasification and Pyrolysis – Reliable Options for Waste Treatment?, https://www.vivis.de/wp-content/uploads/WM3/2012_WM_403_411_Gleis.pdf, accessed 5th February 2020.

Hadidi, L.A. and Omer, M.M. (2017) A financial feasibility model of gasification and anaerobic digestion waste-to-energy (WTE) plants in Saudi Arabia. Waste Management 59, 90-101. https://doi.org/10.1016/j.wasman.2016.09.030.

Haig, S., Morrish, L., Morton, R., Onwuamaegbu, U., Speller, P. and Wilkinson, S. (2010) Plastics to oil, Zero Waste Scotland, https://zerowastescotland.org.uk/content/plastics-oil-report-0, accessed 20th February 2020.

Holland, F.A. and Wilkinson, J.K. (2007) Section 9, Process Economics; in: Perry's, Chemical Engineers' Handbook, McGraw-Hill Education; 8th edition.

Jamradloedluk, J. and Lertsatitthanakorn, C. (2014) Characterization and Utilization of Char Derived from Fast Pyrolysis of Plastic Wastes. Procedia Engineering 69, 1437-1442. https://doi.org/10.1016/j.proeng.2014.03.139.

Jiang, G., Wang, J., Al-Salem, S.M. and Leeke, G.A. (2020) Molten Solar Salt Pyrolysis of Mixed Plastic Waste: Process Simulation and Technoeconomic Evaluation. Energy & Fuels 34(6), 7397-7409. https://pubs-acs-org.ucc.idm.oclc.org/doi/10.1021/acs.energyfuels.0c01052.

Larrain, M., Van Passel, S., Thomassen, G., Kresovic, U., Alderweireldt, N., Moerman, E. and Billen, P. (2020) Economic performance of pyrolysis of mixed plastic waste: Open-loop versus closed-loop recycling. Journal of Cleaner Production, 122442. https://doi.org/10.1016/j.jclepro.2020.122442.

Leng, N. and Li, J.-C. (2020) Forecasting the crude oil prices based on Econophysics and Bayesian approach. Physica A: Statistical Mechanics and its Applications 554, 124663. https://doi.org/10.1016/j.physa.2020.124663.

Lopez, G., Artetxe, M., Amutio, M., Bilbao, J. and Olazar, M. (2017) Thermochemical routes for the valorization of waste polyolefinic plastics to produce fuels and chemicals. A review. Renewable and Sustainable Energy Reviews 73, 346-368. https://doi.org/10.1016/j.rser.2017.01.142.

Maaß, P. and Peißker, P. (2011) Handbook of Hot-dip Galvanization, Wiley-VCH, Weinheim.

Miandad, R., Barakat, M.A., Aburiazaiza, A.S., Rehan, M., Ismail, I.M.I. and Nizami, A.S. (2017) Effect of plastic waste types on pyrolysis liquid oil. International Biodeterioration & Biodegradation 119, 239-252. https://doi.org/10.1016/j.ibiod.2016.09.017.

Miandad, R., Barakat, M.A., Aburiazaiza, A.S., Rehan, M. and Nizami, A.S. (2016) Catalytic pyrolysis of plastic waste: A review. Process Safety and Environmental Protection 102, 822-838. https://doi.org/10.1016/j.psep.2016.06.022.

Moore-Ede, M., Davis, W. and Aguirre, A. (2019) Advantages and Disadvantages of 12-Hour Shifts A Balanced Perspective CIRCADIAN® Report, https://www.circadian.com/blog/item/75-advantages-and-disadvantages-of-12-hour-shifts.html, accessed 9th February 2020.

NYT (2019) Recycling falters as costs surge, New York Times, 19th March 2019.
OECD (2018) OECD Environmental Policy Paper No. 12, Improving Plastics Management: Trends, policy responses, and the role of international co-operation and trade, ISSN 2309-7841, https://www.oecd.org/environment/waste/policy-highlights-improving-plastics-management.pdf, accessed 28th August 2020.

ORA (2015) Ocean Recovery Alliance, 2015 Plastics to Fuel Developer's Guide, https://www.oceanrecov.org/about/plastic-to-fuel-report.html, accessed 30th January 2020.

Page, J.S. (1999a) Estimator's equipment installation man-hour manual, Gulf Publishing Company, Houston, Texas, USA.

Page, J.S. (1999b) Estimator's piping man-hour manual, Gulf Publishing Company, Houston, Texas, USA.

Panda, A.K., Singh, R.K. and Mishra, D.K. (2010) Thermolysis of waste plastics to liquid fuel: A suitable method for plastic waste management and manufacture of value added products—A world prospective. Renewable and Sustainable Energy Reviews 14(1), 233-248. https://doi.org/10.1016/j.rser.2009.07.005.

Peters, M.S., Timmerhaus, K. and West, R.E. (2004) Plant Design and Economics for Chemical Engineers, McGraw Hill, 5th ed., Boston.

Punkkinen, H., Oasmaa, A., Laatikainen-Luntama, J., Nieminen, M. and Laine-Ylijoki, J. (2017) Thermal conversion of plastic containing waste: A review, Research Report NO D4.1-22, Helsinki 2017, http://arvifinalreport.fi/files/Thermal%20conversion%20of%20plastic-containing%20waste%20A%20review.pdf, accessed 15th February 2020.

Rathsack, P., Riedewald, F. and Sousa-Gallagher, M. (2015) Analysis of the pyrolysis oil obtained from whole tyre pyrolysis with molten zinc as the heat transfer media using comprehensive gas chromatography mass spectrometry. Journal of Analytical and Applied Pyrolysis 116, 49-57. https://doi.org/10.1016/j.jaap.2015.10.007.

Riedewald, F. (2020a) Personal communication with investion fund managers, January/February 2020.

Riedewald, F. (2020b) Personal discussion with solid waste management companies, January/February 2020.

Riedewald, F., Conlon, P. and Sousa-Gallagher, M. (2015) Tyre recycling utilising molten metal, Loss Prevention Bulletin.

RT (2019) New rules place restrictions on global plastic scrap trade, Recycling Today, 13th May 2019.

Sahu, J.N., Mahalik, K.K., Nam, H.K., Ling, T.Y., Woon, T.S., Rahman, M.S.b.A., Mohanty, Y.K., Jayakumar, N.S. and Jamuar, S.S. (2014) Feasibility study for catalytic cracking of waste plastic to produce fuel oil with reference to Malaysia and simulation using ASPEN Plus. Environmental Progress & Sustainable Energy 33(1), 298-307. https://doi-org.ucc.idm.oclc.org/10.1002/ep.11748.

Sharuddin, S.D.A., Abnisa, F., Daud, W.M.A.W. and Aroua, M.K. (2016) A review on pyrolysis of plastic wastes. Energy Conversion and Management 115, 308–326. https://doi.org/10.1016/j.enconman.2016.02.037.

Sinnott, R.K. (2005) Coulson & Richardson's, Chemical Engineering, Volume 6, Fourth edition, Chemical Engineering Design, Elsevier Butterworth-Heinemann, Oxford.

Slater, S. and Crichton, T. (2011) Recycling of laminated packaging, Wrap Project Report, http://www.wrap.org.uk/sites/files/wrap/Recycling%20of%20laminated%20packaging.pdf, accessed 1st February 2020.

Treaty (2019) Basel Convention on the Control of Transboundary Movements of Hazardous Waste (COP14), http://www.basel.int/TheConvention/ConferenceoftheParties/Meetings/COP14/tabid/7520/Default.aspx, accessed 25th February 2020.

UC (2006) Technology Evaluation and Economic Analysis of Waste Tire Pyrolysis, Gasification, and Liquefaction, State of California ,https://www2.calrecycle.ca.gov/Publications/Download/774?opt=dln, accessed 23rd April 2020.

Utility (2020) Cost of nitrogen: https://www.plantengineering.com/articles/weigh-the-benefits-of-on-site-nitrogen-generation/, cost of compressed air:

https://www.hydraulicspneumatics.com/technologies/air-compressors/article/21884932/determine-the-cost-of-compressed-air-for-your-plant; accessed 28th February 2020.

VDI (1997) VDI 2225, Konstruktonsmethodik, Technisch-wirtschaftliches konstruieren, Vereinfachte Kostenermittlung (Design engineering methodics, Engineering design at optimum cost, Simplified calculation of costs), Nov. 1997 (in German).

Vendor (2020) Hot dip galvanising oven and kettle manufacturers, Koerner (Germany) http://www.koerner-hagen.com/home.html, Westtech (US) http://www.westechgalv.com/, CBC (US) http://www.cbco.com/index.php, accessed 7th February 2020.

Westerhout, R.W.J., Van Koningsbruggen, M.P., Van Der Ham, A.G.J., Kuipers, J.A.M. and Van Swaaij, W.P.M. (1998) Techno-Economic Evaluation of High Temperature Pyrolysis Processes for Mixed Plastic Waste. Chemical Engineering Research and Design 76(3), 427-439. https://doi.org/10.1205/026387698524857.

Wikipedia (2020) List of oil refineries, https://en.wikipedia.org/wiki/List_of_oil_refineries, accessed 19th February 2020.

Williams, E.A. and Williams, P.T. (1997) Analysis of products derived from the fast pyrolysis of plastic waste. Journal of Analytical and Applied Pyrolysis 40-41, 347-363. https://doi.org/10.1016/S0165-2370(97)00048-X.

Williams, P.T. and Slaney, E. (2007) Analysis of products from the pyrolysis and liquefaction of single plastics and waste plastic mixtures. Resources, Conservation and Recycling 51(4), 754-769. https://doi.org/10.1016/j.resconrec.2006.12.002.

Yan, G., Jing, X., Wen, H. and Xiang, S. (2015) Thermal Cracking of Virgin and Waste Plastics of PP and LDPE in a Semibatch Reactor under Atmospheric Pressure. Energy & Fuels 29(4), 2289-2298. https://doi-org.ucc.idm.oclc.org/10.1021/ef502919f.

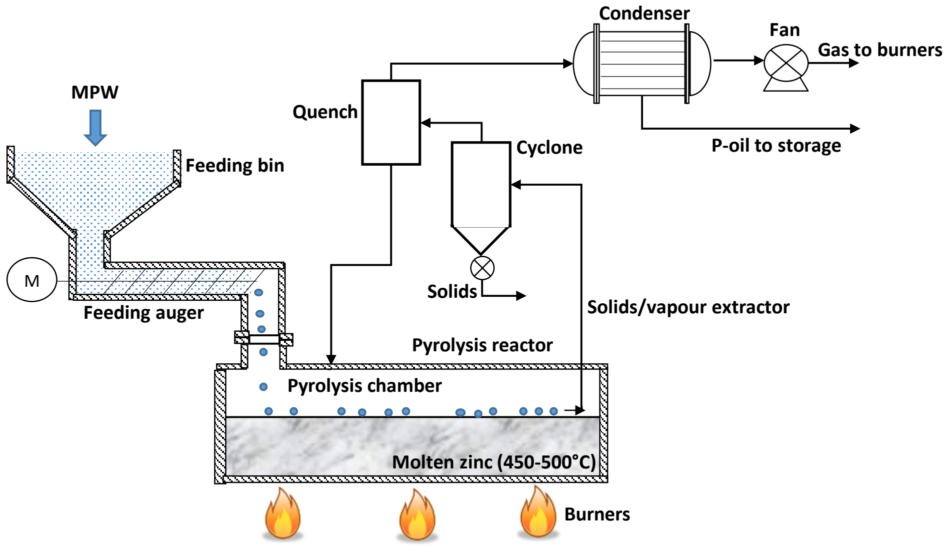

Fig. 1 On the PlastPyro process for MPW pyrolysis.

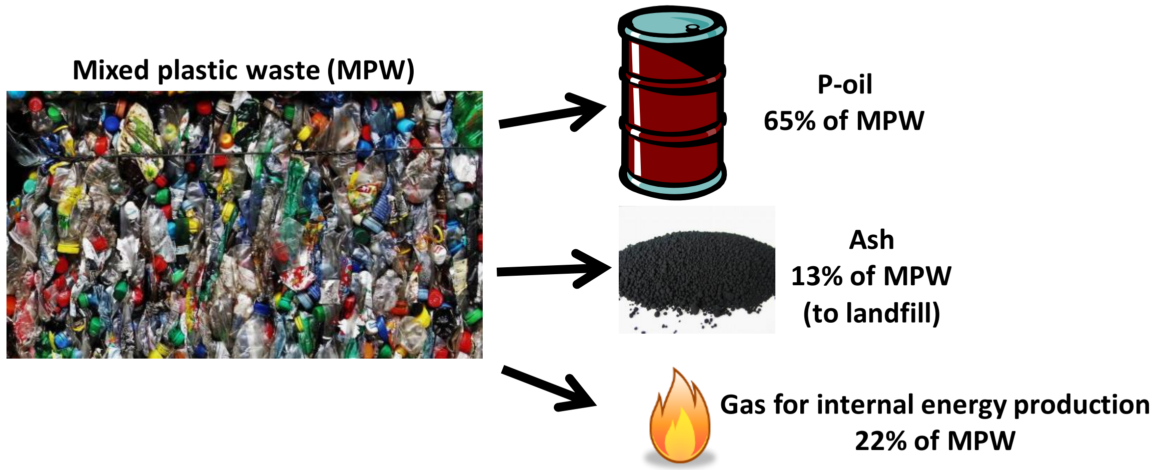

Fig. 2 P-oil, ash and gas yields from the pyrolysis of MPW as assumed for this study.

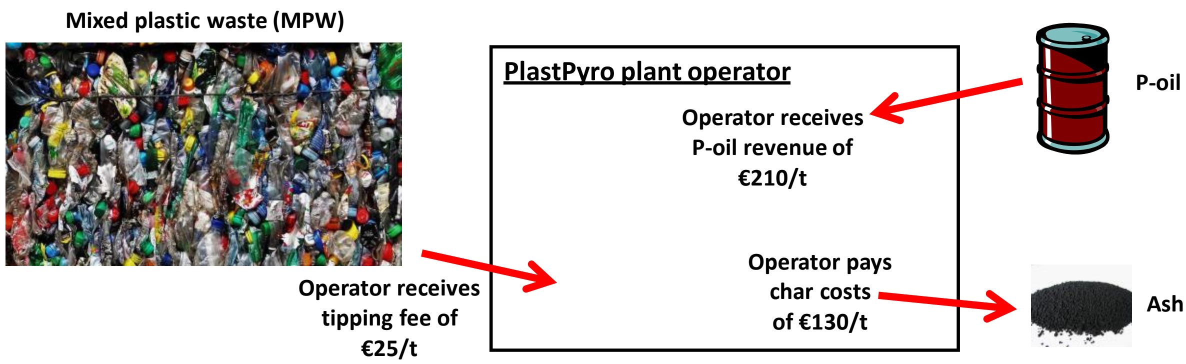

Fig. 3 Revenue streams the operator receives from a PlastPyro plant as used in this study.

Table 1 General assumptions for the economic analysis.

Parameter	Assumption
Location	Belgium e.g. Antwerp
Currency	Euro
Operating time or uptime	7,500/h per year, 85% uptime (2 weeks shutdown), 24 h, 7 days a week, 5 shift operation
Plant financing	100% Bank loan (no equity financing)
Loan period	10 years
Interest rate	5%
Inflation	3%
Plant life	20 years
Discount rate	10%
Carbon credits	None
Government support	No financial support

Table 2 Financials of a 40,000 t/y PlastPyro plant over a period of 11 years; all amounts in thousands of Euro.

Parameter	**Year**										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Revenues	0	6,460	6,654	6,853	7,059	7,271	7,489	7,714	7,945	8,183	8,429
Expenditures											
Capital	20,190										
Capital payments	-2,615	-2,615	-2,615	-2,615	-2,615	-2,615	-2,615	-2,615	-2,615	-2,615	
Personnel		-1,570	-1,617	-1,666	-1,716	-1,767	-1,820	-1,875	-1,931	-1,989	-2,048
Maintenance		-245	-253	-260	-268	-276	-284	-293	-302	-311	-320
Operating cost		-775	-798	-822	-847	-872	-898	-925	-953	-982	-1,011
Business expenses		-835	-860	-886	-913	-940	-968	-997	-1,027	-1,058	-1,090
Kettle replacement						-150					-150
Overall expenditures	-2,615	-6,040	-6,143	-6,249	-6,358	-6,620	-6,586	-6,705	-6,827	-6,954	-4,619
Profit	-2,615	420	511	605	701	651	903	1,009	1,117	1,229	3,908
Taxes	0	0	0	0	0	0	0	0	0	0	383
Capital value of plant	20,190	18,286	16,383	14,479	12,547	10,642	8,709	6,775	4,842	2,908	975
Discounted Cash Flow	-2,615	420	511	605	701	651	903	1,009	1,117	1,229	3,434
Cumulative Cash Flow	-2,615	-2,195	-1,684	-1,204	-510	136	1,037	2,046	3,167	4,402	7,929

Table 3 Classification of cost estimates in the process industries into 5 categories; adapted from (AACE, 2005; Couper et al., 2010; Holland and Wilkinson, 2007; Peters et al., 2004; Sinnott, 2005)

Type of estimate	Estimate accuracy	Purpose	Estimate methodology	Information available
Order of magnitude	Low: -20% to -50% High: +30% to +100%	Concept screening	Cost factored, engineering judgement.	Based on limited information. 0%-2% engineering completed, lab data, plant size.
Study estimate	Low: -15% to -30% High: +20% to +50%	Feasibility study, project screening	Major equipment budget quotations, factoring costing.	1%-15% engineering completed, preliminary layout drawings, flowsheets, list of major equipment.
Preliminary estimate	Low: -10% to -20% High: +10% to +30%	Authorisation of budget	Major equipment cost by quotation with minor factoring costing only.	10%-40% engineering completed; equipment list, heat & mass balance, layout drawings, P&IDs, mechanical layout.
Definite estimate	Low: -5% to -15% High: +5% to +20%	Control / tender	Quoted equipment based on preliminary specifications (process & utilities), material take off (MTO) for piping and instruments.	30%-70% engineering completed; near final P&IDs and layout drawings; motor and instrument list, control system, construction schedule.
Detailed design	Low: -3% to -10% High: +3% to +15%	Final estimate / tender	All equipment costs quoted on final specifications and final MTO for all other items.	60%-95% engineering completed; final P&IDs & layouts, piping ISOs, single line diagrams etc.

Table 4 Estimated capital cost (installed) per plant area.

Plant area	Amount
Waste material feed (weighbridge, storage, distribution, charging screws etc.)	1,843,000
Pyrolysis plant (pyrolysis chamber, burner train, ash cooler, silos etc.)	4,049,000
Quench & tankage (Quench, condensers, tanks, discharge screw, bins etc.)	1,973,000
Utilities (PSA N_2, compressed air, cooling tower and distribution systems)	924,000
Civil, warehouse, steel & piping	4,820,000
Instrumentation & control	2,115,000
Engineering	3,209,000
Contingency (8%)	1,258,000
Total CAPEX	**€20,190,000**

Table 5 Annual operating costs of a 40,000 t/y PlastPyro plant.

Annual operating cost (OPEX)	Subtotal	Amount
Annual maintenance cost (AMC)		244,700
Business expenses (e.g. rent, insurance, permits)		835,500
Electrical (motors, lights etc.)		35,393
Consumables (N_2, natural gas for start-up, zinc replacement, etc.)		63,525
Ash disposal costs (landfill)		676,000
Personnel costs		
Plant operators (4 per shift; 5-shift operation); 20 total	1,100,000	-
Yard team & maintenance; 6 total	350,000	-
Management & Engineering; 3 total	210,000	-
Total Personal cost		1,570,000
Total OPEX		**€3,425,414/y**