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

## 3 a plant located in Belgium

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# 14 Abstract

15 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 16 process, called PlastPyro, located in Belgium, to an accuracy of ±15% i.e. "Definite 17 18 Estimate". The process uses molten metal in a direct heat treatment process to 19 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 20 expenditure (CAPEX) is estimated to be €20.1m or €26.1m if the cost of capital is 21 22 included. The operating expenditures (OPEX) of the plant are estimated €3.4m per 23 year. The sensitivity analysis shows six main variables having major impacts on the 24 financial returns of a PlastPyro plant: (1) the addressable volume and quality of 25 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 26 27 and (6) the potential to co-locate a PlastPyro plant with a waste plastic sorting 28 facility. For example, the 15-year low P-oil revenue price of €210/t results in an IRR of 20%; but on the 6<sup>th</sup> of March 2020 the P-oil price may have achieved €227/t, 29 30 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, 31 32 cost estimates should state their accuracy and usually factorial cost estimates are 33 not accurate enough to state the IRR.

34

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

37

# 38 **1. Introduction**

39 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 40 recycling rate is due to a number of factors: (1) Waste plastic bags, polystyrene 41 42 packaging or coffee cups can only be recycled if the material is available in clean, 43 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., 44 45 2017); (3i) Most plastics polymer chains break down during reprocessing and, as a 46 result, many plastics can only be recycled once or twice (Anonymous, 2017). 47

48 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 49 (MPW) is a waste stream composed of different plastics, often various colours and is 50 51 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 52 (Chruszcz and Reeve, 2018; Punkkinen et al., 2017). In the United Kingdom, MPW 53 54 consists of various plastics with an average composition of 38.5% polyethylene. 55 22.5% polypropylene, 15.3% polyethylene terephthalate, 4% polystyrene, 3.5% polyvinylchloride and 16.5% contamination (Chruszcz and Reeve, 2018; Foster, 56 57 2008).

58

59 For many countries, a convenient outlet for mixed waste plastic used to be China, 60 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

- 62 meeting the quality demands of the plastic reprocessing sector i.e. plastic waste
- 63 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
- 66 unsuitable for reprocessing without extensive pre-processing. After the Chinese ban,
- 67 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
- 69 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).
- 73

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 10<sup>th</sup> 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).

81

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 longchain plastic macromolecules into smaller ones in the absence of oxygen (Achilias et al., 2007; Aguado et al., 2002; Yan et al., 2015).

88

89 The chemistry of plastic pyrolysis is complex as four cracking mechanisms are 90 involved, namely end-chain scission or unzipping, random chain scission, chain 91 stripping, and cross-linking (Panda et al., 2010). As each plastic type has different 92 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, 93 94 propane etc.) (Ciliz et al., 2004; Williams, Elizabeth and Williams, 1997; Williams, 95 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 96

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).

103

The pyrolysis operating temperature is one of the main parameters determining the 104 yield and composition of the pyrolysis products, and its influence has been 105 extensively studied (Al-Salem et al., 2017; Lopez et al., 2017; Panda et al., 2010; 106 Sharuddin et al., 2016; Williams, Elizabeth A. and Williams, 1997; Williams, Paul T. 107 108 and Slaney, 2007). It was found that higher operating temperatures result in higher 109 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 110 pyrolysis, ranges from of 400 to 550°C (Al-Salem et al., 2017; Sharuddin et al., 2016; 111

- 112 Williams, Elizabeth A. and Williams, 1997).
- 113

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).

120 /

122 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 123 compare and assess their validity. Westerhout et al. (1998) assessed three different 124 125 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 126 pyrolysis plant located in Malaysia (Sahu et al., 2014). A catalytic fluidised bed 127 reactor was simulated using ASPEN, and the economic performance analysed, 128 129 showing that the plant must have a throughput of at least 120,000 t/y to be 130 economically viable with an investment cost of \$58 million. Fivga and Dimitriou (2018) used ASPEN to investigate the economic performance of another fluidised 131 132 bed reactor with three different throughputs (1,000, 10,000, and 100,000 kg/h). The 133 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 134 135 800,000 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 136 circumstances. A recent study (Jiang et al., 2020), again using ASPEN, reports on 137 the economic performance of a molten salt MPW pyrolysis plant, which found that a 138 16,000 t/y plant achieves an internal rate of return (IRR) of 33%. Larrain et al., 139 (2020), estimated that the minimum throughput of a waste plastic pyrolysis plant 140 141 must be about 80,000 t/y to achieve an IRR of at least 15% i.e. being economically 142 viable. The preferred throughput is, however, 120,000 t/y to achieve the financial 143 returns which may satisfy investors. 144

Pyrolysis is advocated by some conservation pressure groups, for example, theOcean Recovery Alliance, as an environmentally sound plastic waste treatment

147 option (ORA, 2015). Moreover, a life cycle analysis of plastic pyrolysis shows that 148 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 149 success (Gleis, 2012). The main reason why conventional rotary kilns, or their 150 variations, are uneconomical is that they cannot be scaled up beyond a throughput 151 of 10,000 t/y (Haig et al., 2010; Punkkinen et al., 2017). Instead, two or more rotary 152 153 kiln reactors must be installed in parallel to achieve commercially attractive throughput requirements (Haig et al., 2010; Punkkinen et al., 2017). 154 155 156 This paper investigates the economics of a future, commercial scale MPW pyrolysis

157

process, named PlastPyro. The I economic analysis aims to determine under which 158 conditions a PlastPyro plant is financially interesting for private investors, as MPW 159 recycling plants will only be built and operated if the financial incentive is large 160 enough. The difficulty of an economic analysis are the many uncertainties when trying to predict future market conditions. Consequently, this paper takes the worst-161 162 case approach, i.e., the lower revenue stream, the lower yield and the lower gate

163 fee. This reduces the revenue stream an operator achieves, resulting in a more 164 conservative estimate of the financial returns.

165

#### The PlastPyro process 166 2.

The PlastPyro process brings MPW into direct contact with molten zinc, which is held 167 at an operating temperature of 450°C. A reaction time of 10 minutes was chosen as 168 169 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 170 171 pyrolyse faster; and (2) Zincoxide (ZnO), which is part of the slag floating on the 172 molten zinc, is a catalyst, increasing the plastic pyrolysis reaction rate (Ahmad et al., 173 2017; Miandad et al., 2016).

174

175 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 176 feeding auger into the pyrolysis chamber, i.e., onto molten zinc, which is held at a 177 temperature between 450 and 500°C. On the molten zinc, the MPW pyrolyzes into 178 179 hydrocarbon vapours, gases and solids. The solids, a carbon rich ash, float on the 180 molten zinc. The vapours and the solids are removed simultaneously from the 181 pyrolysis chamber via a solids/vapour extractor in a hoover-like fashion. The solids 182 are separated from the vapours by a cyclone and exit the system via a rotary valve. 183 A quench may be installed to separate the waxes (longer chain hydrocarbons) and 184 return them to the pyrolysis chamber to be cracked into smaller molecules. The 185 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 186 187 methane, propane and other gases. These may be (1) sent to the burner(s) to heat 188 the pyrolysis process, making it self-sustaining, (2) used to generate electricity or (3) 189 both of the previous options. The molten zinc is the heat transfer media only and is 190 not consumed by the process.

191

192 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 193

194 (Maaß and Peißker, 2011) while the safety of the remaining process matches those

from the chemical industry (Crowl and Louvar, 2011). 195

### 197 **2.1. P-oil yield**

198 Depending on the plastic-type, the P-oil yield varies. Pure, single type, 199 uncontaminated mixed plastic waste may have a P-oil yield as high as 90wt% 200 (Sharuddin et al., 2016), whereas Aguado et al. (Aguado et al., 2002) report on 201 yields between 80 and 92wt% for various plastics. But as MPW is of varied 202 composition, the yields are best given as a range: Haig et al., 2010 state that the P-203 oil yield of MPW pyrolysis is between 67 and 80wt%, the solids yield 2 to 15wt% and 204 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, 205 206 electricity generation. This work also assumes that the solids do not offer any 207 commercial value and that they are landfilled. Furthermore, this study takes a low P-208 oil yield of 65wt% and a high solid yield of 13wt%, making the financial returns more 209 conservative (summarised in Fig. 2).

210

## 211 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.

215

## 216 **3.1. Waste plastics market**

217 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 218 219 500,000 tonnes of MPW were collected in 2015 (Chruszcz and Reeve, 2018). Both 220 statistics indicate the scale of the non-recyclable plastic waste in the EU, the UK and 221 indeed worldwide. To make any inroads into MPW treatment, the facility is assumed 222 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 223 224 collection and sorting operation. Therefore, no shortage of mixed, non-recyclable 225 plastics waste is predicted.

226

227 On the contrary, the global plastic production currently stands at some 400 million 228 tons per year, and in tandem, plastic waste is predicted to double until 2035 as 229 plastic is such a useful material (EEA, 2019).

230

## 231 **3.2. P-oil market**

P-oil, the product from a plastic pyrolysis process, has a high economic value (Runkkingen et al. 2017: Sharuddin et al. 2016: Slater and Crichton 2011). The R oil

(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).
- 239

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.

249

250 With the emergence of the US shale oil boom in 2010, the price of crude oil went 251 downwards. This trend reached a bottom in February 2016 when the crude oil price 252 sank to a 15-year low of \$28.14/barrel (EIA, 2020). This oil price was so low that 253 some shale oil companies reduced production as their margins became 254 uneconomical (Economist, 2015). At that time, US refineries received \$1.2/gallon or 255 €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 256 257 revenue figure of €210/t for the PlastPyro operator was calculated.

258

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<sup>3</sup>/d (Wikipedia,
2020). Hence, even a 100,000 m<sup>3</sup>/y or 280 m<sup>3</sup>/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.

266

## **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  $\in$ 50 and  $\in$ 80/t (CEWEP, 2017). For this economic assessment, a tipping fee of  $\in$ 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.

## 274 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:

282 NPV = 
$$\sum_{t=0}^{n} \frac{CF_t}{(1+k)^t}$$
 (1)

283

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

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

- 287 mathematically:
- 288

289 NPV = 0 = 
$$\sum_{t=0}^{n} \frac{CF_t}{(1 + IRR)^t}$$
 (2)

291 The IRR gives an indication of the relative return of an investment without taking the 292 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 293 294 investors if the IRR exceeds 15% (Riedewald, 2020a). Privately operated waste 295 companies require an IRR of 15% for new technologies and 10% for established 296 ones (Riedewald, 2020b). In special circumstances, the IRRs of waste management 297 plants may be lower than 15% and still considered investable. In one municipal 298 waste incinerator project, with discount rates as low as 3.3%, the IRR was just 6.9%, 299 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 300 government supported investments. For the purposes of this financial evaluation 301 302 study, a desired minimum IRR of 20% is assumed. The reason for setting a more 303 challenging IRR target value of 20% is that financial uncertainties on the revenue 304 stream exist. The evaluation period of the IRR is 10 years (same as the bank loan 305 period).

306

307 The location of the plant is assumed to be in Belgium, close to Antwerp. This location 308 has a relatively high-cost base, but is also close to major areas of population with 309 heavy industry minimising transportation costs for both waste materials and products. It is further assumed that all considerations made in the market analysis 310 311 chapter for the UK also apply for Belgium. Furthermore, it is assumed that the 312 PlastPyro operator has a 10-year contract with a waste sorting facility, which ensures 313 a continuous and reliable supply of waste plastics. Moreover, it is assumed that state 314 financial support is not available; that the uptime of the plant is 85% equating to 315 7,500 hours per year which includes a 2-week annual plant shutdown. All prices 316 were estimated or obtained in January or February 2020. An inflation rate of 3%, an 317 interest rate of 5% and a discount rate of 10% was applied. Finally, the plant life is 318 20 years. All of these assumptions are summarised in Table 1.

319

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.

325

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

328

#### 329 **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

- 337 required, demanding a higher level of engineering: P&IDs, layout drawings, and 338 detailed piping and instrumentation costs are necessary (AACE, 2005).
- 339

340 Commercial quotations for the major pieces of equipment were obtained based on engineering specifications, which also established the technical feasibility of the 341 342 PlastPyro plant. For smaller pieces of equipment such as pumps, historical prices 343 were used. The tankfarm, equipped with two 100 m<sup>3</sup> above ground, 304 stainless steel P-oil storage tanks according to EN 12285-2, includes pipes, instrumentation, 344 pumps etc. and was quoted as a complete package. Table 4 gives a breakdown of 345 346 the CAPEX per plant area, the instrumentation & control and utilities.

347

348 The molten zinc pyrolysis reactor was sized as follows: a reactor with a molten zinc 349 area of 22 m length and 2 m width has an estimated MPW throughput of 42,000 t/y 350 based on a 10-minute reaction time. The molten zinc depth is 1.5 m allowing space 351 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 352 been used. The reactor is filled with 69 m<sup>3</sup> of zinc at a cost of €740,520. According to 353 hot-dip galvanising plant manufactures (Vendor, 2020), the maximum dimension of a 354 molten zinc kettle is 25 m long, 3.5 m wide and 4 m deep. Therefore, the size chosen 355 356 is well within the maximum size of a molten zinc kettle.

357

358 The layout of the PlastPyro plant is relatively compact and small with the pyrolysis 359 chamber requiring the largest footprint. The pyrolysis chamber, cyclone, quench 360 reactor and condensers are very close to each other, minimising pipe runs. The 361 installation cost of the equipment was estimated by comparing it with similar plants 362 and checking those costs with references (Page, 1999a; Page, 1999b). The civil costs associated with the installation of the weighbridge, tankfarm and other 363 equipment was also based on similar plants and checked with references (Page, 364 365 1999a: Page, 1999b). A material take-off for piping (diameter, length, specification) and instruments (temperature, pressure, level, control, etc.) was performed. The 366 367 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. 368 Instrumentation and electrical costs were based on historical prices from other 369 370 plants.

371

372 A warehouse large enough to store two days' worth of plastic waste is included at a 373 cost of €2.9m. This warehouse also includes offices, a canteen and other facilities. 374

375 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 376 is estimated at a higher percentage, as it is the first of its kind requiring more 377 378 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 379 suggested by Peters et al. (Peters et al., 2004). This contingency is an allowance for 380 381 uncertainties, as estimating is not an exact science. Acts of God, such as 382 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, 383 384 ringfencing capital for returning the site to its former condition should the company go bankrupt. 385

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.

392

#### 393 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.
- 405

406 The consumables (nitrogen, compressed air, water, etc.) are estimated to amount to 407 €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, 408 409 2019) or €35,400/y. Natural gas is required for start-up and holding the plant at the 410 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 411 be used at a rate of 20 m<sup>3</sup>/h at a cost of €0.03/m<sup>3</sup> (Utility, 2020) or €4,500/y. Nitrogen 412 413 is consumed at a rate of 30 m<sup>3</sup>/h at an estimated running cost for the PSA (pressure swing adsorption) plant of €0.07/m<sup>3</sup> (Utility, 2020) amounting to €15,750/y. Also 414 included are zinc losses, estimated to amount to €1,300/y or 0.1 kg/h. The zinc 415 416 losses are associated with evaporation and are grossly overstated. Ideally, the waste 417 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 418 419 and to treat to emission limits. Overall a cost of €27,000/y is allowed for waste usage 420 and offsite wastewater treatment. 421

- 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.
- 425

426 Twentynine personnel, at a cost of €1.57m per year, are employed to operate the 427 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 428 429 also more expensive, providing a more significant financial challenge for the 430 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 431 432 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 433 434 Table 5 (average industrial wage in Belgium: €60,000/y (Eurostat, 2018)). 435

436 The OPEX also includes: (1) The insurance cost of the plant is estimated at 1% of 437 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 438 439 replacement necessary (Maaß and Peißker, 2011). A five-year kettle replacement frequency at a cost of  $\leq 150,000$  is assumed. (3) Rent for the site is  $\leq 360,000/y$ , 440 whereas rates, office expenses, heating, telecom, professional fees, permits and 441 442 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. 443

444

### 445 **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%.

448

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

451

### 452 **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.

457

## 458 **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:

462

463 **Revenue:** (1) P-oil: As the P-oil revenue contributes 84.5% to the overall revenue of 464 the plant, any variation in its sales price or yield will significantly influence the financial returns of the plant. On the 6<sup>th</sup> of March 2020, the Brent oil price was 465 \$52.02/barrel, equating to a P-oil sales price of €227/t, resulting in an IRR of 37%. 466 467 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 468 469 reduces to 4%; likewise, a P-oil yield increase by 5% increases the IRR to 36%. 470 Indeed, the better the quality or contamination free the plastic waste is, the better the 471 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, 472 473 2017) – will result in an IRR increase from 20 to 45%. Therefore, any tipping fee 474 increase would be beneficial for the financial returns of the plant and would likely 475 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. 476 477

478 CAPEX: Increasing the CAPEX by +10% results in an IRR decrease from 21 to 8%,
479 demonstrating that CAPEX spending has a significant influence on the financial
480 returns. Moreover, it also shows that CAPEX spending must be tightly controlled.
481

- 482 **OPEX**: Increasing the OPEX by +20% reduces the IRR by sixteen percentage
- 483 points. Consequently, an operator must tightly control the operating costs (salaries,

- 484 business expenditures, etc.). A simple way to decrease the OPEX is to run the plant 485 on a 4 rather than a 5-shift operation increasing the IRR to 27%.
- 486
- 487 **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%.
- 490
- 491 Throughput: Increasing the plant capacity to 50,000 t/y results in an increase of the
   492 IRR to 59%, although both CAPEX and OPEX were increased by 10% to account for
   493 the larger throughput.
- 494

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

- 501
- 502 Combinations of the measures above may also be possible, for example, a 4-shift 503 operation and co-locating the plant with a municipal waste sorting facility. But such 504 combinations were not investigated by this study.
- 505 In summary, the IRR of a 40,000 t/y PlastPyro plant is most sensitive to variations in 506 the sale price of the P-oil, tipping fees, CAPEX, OPEX, and the interest rate charged. 507

## 508 6. Discussion

509 From the financial analysis of a 40,000 t/y or larger MPW PlastPyro plant, it can be 510 concluded that such a plant is economic as it achieves an IRR of over 20% with 511 meagre oil prices. Moreover, a reliable, ample supply of MPW is available as are 512 reliable, accessible markets for the P-oil.

513

514 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 515 in this paper were based on estimated 15-year low prices for the P-oil and other 516 517 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 518 519 cost estimate, as the plant location has a significant influence on the financial 520 returns. Moreover, commercial agreements must be put in place to accurately predict 521 the financial returns of an MPW recycling plant.

522

523 From an environmental and financial perspective, PlastPyro plants with throughputs 524 exceeding 40,000 t/y may be desirable. The amount of MPW available would justify 525 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 526 527 plants are also desirable, having higher IRRs due to increased economies of scale. 528 Such large throughput plants are possible with a PlastPyro reactor as it can be made 529 even larger than assumed in this paper, allowing higher throughputs. But MPW transport distances will become increasingly challenging with higher throughput 530 531 plants as the transport cost of bringing the MPW from distances further away 532 increases.

534 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 535 536 location and other parameters. However, should such a plant operate with low 537 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. 538 539 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 540 CAPEX of facilities with multiple reactors operating in parallel would be higher 541 542 compared to a PlastPyro plant with just one reactor. As a result, the economics of a 543 PlastPyro plant with one reactor is better than plants with multiple lower throughput 544 reactors. 545

546 This study is accurate to  $\pm 15\%$ , making it the most accurate economic study of an 547 MPW pyrolysis plant available in the literature. With such an accuracy, the predicted 548 IRR of 20% can be stated with a high degree of confidence. Moreover, in light of this 549 study, comments can be made on other studies assessing the financial performance 550 of various full-scale MPW pyrolysis plants.

551

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).

558

559 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. 560 561 According to the Association for the Advancement of Cost Engineering (AACE) (AACE, 2005), the factored cost estimate method has the lowest level of accuracy 562 563 (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 564 classifications given in Table 3. Moreover, they applied the factored cost estimate as 565 566 intended by comparing three different reactor types with the same throughput to find 567 the one with the highest financial returns; that is, they were concept screening. 568

Sahu et al. (2014), Fivga and Dimitriou (2018) and Jiang et al. (2020), on the other 569 570 hand, all omit to state the accuracy of their cost estimates and therefore these 571 studies may give a false impression of accuracy. Fivga and Dimitriou (2018) may 572 also have exceeded the validity of the factorial method. They estimated the economic performances of MPW pyrolysis plant with throughputs of 1,000, 10,000 573 574 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 575 breaking down. Scaling from a 1,000 to a 100,000 t/y plant using factored methods 576 577 may work mathematically, but expecting a good cost accuracy is guestionable to say 578 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 579 580 recycling plant would be excessively large and unrealistic.

- Jiang et al. (2020) estimated the economics of a 16,000 t/y molten salt MPW
- 583 pyrolysis plant and concluded that such a plant achieves an IRR of 33%; an
- 584 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
- 586 Fivga and Dimitriou (2018). Such a revenue value is 3.5 times higher than the P-oil 587 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
- 589 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.
- 592 593

594 Clearly, accurate cost estimates require more effort than factored estimates.

- 595 Factored cost estimates may be convenient as they are fast and easy to do, but 596 should only be used for project screening i.e. comparing one option with another.
- 597 **7. Conclusion**
- 598 From the economic analysis, it can be concluded that a PlastPyro plant is economic 599 from a throughput of 40,000 t/y onwards. Plants with a higher throughput will result in 600 improved financials, due to increased economies of scale.
- 601

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.

606

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.

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- 611

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**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 thisstudy.

# **Table 1** General assumptions for the economic analysis.

Parameter	Assumption
Location	Belgium e.g. Antwerp
Currency	Euro
Operating time or	7,500/h per year, 85% uptime (2 weeks shutdown), 24 h, 7 days a
uptime	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

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

**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.
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**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 <sub>2</sub> , 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

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98.3	<b>Lable 5</b> Annual operating	COSTS OF A 4U	()()() T/V P	lastevro plant
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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 <sub>2</sub> , 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/