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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 a plant located in Belgium

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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 $\pm 15\%$ 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).

48 A plastic waste stream composed of a single, clean plastic-type often has a
49 commercial value and may be recycled back to virgin plastic. But mixed plastic waste
50 (MPW) is a waste stream composed of different plastics, often various colours and is
51 usually contaminated with foreign objects, turning it into a stream for which a waste
52 collection company has to pay for to landfill or incinerating it as it cannot be recycled
53 (Chruszcz and Reeve, 2018; Punkkinen et al., 2017). In the United Kingdom, MPW
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%
56 polyvinylchloride and 16.5% contamination (Chruszcz and Reeve, 2018; Foster,
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
61 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
64 very few plastic waste streams meet. Household plastics waste, for example,
65 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
68 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
70 and non-recyclable (FAZ, 2020). In response to the Chinese ban, many municipals in
71 Europe and the US are now sending more plastic waste to landfill or incineration as
72 recycling at home is too expensive (FT, 2018; NYT, 2019).

73
74 In the meantime, the regulatory pressure to increase waste plastic recycling is
75 stepping up. In January 2018, the EU Plastics Strategy (Commission, 2018)
76 designated plastic waste recycling as a priority in the Circular Economy Action Plan
77 (Commission, 2015), and on the 10th of May 2019, the EU, along with most other
78 states of the world (the US a notable exception), agreed to reclassify plastic waste
79 as hazardous, significantly reducing the capabilities to legally export plastic waste to
80 the third world (RT, 2019; Treaty, 2019).

81
82 Pyrolysis has long been identified as an ideal process to recycle MPW and pure
83 plastics (Aguado et al., 2002; Punkkinen et al., 2017; Sharuddin et al., 2016) and
84 maybe one of the solutions to manage the growing amounts of plastic waste
85 (Czajczynska et al., 2017; EEA, 2019). Pyrolysis is the process of cracking the long-
86 chain plastic macromolecules into smaller ones in the absence of oxygen (Achilias et
87 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
93 are also complex in composition. The gas is a mixture of light organics (methane,
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
96 it self-sustaining (Haig et al., 2010). The pyrolysis oil (P-oil) is a mixture of hundreds

97 of hydrocarbons (Bhaskar et al., 2003; Ciliz et al., 2004; Dobó et al., 2019; Miandad
98 et al., 2017; Williams, Elizabeth and Williams, 1997; Williams, Paul and Slaney,
99 2007) and may be upgraded to a transport fuel such as diesel, used as a basic
100 chemical or both (Dobó et al., 2019; Lopez et al., 2017). Finally, the solids are a
101 carbon-rich ash, which may, for instance, be used as a solid fuel (Jamradloedluk and
102 Lertsatitthanakorn, 2014; Williams, Elizabeth A. and Williams, 1997).

103

104 The pyrolysis operating temperature is one of the main parameters determining the
105 yield and composition of the pyrolysis products, and its influence has been
106 extensively studied (Al-Salem et al., 2017; Lopez et al., 2017; Panda et al., 2010;
107 Sharuddin et al., 2016; Williams, Elizabeth A. and Williams, 1997; Williams, Paul T.
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
110 temperature maximising the P-oil yield, the most valuable product of plastic
111 pyrolysis, ranges from of 400 to 550°C (Al-Salem et al., 2017; Sharuddin et al., 2016;
112 Williams, Elizabeth A. and Williams, 1997).

113

114 One advantage of pyrolysis over other plastic recycling processes is that plastic
115 contaminated with food residue can be treated, eliminating an expensive washing
116 step. Moreover, sorting by colours and plastic-type is not necessary (Punkkinen et
117 al., 2017; Sharuddin et al., 2016; Slater and Crichton, 2011). Notably, the financial
118 returns from plastic pyrolysis are higher than the financial returns from chemical
119 depolymerisation or gasification as the capital requirements are lower (Haig et al.,
120 2010).

121

122 Few studies assessing the economic performance of an MPW pyrolysis plant are
123 available in the literature and all of these studies lack detail, making it difficult to
124 compare and assess their validity. Westerhout et al. (1998) assessed three different
125 reactors i.e. a bubbling fluidised bed, a circulating fluidised bed and a rotating cone.
126 Another study investigated the economic performance of a plastic waste to fuel
127 pyrolysis plant located in Malaysia (Sahu et al., 2014). A catalytic fluidised bed
128 reactor was simulated using ASPEN, and the economic performance analysed,
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
131 (2018) used ASPEN to investigate the economic performance of another fluidised
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.
134 Such a plant would be huge, as 100,000 kg/h equates to a yearly throughput of
135 800,000 tons, which is a higher throughput than the MPW collected in the UK in
136 2015 (Chruszcz and Reeve, 2018) making such a plant unrealistic for most
137 circumstances. A recent study (Jiang et al., 2020), again using ASPEN, reports on
138 the economic performance of a molten salt MPW pyrolysis plant, which found that a
139 16,000 t/y plant achieves an internal rate of return (IRR) of 33%. Larrain et al.,
140 (2020), estimated that the minimum throughput of a waste plastic pyrolysis plant
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

145 Pyrolysis is advocated by some conservation pressure groups, for example, the
146 Ocean 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
149 pyrolysis based on conventional rotary kiln technology has not been a commercial
150 success (Gleis, 2012). The main reason why conventional rotary kilns, or their
151 variations, are uneconomical is that they cannot be scaled up beyond a throughput
152 of 10,000 t/y (Haig et al., 2010; Punkkinen et al., 2017). Instead, two or more rotary
153 kiln reactors must be installed in parallel to achieve commercially attractive
154 throughput requirements (Haig et al., 2010; Punkkinen et al., 2017).

155

156 This paper investigates the economics of a future, commercial scale MPW pyrolysis
157 process, named PlastPyro. The 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
161 trying to predict future market conditions. Consequently, this paper takes the worst-
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

166 **2. The PlastPyro process**

167 The PlastPyro process brings MPW into direct contact with molten zinc, which is held
168 at an operating temperature of 450°C. A reaction time of 10 minutes was chosen as
169 the design parameter for the PlastPyro process for two reasons: (1) Whole tyres
170 pyrolyse within 15 minutes on molten zinc (Rathsack et al., 2015), but plastic should
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
176 shown in Fig. 1. The MPW is provided in a feeding bin and is transported by a
177 feeding auger into the pyrolysis chamber, i.e., onto molten zinc, which is held at a
178 temperature between 450 and 500°C. On the molten zinc, the MPW pyrolyzes into
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
186 suction force to remove the vapour and solids. The non-condensable gases include
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
193 standards (EN, 2000; Riedewald et al., 2015) from the hot-dip galvanising industry
194 (Maaß and Peißker, 2011) while the safety of the remaining process matches those
195 from the chemical industry (Crowl and Louvar, 2011).

196

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 to 10wt%. This study assumes that all the gases are used for internal
205 energy generation and are therefore not available for other uses; for example,
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**

212 A market analysis on waste plastic pyrolysis was carried out to establish: (1) the
213 addressable MPW volumes, (2) the price for the products of plastic pyrolysis i.e. P-oil
214 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
218 recycling or 3 million tons to Asia, mostly to China (EEA, 2012). In the UK just over
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
223 recycling plant is located close to a large city with an efficient municipal plastic waste
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**

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

239

240 Therefore, for the purpose of this economic study, it is assumed that the P-oil is sold
241 as Fuel Oil No. 6 (US specification) or Heavy Bunker Oil (European specification) to
242 an oil refinery, as the properties of these are similar to P-oil. Such fuels are used in

243 the shipping industry, are of relatively low quality, and, hence, the revenue
244 achievable from such fuels is relatively low. The P-oil may command a higher price,
245 as fuels produced from plastic waste have lower sulphur levels than conventional
246 petroleum fuels, as plastic contains no sulphur. This potentially higher price is
247 ignored as the P-oil market is uncertain and, therefore, it is prudent to assume a
248 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
256 for the refinery and a transport cost of €40/t (Bains and Robinson, 2012), a P-oil
257 revenue figure of €210/t for the PlastPyro operator was calculated.

258

259 Selling the P-oil to an oil refinery should be put into context. For instance, the TOTAL
260 oil refinery in Antwerp, Belgium, has an oil throughput of 57,000 m³/d (Wikipedia,
261 2020). Hence, even a 100,000 m³/y or 280 m³/d addition of P-oil generated from the
262 pyrolysis of ca. 154,000 t/y of MPW is negligible as an input for most oil refineries.

263

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

266

267 **3.3. Tipping fee**

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

273

274 **4. Financial assessment**

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

281

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

283

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

285

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

288

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

290

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
 293 projects such as a waste plastic pyrolysis plants are considered profitable by private
 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
 300 investment (CSIL, Various Years). But these are financially secure, and long-term
 301 government supported investments. For the purposes of this financial evaluation
 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
 310 products. It is further assumed that all considerations made in the market analysis
 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

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

325

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

328

329 **4.1. Capital expenditure**

330 The capital expenditure (CAPEX) of a 40,000 t/y PlastPyro plant may be estimated
 331 by various methods depending on the desired accuracy and the available
 332 information. Aiming at an accuracy of ±15% places this estimate according to Table
 333 3 between “Preliminary Estimate” and “Definite Estimate”. To achieve a ±15%
 334 accuracy, factorial estimating techniques by, for instance, the VDI standard 2225
 335 (VDI, 1997) or given in (Couper et al., 2010; Holland and Wilkinson, 2007; Peters et
 336 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
341 engineering specifications, which also established the technical feasibility of the
342 PlastPyro plant. For smaller pieces of equipment such as pumps, historical prices
343 were used. The tankfarm, equipped with two 100 m³ above ground, 304 stainless
344 steel P-oil storage tanks according to EN 12285-2, includes pipes, instrumentation,
345 pumps etc. and was quoted as a complete package. Table 4 gives a breakdown of
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
352 a throughput of only 40,000 t/y is specified and hence a smaller reactor could have
353 been used. The reactor is filled with 69 m³ of zinc at a cost of €740,520. According to
354 hot-dip galvanising plant manufactures (Vendor, 2020), the maximum dimension of a
355 molten zinc kettle is 25 m long, 3.5 m wide and 4 m deep. Therefore, the size chosen
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
363 costs associated with the installation of the weighbridge, tankfarm and other
364 equipment was also based on similar plants and checked with references (Page,
365 1999a; Page, 1999b). A material take-off for piping (diameter, length, specification)
366 and instruments (temperature, pressure, level, control, etc.) was performed. The
367 prices for the supply, installation and testing of the piping were provided by a
368 mechanical contractor. Insulation and heat tracing, if applicable, is also included.
369 Instrumentation and electrical costs were based on historical prices from other
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
376 plant is estimated to be 15% of the CAPEX. The engineering effort for the first plant
377 is estimated at a higher percentage, as it is the first of its kind requiring more
378 engineering input, whereas the engineering for subsequent plants may be set at 9%
379 CAPEX. A contingency of 8% CAPEX (excluding engineering costs) is included as
380 suggested by Peters et al. (Peters et al., 2004). This contingency is an allowance for
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
383 bond for site remediation is also included in the CAPEX. Such a bond is not unusual,
384 ringfencing capital for returning the site to its former condition should the company
385 go bankrupt.

386

387 The CAPEX is not spent equally across the three-year design and commissioning
388 phases of the plant. Instead, the CAPEX spending schedule is 20% in year 1, 50% in
389 year 2 (including purchase of long-lead items, for example, the pyrolysis plant,
390 quench and condensers) and 30% in year 3. The design and project management
391 CAPEX is spent at a rate of 2.5 to 5% each month throughout the project.
392

393 **4.2. Operating expenditure**

394 The operating expenditures (OPEX) of the plant are anticipated to be €3.4m per
395 year. These costs consist of direct (operating materials or consumables, salaries,
396 maintenance, etc.), indirect (depreciation, taxes, etc.), and general costs
397 (administration, permits, travel, insurance, etc.) and are summarised in Table 5.
398

399 The annual maintenance costs (AMC) is estimated as typical for chemical plants
400 (Peters et al., 2004). The AMC of the material handling part of the plant is estimated
401 4.0% of CAPEX, due to the high number of moving parts; the AMC of the utilities
402 plant at 1.5% of CAPEX, the civil at 0.1% of CAPEX, whereas the AMC for the
403 remaining plant is estimated at 3% of CAPEX. The yearly maintenance cost is an
404 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
408 (fan and pump motors, lights etc.) of the plant, at a cost of €0.13/kWh (Commission,
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
411 €15,000/y at a unit cost of €0.04/kWh (Utility, 2020). Compressed air is estimated to
412 be used at a rate of 20 m³/h at a cost of €0.03/m³ (Utility, 2020) or €4,500/y. Nitrogen
413 is consumed at a rate of 30 m³/h at an estimated running cost for the PSA (pressure
414 swing adsorption) plant of €0.07/m³ (Utility, 2020) amounting to €15,750/y. Also
415 included are zinc losses, estimated to amount to €1,300/y or 0.1 kg/h. The zinc
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
418 pyrolysis process. Water is expensive to evaporate, condense, remove from the P-oil
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

422 The ash from the plastic pyrolysis is landfilled. In Belgium, the upper range of the
423 landfill fee is €80/t (CEWEP, 2017). Adding transport costs of €50/t (solids) to that
424 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
428 five-shift working schedule was used for this study as it is best for flexibility, but it is
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
431 estimated based on the operation of the plant, whereas the number of administrative
432 and management personnel was based on similar chemical plants. The personnel
433 cost varies between €50,000/y and €90,000/y depending on duties; summarised in
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.,
438 2004) or €15,000/y. (2) Molten zinc corrodes stainless steel making regular kettle
439 replacement necessary (Maaß and Peißker, 2011). A five-year kettle replacement
440 frequency at a cost of €150,000 is assumed. (3) Rent for the site is €360,000/y,
441 whereas rates, office expenses, heating, telecom, professional fees, permits and
442 other expenses amount to €118,000/y. (4) Finally, an annual licence fee of €200,000
443 payable to the owner of the PlastPyro technology is included.
444

445 **4.3. Revenue and depreciation**

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

448
449 The equipment is depreciated depending on their expected life-span on a straight-
450 line basis, either 5, 10 or 20 years.
451

452 **4.4. Throughput and market potential**

453 The worldwide market, based on studies (ACC, 2014), maybe about 100 PlastRec
454 plants with MPW throughputs ranging from 30,000 to 120,000 t/y. The UK would
455 require about 5 plants, France 5, Italy 5, etc. resulting in about 30 plants in Europe
456 and another 30 in the US.
457

458 **5. Sensitivity analysis**

459 A sensitivity analysis was performed to determine the most relevant factors
460 influencing the financial returns. The parameters affecting the IRR of the plant were
461 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
465 financial returns of the plant. On the 6th of March 2020, the Brent oil price was
466 \$52.02/barrel, equating to a P-oil sales price of €227/t, resulting in an IRR of 37%.
467 Clearly, using the lowest oil price of the last 15 years grossly underestimates the
468 financial returns of the plant. Should the P-oil yield be 60% rather than 65%, the IRR
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
472 to €40/t – a value still €10 off the lower range of the Belgian tipping fee (CEWEP,
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
476 returns more stable as the tipping fee is not influenced by market forces.
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
488 underestimated. For example, reducing the interest rate from 5 to 4% increases the
489 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
515 of the theoretical facility presented in this study. This is, as the revenue values used
516 in this paper were based on estimated 15-year low prices for the P-oil and other
517 assumed financials rather than on agreed commercial terms. Therefore, once the
518 location for a plant is agreed, more detailed studies are required to firm up on the
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
526 collected in 2016 (Chruszcz and Reeve, 2018). From a financial perspective, larger
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
530 transport distances will become increasingly challenging with higher throughput
531 plants as the transport cost of bringing the MPW from distances further away
532 increases.

533

534 Likewise, smaller plants with throughputs of 30,000 t/y or less may also be desirable.
535 Moreover, they may be economic depending on commercial agreements, plant
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.
538 (2017) lists a number of reactors having MPW throughputs of 7,000 – 21,000 t/y.
539 Plants operating with such low throughput reactors would have to operate with three
540 or more reactors in parallel to achieve economies of scale i.e. 30 - 40,000 t/y. But the
541 CAPEX of facilities with multiple reactors operating in parallel would be higher
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

552 Larrain et al. (2020) used equipment and infrastructure costs provided by a waste
553 treatment company, which should give a high level of confidence in their cost
554 estimate. But due to confidentiality issues, no details are disclosed; in fact, not even
555 the type of pyrolysis reactor is disclosed. Therefore, it is not clear how the cost
556 estimate was put together, nor is its accuracy stated by the authors. Consequently,
557 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
560 and Dimitriou (2018), and Jiang et al. (2020) use the factored cost estimate method.
561 According to the Association for the Advancement of Cost Engineering (AACE)
562 (AACE, 2005), the factored cost estimate method has the lowest level of accuracy
563 (Table 3). Only Westerhout et al. (1998) acknowledge the limitations of the factored
564 cost estimate, stating that it is accurate to $\pm 40\%$, which is in line with the
565 classifications given in Table 3. Moreover, they applied the factored cost estimate as
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

569 Sahu et al. (2014), Fivga and Dimitriou (2018) and Jiang et al. (2020), on the other
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
573 economic performances of MPW pyrolysis plant with throughputs of 1,000, 10,000
574 and 100,000 kg/h with factorial methods. It is likely that the plant throughput variation
575 is too large, because the validity of the factored cost scaling method may be
576 breaking down. Scaling from a 1,000 to a 100,000 t/y plant using factored methods
577 may work mathematically, but expecting a good cost accuracy is questionable to say
578 the least, as the scaleup factor is in the order of 100. Moreover, a 100,000 t/h plant
579 throughput exceeds the MPW available in the UK. Therefore, a 100,000 t/h MPW
580 recycling plant would be excessively large and unrealistic.

581

582 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
585 unquestioned use of a revenue value of €780/t for the waxes, which was taken from
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
588 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
590 compared to the typical values of 10-25% for waste to energy or similar waste plants
591 (CSIL, Various Years; Hadidi et al., 2017). Consequently, the P-oil revenue value of
592 €750/t used by Jiang et al. (2020) is not realistic, and the IRR is too high.

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

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

606

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

610

611

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616

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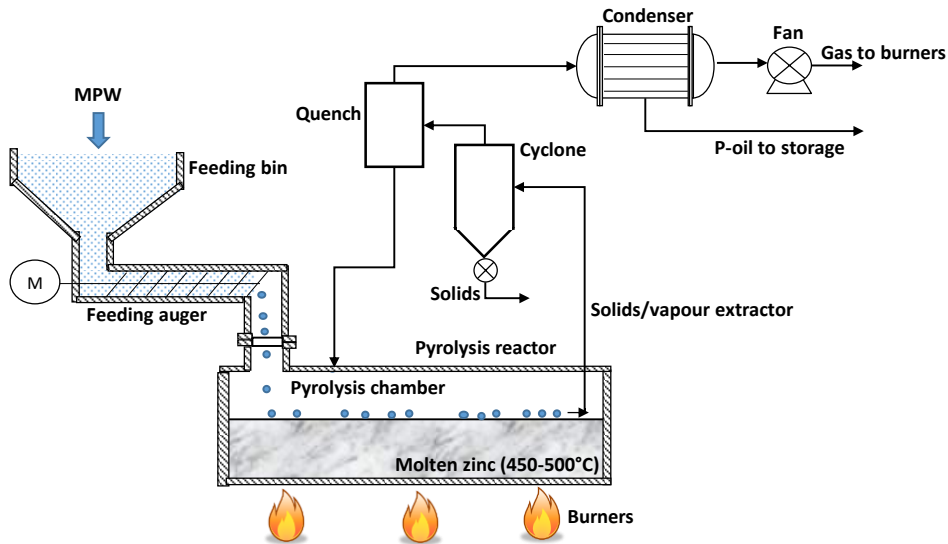
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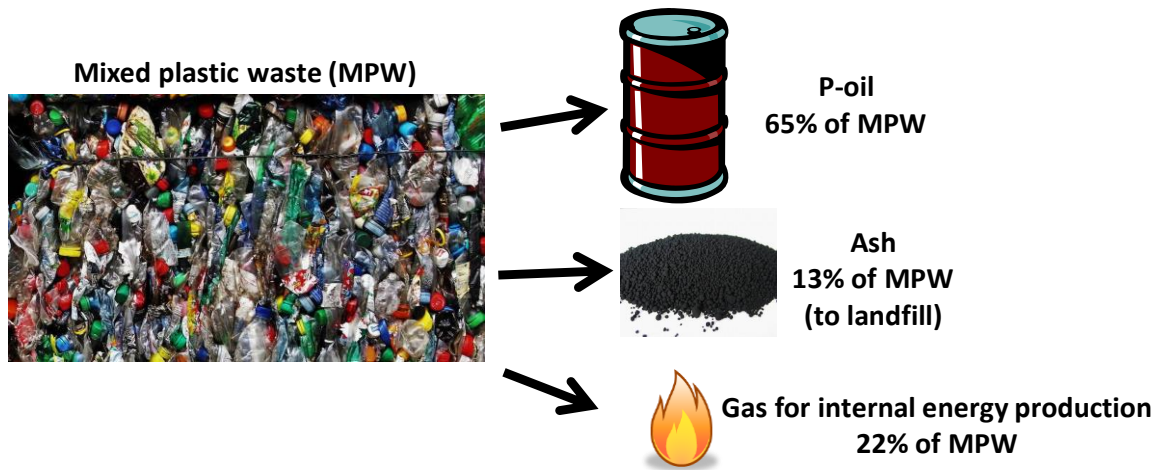
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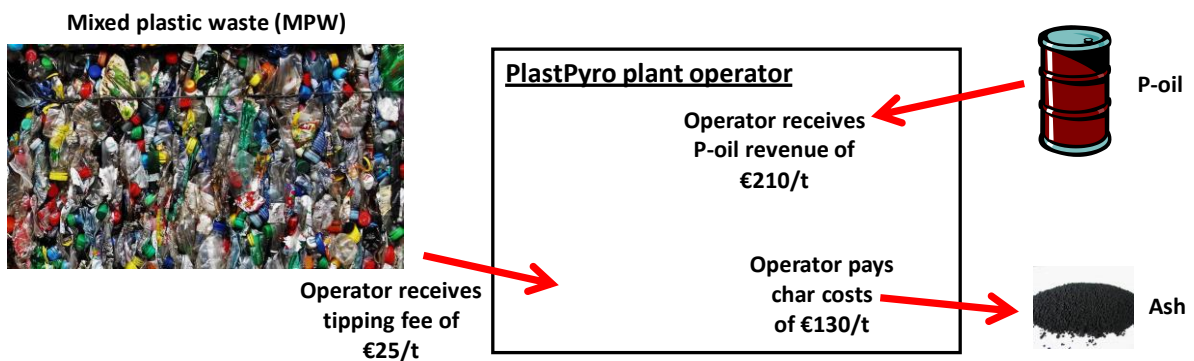
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957 **Fig. 1** On the PlastPyro process for MPW pyrolysis.



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



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

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966 **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

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969 **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

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Table 3 Classification of cost estimates in the process industries into 5 categories; adapted from (ACE, 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 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

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983 **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

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