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Economic performance of pyrolysis of mixed plastic waste : open-loop versus closed-loop recycling

1   **Title:**

2   **Economic performance of pyrolysis of mixed plastic waste:**

3   **open-loop versus closed-loop recycling**

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19 **ABSTRACT**

20 In recent decades new recycling technologies for mixed plastic waste have emerged. In pyrolysis, the

21 polymer chains are thermally broken (pyrolyzed) to obtain hydrocarbon materials of different molecular

22 weights such as naphtha, oil or waxes, whose yields can be controlled by varying the reaction parameters.

23 Naphtha represents a closed-loop recycling process as it is a feedstock for (poly)olefins; while the co-

24 production of waxes, having several applications in e.g. the construction industry, exemplifies an open-

25 loop recycling process. This paper compares the economic performance of the pyrolysis of mixed

26 polyolefin waste in a closed-loop and open-loop scheme, including a probabilistic approach to the most

27 important variables. From an economic perspective, open-loop pyrolysis as presented outperforms

28 closed-loop recycling, due to the high prices of wax. However, the results present a high dispersion caused

29 by the volatility of the prices of crude oil and its derivates. Considering the current oil price projections,

30 our case study analysis showed that for open-loop recycling there is a future probability of almost a 98 %

31 of observing positive results and around 57 % of probability in the case of closed-loop recycling, under the

32 assumptions made. Yet, in a future scenario where decarbonized electricity would decrease oil prices, the

33 probability of a positive outcome reduces to 57 % for the open-loop case and to less than 8 % in the case

34 of closed-loop recycling. To make these pathways attractive to investors, the nameplate capacity should

35 be at least 70 kt/year for open-loop recycling and 115 kt/year for closed-loop recycling. A 120 kt/year plant

36 should operate minimally at 80 % of its capacity for open-loop recycling, while closed-loop recycling would

37 demand running close to maximum capacity. Security of feedstock supply therefore is required.

38 **KEYWORDS**

39 Polyolefin; thermochemical; recycling; closed-loop; open-loop; techno-economic assessment

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41 **HIGHLIGHTS**

42 • Open-loop recycling has better economic performance than closed-loop recycling.

43 • Oil price variability and CAPEX estimation uncertainty affect the variance.

44 • Technology is profitable for 70 kt/year capacity plants or larger.

45 • Provision of plastic waste feedstock should be ensured.

46

47 **1   Introduction**

48 The use of plastic packaging has increased twenty-fold in the past half-century and is expected to double

49 in the next 20 years. Additionally, 90 % of this industry's feedstock comes from finite stocks of oil and gas

50 (Ellen MacArthur Foundation, 2017). These facts have increased the interest in the development of

51 strategies that intend to keep the value of plastics as long as possible, aiming for the transition to a circular

52 economy scheme.

53 Circular economy is an economic system that entails to decouple gradually the economic activity from the

54 consumption of finite resources, reducing maximally the production of waste and the loss of value of

55 materials and products throughout the value chain (European Commission, 2018).

56 Circular economy strategies can be applied to different stages of the value chain: design, production, use

57 (and reuse) and end-of-life, which may include several recycling techniques. Recycling can be classified

58 according to the technology that is used (mechanical recycling or (thermo)chemical recycling) and to the

59 products aimed at (closed-loop recycling or open-loop recycling). In closed-loop recycling, the recycled

60 material can substitute the original virgin material and can be used in the same type of products. In open-

61 loop recycling, the properties of the recycled material differ from those of the virgin material, so it is used

62 in other product applications, substituting other materials (Huysman et al., 2017).

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63 Chemical recycling or feedstock recycling is a broad group of techniques that work by breaking up the

64 polymer into smaller molecular fragments to produce oil, fuel, syngas, monomers or other by-products.

65 Pyrolysis is a type of thermochemical recycling in which heating occurs in the absence of oxygen. In this

66 process the organic compounds are decomposed, generating gaseous and liquid hydrocarbon products

67 while keeping the inorganic material unchanged (Almeida and Marques, 2016).

68 In pyrolysis of plastic waste, the obtention of the desired products can be targeted by varying the process

69 parameters (pressure, temperature, feedstock, etc.). Lopez et al. (2017), reviewed studies referring to the

70 chemical recycling of polyolefins to produce light olefins, fuel, aromatics or waxes. They concluded that in

71 pyrolysis, higher temperatures and short residence time favor the production of light olefins and mild

72 temperatures favor the production of waxes. Likewise, Al-Salem et al. (2017) collected research regarding

73 the effect of feedstock, temperature, residence time and pressure on the product distribution. They

74 signaled that temperature is the factor with the highest influence on the product distribution that was

75 more extensively studied thus far. However, they indicate that a high temperature or a long residence

76 time may provoke secondary reactions potentially leading to unwanted products. Regarding the pressure,

77 the aforementioned review refers to Murata et al. (2004), who compared the degradation rate and the

78 product distribution of the thermal degradation of polyethylene (PE) under atmospheric and elevated

79 pressure. Increasing the pressure allows shifting the product distribution to liquid hydrocarbons.

80 Specifically, at high pressure the mass fractions of the products with carbon numbers between 1 and 12

81 increased (as shown indicatively in Figure 1). Although these studies indicate that in pyrolysis it is possible

82 to target the process parameters to certain products, they do not evaluate which products are more

83 desirable.

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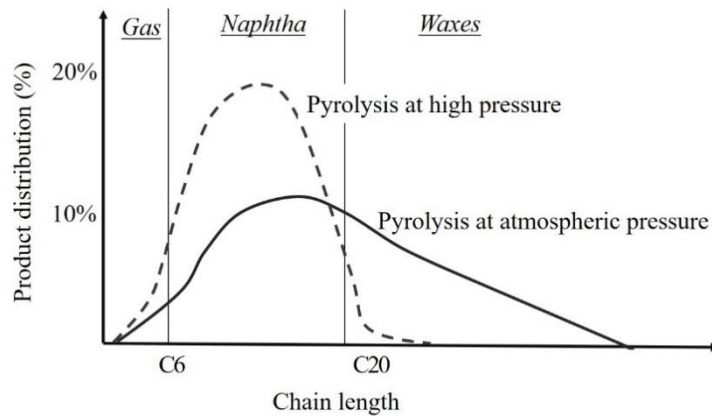
Figure 1: Carbon number distribution under different pressures. Illustration based on Murata et al. (2004)

The assessment of potential solutions for the transition to a circular economy requires comprehensive analyses (Ghisellini et al., 2016). Concerning new technologies, this entails addressing their economic implications, considering all costs related to their acquisition and operation and the revenues of their attained products. Techno-Economic Assessment (TEA) has been broadly used to study the economic performance of technologies under development (Thomassen et al., 2019).

Related to the recovery of different types of waste TEA has been applied to sorting waste facilities (Cimpan et al., 2016), industrial waste (Mellouk et al., 2016), electronic waste (Ghodrat et al., 2016; Yong et al., 2019) and recycling of metal and steel (Schultmann et al., 2004), among others. Preliminary work undertaken by Athanassiou and Zabaniotou (2007) suggested that sorting at source allows to cost-effectively recycle several municipal solid waste materials. One study by Arena et al. (2011) revealed that an internal rate of return (IRR) of around 8 % is obtained by the generation of electricity using a gasification process of mixed plastic waste. A relevant analysis on the subject of our study was presented by Fivga and Dimitirou (2018), who investigated the technical and economic feasibility of a plastic waste pyrolysis plant for the production of fuel oil. This study, performed in the UK, concluded that the production cost of pyrolysis fuel was around 10 times lower than the market fuel prices in case of a 10 000 kg/hour plant. Similar work was carried out by Sahu et. al (2012) who showed that, in Malaysia, an IRR of 36 % could be

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103   obtained if 120 kt/year of waste plastics were treated by catalytic cracking to produce fuel oils. Together,

104   these studies prove that the pyrolysis of plastic waste is profitable for large scale plants, but that capital

105   costs and operating time have a critical role in the results.

106   With respect to the environmental assessment of plastic waste treatments, an early contribution was an

107   LCA done by Perugini et al. (2005). They compared the impacts of landfilling, incineration, mechanical

108   recycling, pyrolysis and hydrocracking and reported that the highest energy savings are observed with

109   hydrocracking but that the lowest water consumption, CO_2 emissions, air emissions and waste generation

110   is reached with mechanical recycling. A detailed examination of treatment options by Lazarevic et al.

111   (2010) showed that mechanical recycling is preferred over feedstock recycling and incineration in case

112   there is little organic contamination and there is a replacement virgin plastic ratio close to 1:1. In addition,

113   Arafat et al. (2015) revealed that mechanical recycling is better than incineration and gasification from an

114   energy recovery point of view. Huysman et al. (2017) developed a recyclability benefit rate indicator based

115   on LCA and found that environmental benefits can be obtained with open-loop and closed-loop recycling

116   when comparing them to landfilling or incineration. To our knowledge, no studies comparing the

117   economic performance of open-loop vs closed-loop recycling of polyolefin waste have been published

118   thus far.

119   Overall, there is much evidence that the environmental impact of recycling is lower than the

120   environmental impact of landfilling and incineration, mainly because of the avoided impact of the recycled

121   products. Furthermore, the reviewed studies support the notion that new plastic recycling technologies

122   can realize economic benefits. Yet, very little attention has been paid to the role of the process parameters

123   and product characteristics in the economic performance of a given technology. Therefore, it is not clear

124   which products should be aimed at in the case of pyrolysis of plastic packaging waste, now that the

125   technology is moving beyond recovery to fuels (Zhao et al., 2020).

126   Moreover, previous TEAs of chemical and thermal recycling, among which pyrolysis, have been

127   deterministic in nature and therefore failing to deal with a crucial factor for investors: uncertainties related

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128   to oil prices and investment costs. The oil price is highly volatile and the forecasting of specialized energy

129   agencies may present errors of almost 50 % in a 10 year horizon (Wachtmeister et al. 2018). Regarding the

130   investment, preliminary cost studies can have accuracy ranges of -50 % to +100 % (Cheali et al., 2015) and

131   most empirical analyses find a negative effect of uncertainty on investment (Koetse et al., 2006).

132   Consequently, it is imperative to consider uncertainty in prospective economic assessments.

133   This paper compares the potential economic returns of closed-loop versus open-loop pyrolysis of mixed

134   polyolefin waste, a contrast that so far has not been studied. Naphtha, used as a feedstock for ethylene

135   and propylene and subsequently polyethylene (PE) and polypropylene (PP), is taken as a representative

136   product of closed-loop recycling (Zhao et al., 2020), and wax is considered as a representative product for

137   open-loop recycling. Both can be produced by changing the process parameters of pyrolysis of polyolefins,

138   as shown before. Moreover, until now, TEAs that take into account the uncertainty of oil prices assume a

139   certain variability or consider the observed past price variability (e.g. Li et al., 2015). Innovatively, this study

140   uses forecasted oil prices and the uncertainty of the accuracy of these forecasts together with the

141   uncertainty of projected investment costs. In doing so we capture the apprehensions of petrochemical

142   industry investors.

143   **2   Materials and Methods**

144   To compare the economic performance of open-loop and closed-loop pyrolysis, a prospective TEA is

145   applied to two case studies. TEA is used to calculate the profitability of a project by bringing all future costs

146   and revenues to a net present value. It is an iterative process that consists of four phases: market study,

147   process flow diagrams and mass and energy balances, economic assessment and sensitivity analysis

148   (Thomassen et al., 2016).

149   Prospective TEA is applied when the technology is still in an early stage of development and there is a need

150   to study it at a future stage (Thomassen et al., 2019). Pyrolysis of plastic waste into naphtha and waxes is

151   in technology readiness level 6 out of 9 with pilot plants in Norway (BASF, 2019), Germany (Recenso

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152   Germany, 2019) and the UK (Recycling Technologies, 2018), and this research intends to study the

153   installation of a commercial scale plant.

154   *2.1   Description of the case studies*

155   The circular plastic packaging value chain involves several steps, as depicted in Figure 2. This research is

156   focused only on the processes that are directly related to the pyrolysis of mixed polyolefins (MPO). MPO

157   is a plastic waste fraction composed of mainly low-density PE and PP residue. The origin of this waste

158   fraction could be a source separated bag containing other recyclable waste, for example the *plastics, cans*

159   *and drink cartons* bag as collected in Flanders, Belgium. To separate the MPO, tetra-brick packaging, PET

160   bottles, PP and PE bottles should be sorted by several specialized equipment. Then, to be used as

161   feedstock for the pyrolysis process, the remaining fraction should be compressed into MPO pellets. The

162   pyrolysis process delivers a hydrocarbon mix that is later separated and processed. For the production of

163   new plastics the naphtha is subsequently cracked and the resulting ethylene and propylene monomers

164   polymerized to obtain polyethylene and polypropylene. In this research, the recycled naphtha is assumed

165   to be of equivalent quality and characteristics as the naphtha derived from crude oil, and thereby the

166   naphtha cracking and polymerization processes will not be accounted for. Open-loop recycling in this study

167   corresponds to the production of a naphtha only, whereas in closed-loop recycling the crude pyrolysis oil,

168   with heavier hydrocarbons because of the lower pressure, is separated into a wax and a naphtha product.

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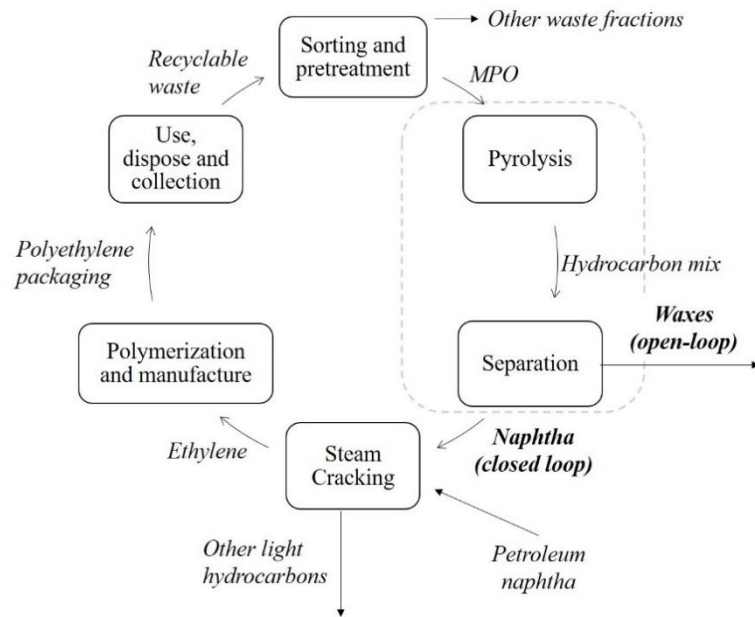
Figure 2: Polyolefin packaging value chain in the case of closed-loop and open-loop recycling.

The hydrocarbon mix obtained from the pyrolysis process is composed of molecules of diverse size: between 1 and 5 carbon atoms are gaseous species, between 6 and 20 correspond to naphtha and 20 or more are defined as wax (Lopez et al 2017). As mentioned, the mix composition depends on the process parameters. Because increasing temperature and residence time may lead to secondary reactions (Al Salem et al 2017), pressure is varied in this study to compare open-loop recycling in which the obtention of wax is aimed at (case 1), with closed-loop recycling were the obtention of naphtha is aimed at (case 2). When the process is carried at atmospheric pressure a mix of gas, naphtha and waxes is obtained. Yet, when high pressure is applied the yields of smaller molecules increase, and the fraction of wax molecules is negligible (Figure 1) (Murata et al 2004).

The applications for wax range from candle production to particle board sealers, thus the recycling of plastics into wax is a fair representation of open-loop recycling. In contrast, around 90 % of the naphtha that enters the chemical industry is used as feedstock for high value chemicals, such as ethylene and propylene (International Energy Agency, 2018a). Therefore, the obtention of naphtha out of polyolefin waste is a good example for a closed-loop recycling process (Figure 2).

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186 In a strict sense, case 1 does not exactly represent an open-loop process because also naphtha is produced.

187 Similarly, case 2 is not a completely closed-loop process because of the losses occurring in the process.

188 Therefore, the terms open-loop and closed-loop should be understood as a representation and not as an

189 exact description of the material flows.

190 *2.1.1   Case 1: Pyrolysis under atmospheric pressure for open-loop recycling.*

191 The cracking occurs at atmospheric pressure and a temperature of 460 ºC to 500 ºC, delivering a

192 hydrocarbon mix in a molecular weight distribution covering non-condensable gases, naphtha and waxes.

193 By condensing the mix, the non-condensable gaseous fraction is separated from the liquid fraction. The

194 gaseous fraction is fed into a co-combustion engine to generate electric and thermal energy required for

195 the process. The production of thermal energy is fully supplied by the engine, and the lacking electric

196 energy is taken from the electric network. The liquid fraction follows a two-step steam distillation process

197 where the naphtha is separated from the waxes. The products finally pass through a hydrogenation

198 process, to eliminate impurities and increment the content of paraffins by saturating the hydrocarbon

199 molecules under high pressure of hydrogen and relatively high temperature.

200 *2.1.2   Case 2 - Pyrolysis under high pressure for closed loop recycling.*

201 To obtain a larger proportion of naphtha, high pressure is applied to the pyrolysis process at the same

202 temperature as for case 1. This cracking process yields a hydrocarbon mix composed mainly by molecules

203 in the naphtha range. As in case 1, the gaseous fraction is separated from the liquid fraction by a

204 condensation process and then fed into a co-combustion engine to generate electric and thermal energy.

205 The remaining electric energy generated in this case is plugged into the network and accounted as an

206 additional product. A distillation step is not necessary for the liquid fraction because naphtha is the only

207 non-gaseous product obtained. This product passes through a hydrogenation process, to eliminate

208 impurities and increase the content paraffin contents.

10

2.2   Techno - economic assessment

210   Following the TEA phases (Thomassen et al., 2016), expert market studies are used to project naphtha and

211   slack wax prices. Then, the process flows and mass and energy balances are built based on product yields,

212   residue yields, energy and consumable requirements. These values are retrieved from industrial

213   references and are shown in Table 1. Because of confidentially reasons, specific process parameters are

214   not disclosed in this paper. Following the guidelines of Van Dael et al. (2015), with the market study and

215   the mass and energy balances we calculate the yearly revenues and operational costs. The net present

216   value[1] (NPV), NPV per metric ton of plastic treated (NPVt), the IRR over a 15-year period and the

217   discounted payback period (DPP) are calculated with the software Analytica, including the investment

218   costs and considering the assumptions presented in Table 1.

219   The one-at-a-time sensitivity analysis exposes the variables that need a more thorough estimation

220   because they have a dominant effect on the results. To perform it, the expected value of the NPVt is

221   calculated after varying each one of the parameters independently to a low scenario and a high scenario.

222   The low and high scenario correspond to 90 % and 110 % of the median values.

223   To incorporate uncertainty in the evaluation, some of the most important variables detected with the one-

224   at-a-time sensitivity analysis are defined as probabilistic rather than deterministic numbers. With these

225   probability density functions (PDFs) we calculate a PDF for the NPV with a Monte Carlo simulation. The

226   PDFs of the variables are derived from observed data and constructed using 10 000 samples with median

227   Latin Hypercube sampling. This sampling technique spreads the sample points by selecting the median

228   values of intervals of equal probability instead of generating a random sample of points (Chrisman, 2014).

229   In addition, the PDFs of the resulting Monte Carlo simulations are smoothed using Kernel Density

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[1]

$$NPV = \sum_T \frac{Revenue - Operationals\ costs}{(1 + Discout\ Rate)^t} - Investment\ costs$$

230   Estimation, that replaces each sample point with a Gaussian kernel and then obtains the resulting estimate

231   for the density by adding up these Gaussians (Analytica, n.d.).

232   A global sensitivity analysis is performed to determine the contribution of each probabilistic variable *"i"* to

233   the total variance of the NPVt. We first calculate the Spearman's rank correlation coefficient (ρ_i), that

234   corresponds to the correlation of the ranking of each input sample with the ranking of its respective NPVt.

235   Then, using the formula $\rho_i / \sum \rho_i$ we calculate the contribution to the variance of each variable. To avoid

236   double accounting for the uncertainty of the oil prices, for this analysis we leave naphtha and wax prices

237   as a function of oil prices.

238   A parametric sensitivity analysis is done for those variables who have an important effect on the results

239   (detected with the one-at-a-time sensitivity analysis) but that is not possible to derive a realistic PDF. These

240   variables include the feedstock price (gate fee), oil price, nameplate capacity and feedstock availability.

241   Finally, to test the robustness of the results, four alternative scenarios related with the product prices are

242   analyzed. In the *sustainable development scenario* (SDS) the oil prices are expected to decrease instead of

243   increase, and in the *wax decoupling scenario* the wax price is assumed to be decoupled from the oil price.

244   *2.3   Economic assumptions and cost modelling*

245   The general economic assumptions are similar for both case studies and are summarized in Table 1. The

246   initial year is 2019 and all prices are calculated on EUR 2019. The discount rate is set at 15 %, as commonly

247   used for the expansion of new technologies (Van Dael et al., 2015). The feedstock input is 120 kt/year,

248   representing an equilibrium between economies of scale as observed by Fivga and Dimitriou(2018) and

249   Sahu et al. (2012) and considering sourcing capabilities. In fact, it is equivalent to the recycling of the 6.7

250   kg per capita of MPO waste[2] generated by people living 120 km around in an area with a density[3] of 394

251   people-km^{-2}.

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[2] PP and PE trays and foils generated in Belgium per capita (RDC, 2018)
[3] Belgium, Netherlands and Luxemburg average population density.

Table 1: Financial assumptions for the TEA

	Detail	Value	Source
Technical parameters			
Case 1: naphtha-wax [Open-loop]	Naphtha yield	40 %	Industrial reference
	Wax yield	34 %	
	Gas yield	11 %	
	Hydrogen-to-product ratio	13 kg H_2/ton	
	Overall engine efficiency	64 %	
	Thermal energy consumption	13226 MWh/year	
	Electric energy consumption	44000 MWh/year	
Case 2: only naphtha [closed-loop]	Naphtha yield	69 %	Industrial reference
	Gas yield	15 %	
	Hydrogen-to-product ratio	16 kg H_2/ton	
	Overall engine efficiency	45 %	
	Thermal energy consumption	91102 MWh/year	
	Electric energy consumption	44000 MWh/year	
Case 1 and Case 2	Light hydrocarbon yield	1 %	Industrial reference
	Solid residue yield	10 %	
	Water residue yield	5 %	
	Low heating value gas	37 MJ/t	Channiwala and Parikh, 2002
Economic parameters			
Operational	Plant capacity	120 kt/y	[Assumption]
	Operating time	8 000 hr/y	
	Land	30 000 m^2	
	Operators per shift	4[+]	Sinnott and Towler, 2019
	Regular operators	3	
Financial	Evaluation period	15 years	[Assumption]
	Discount rate	15 %	Van Dael et al., 2015
	Corporate tax rate	25 % over net profits	[Assumption]
	Working capital	15 % of E&I[++]	Sinnott and Towler, 2019
	Depreciation rate	10 % for 10 years	
Investment cost	Project management costs	10 %-30 % of E&I	Sinnott and Towler, 2019
	Contingency charges	15 % of E&I	
Fixed operational costs	Operator annual wage	62 400 EUR/year [+++]	STATBEL, 2019
	Premium for shift operators	23 % over annual wage	Werner International, 2014
	Cost of labor (including supervision and engineering)	125 % of operator wages	
	Maintenance	4 % of E&I	Sinnott and Towler, 2019
	Yearly insurance	1.5 % of equipment cost	
	General plant overhead	65 % of labor and maintenance[++++]	
	Land	1400 EUR/ m^2	JJL Belgium, 2019
Variable operational costs	Feedstock price	50.0 EUR/t*	RDC, 2018
	Hydrogen price	3023 EUR/t**	Thomas et al., 2016
	Gas price	23.7 EUR/MWh	(PWC, 2019)
	Electricity price	74.2 EUR/MWh	
	Water residue disposal	1.2 EUR/t	Sinnott and Towler, 2019
	Solid residue disposal	130.9 EUR/t***	OVAM, 2019

253 [+]**For smaller plants this value is adapted starting from 2 operators per shift.** [++]**Commonly observed ratios for the**
254 **petrochemical industry.** [+++]**Average gross wage for factory and machinery workers in Flanders.** [++++] **For human**
255 **resources, research and development, information technology, finance, legal, etc.*** Including pre-treatment
256 **costs. ** For a flux of 1500 Nm3/h. *** Gate fee for industrial residue of low heating value.**

257

258 *2.3.1 Revenues*

259 We consider that the recycled naphtha and wax are of similar quality than naphtha and slack wax traded

260 in the market. Thus, market prices for naphtha and slack wax are used as a reference. We collect the mean

261 value of the projected price for naphtha and crude oil from the "Future of Petrochemicals" report

262 developed by the International Energy Agency (International Energy Agency, 2018a). The model of this

263 report estimates the future prices of naphtha based on its historical relationship with oil prices, using the

264 long-term oil prices defined in the "World Energy Outlook" 2017 as a basis. The price for slack wax was

265 680 EUR/t on January 2018 (Argus Media, 2018), being 68 % higher than the average crude oil price. We

266 calculate the future price of waxes considering this relationship constant. The International Energy Agency

267 (2018a) presents forecasted values for 2020, 2025, 2030 and 2040 for crude oil and naphtha, these values

268 are linearly interpolated.

269 It is well known that oil prices and those of its derivates are highly volatile and usually subject to a large

270 estimation error. Hence, to have a better overview of the incentives to invest, it is crucial to acknowledge

271 these uncertainties. Empirical density forecasting methods, based on forecasting errors, are a valuable

272 approach for including an estimate of uncertainty with a forecast (Kaack et al., 2017). Following this, we

273 take the standard deviation of the normal distribution of the forecasted values equivalent to the observed

274 mean of forecasted errors of the "World energy outlook" from 2000 to 2016, as presented by

275 Wachtmeister et al. (2018). The mean absolute percentage error of forecasted price for oil of the "World

276 energy outlook" on a five year horizon is 37 % and on a 10 year horizon is 46 % (Wachtmeister et al., 2018).

277 For the electricity supply price, the average electricity EPEX price of 2017 in an annual contract (51

278 EUR/MWh) (CREG, 2018) is used and it is assumed to be normally distributed with a standard deviation of

279 16 % (Ruibal and Mazumdar 2008).

280 *2.3.2 Capital Expenditure (CAPEX)*

281 The investment cost for the 120 kt/year plant is the result of an engineering project of Indaver NV (Indaver,

282 2019). The equipment cost and infrastructure cost (E&I) were provided by this company and are not

15

283   disclosed in this paper. For the sensitivity analysis, to calculate the CAPEX of plants of lower nameplate

284   capacity (B), we use the equation presented by Sinnott and Towler (2019), with an exponent for pyrolysis

285   plants of 0.69 (Kuppens et al., 2015) and the CAPEX for a 120 kt/year plant: $CAPEX_B = CAPEX_{120} *$

286     $(Capacity_B/120) \exp(0.69)$.

287   Engineering and project management costs and contingency charges are calculated according to

288   commonly observed ratios and are shown on Table 1.

289   For the uncertainty analysis, the CAPEX was modelled with a negatively skewed PERT distribution,

290   commonly used in modelling cost with expert opinion (VOSE, 2000). The accuracy range was set between

291   -22.5 % and +35 %, corresponding to expected values for a technology readiness level 6 (Tsagkari et al.,

292   2016). Figure 3 shows the probability density function of the CAPEX.
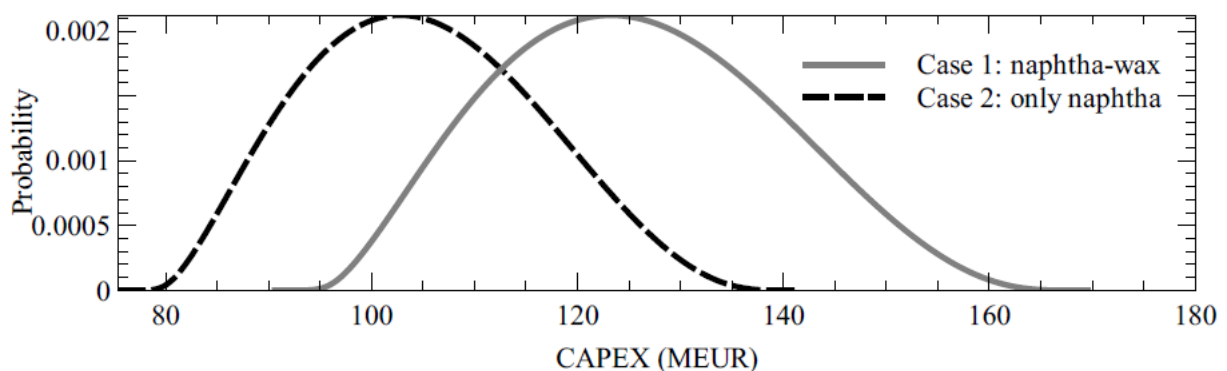
293

294   Figure 3: Probability density function of CAPEX.
295

296   *2.3.3   Operational Cost (OPEX)*

297   Table 1 shows the prices and ratios used to calculate the fixed operational costs, that do not depend on

298   the amount of input treated, but may depend on the nameplate capacity; and the variable operational

299   costs, that are directly proportional to the amount of feedstock processed.

300   For the uncertainty analysis and the global sensitivity analysis, the feedstock cost was modelled with a

301   triangular distribution. The range of this distribution (+/- 10 EUR/t) is equivalent to the observed ranges of

      16

302 plastic fractions traded by the Belgian organization Fost Plus (RDC, 2018). The hydrogen price is assumed

303 to distribute normally with a 10 % standard deviation.

304 **3   Results and Discussion**

305 *3.1   Market Study*

306 Figure 4 shows the forecast of the naphtha (a) and slack wax (b) price with the 50 % and 95 % probability

307 bands (interquartile ranges), represented by the different shades of grey in the base case scenario or

308 *Stated Policies Scenario (STEPS)*. The mean value of the naphtha and crude oil prices was obtained from

309 the "Future of Petrochemicals"(International Energy Agency, 2018a). The standard deviation was

310 calculated with the forecasting errors of the "World energy outlook" presented by Wachtmeister et al.

311 (2018). For waxes, a constant relationship between the price of slack wax and crude oil was assumed.

312 The International Energy Agency presents an alternative scenario with different price forecasts for the oil

313 derivates. The *sustainable development scenario* (SDS) estimates the future oil prices assuming the

314 fulfillment of the sustainable development goals (International Energy Agency, 2018a). It is constructed

315 considering a decarbonization of the energy production that would lead to a decrease in the demand for

316 oil products, reflected in a decline of their price (International Energy Agency, 2018b). The standard

317 deviation of the normal distribution is assumed to be equivalent to the one in the STEPS and the

318 relationship between naphtha and wax prices is also assumed constant. In this scenario, naphtha and wax

319 prices, slowly decrease (Figure 4.c and 4.d), whereas in the STEPS they show a constant increase (Figure

320 4.a and 4.b). The SDS prices are only used in the section *3.6.*

17
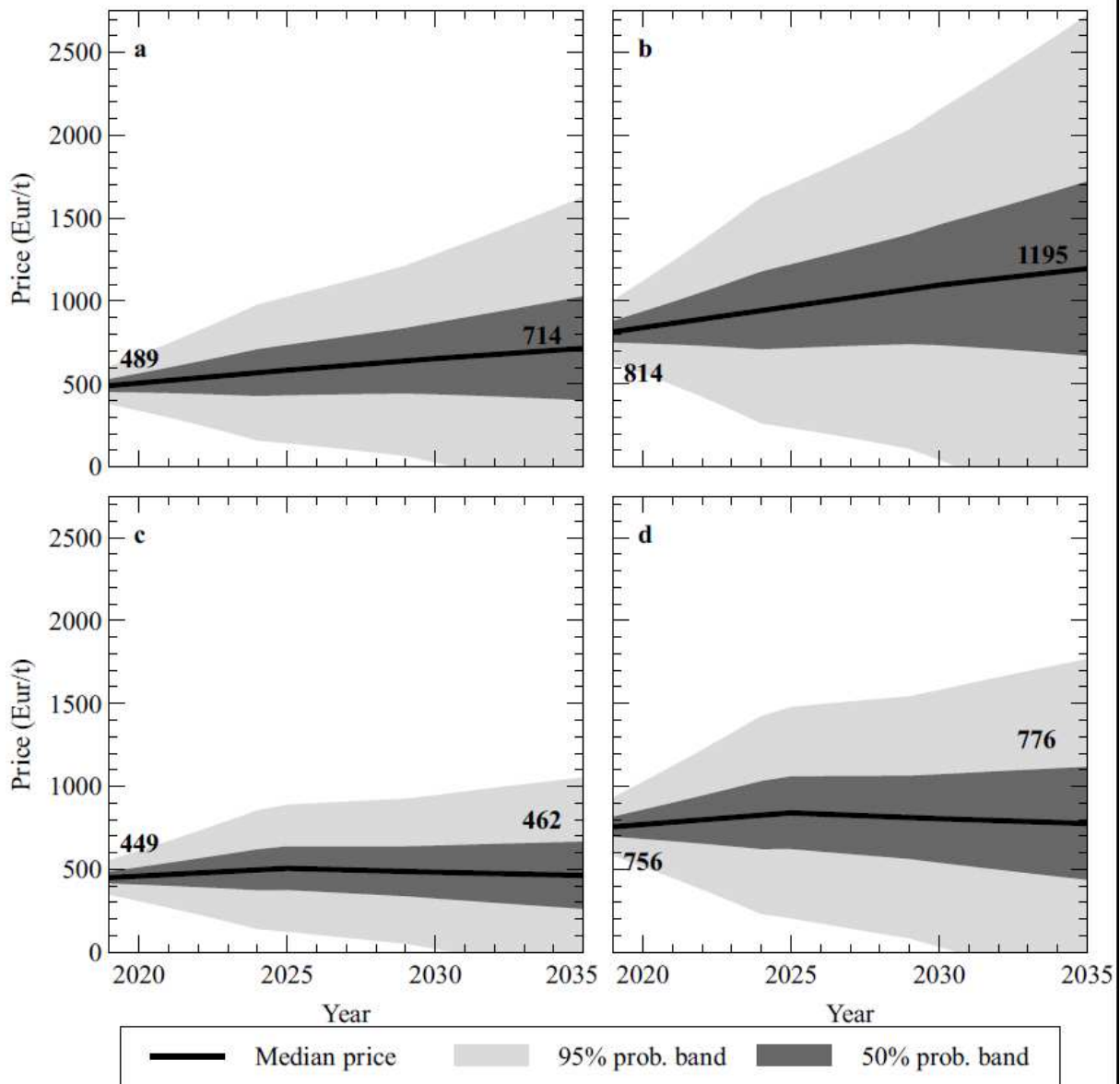
Figure 4: Naphtha (a) and slack wax (b) price forecast in STEPS. Naphtha (c) and slack wax (d) price forecast in the SDS.

3.2   Process Flow Diagram and Mass and Energy Balances

The process flow diagrams for case 1 (open-loop) and case 2 (closed-loop) are shown in Figure 5 and Figure 6, with the overall mass and energy balances. The combustion of the gaseous fraction provides the 68 % of the energy required for case 1 and the total energy required for case 2, leaving in the latter some remaining electricity to deliver to the grid. For case 1, natural gas to produce steam for distillation and electricity from the grid are required as inputs. The significant difference on the net energy input is due to
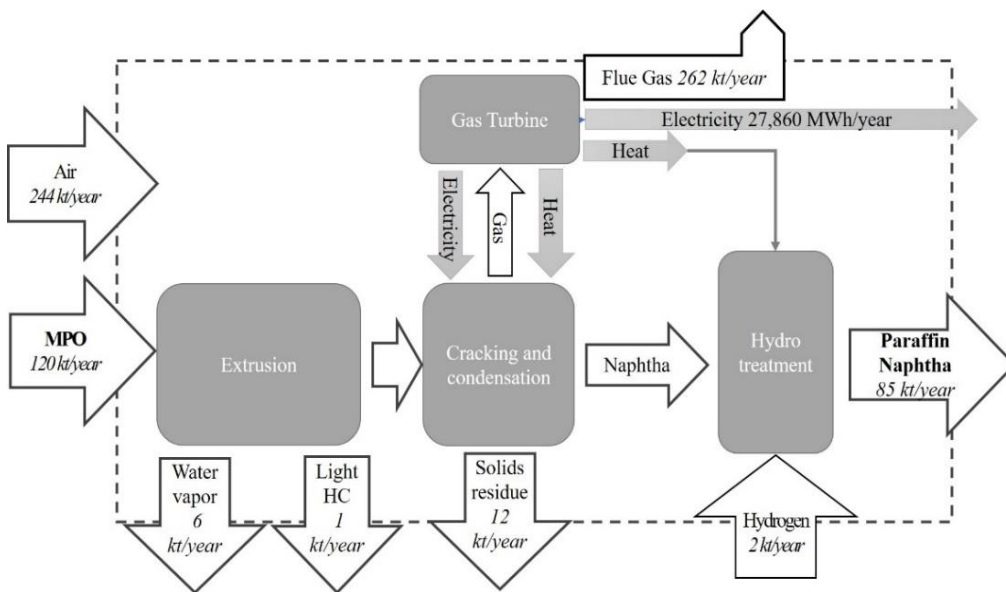
18

331   the increased heat requirement for the distillations process in the open-loop recycling of case 1 and to the

332   higher production of gas for case 2, given the shifted product distribution as schematically shown in Figure

333   1.
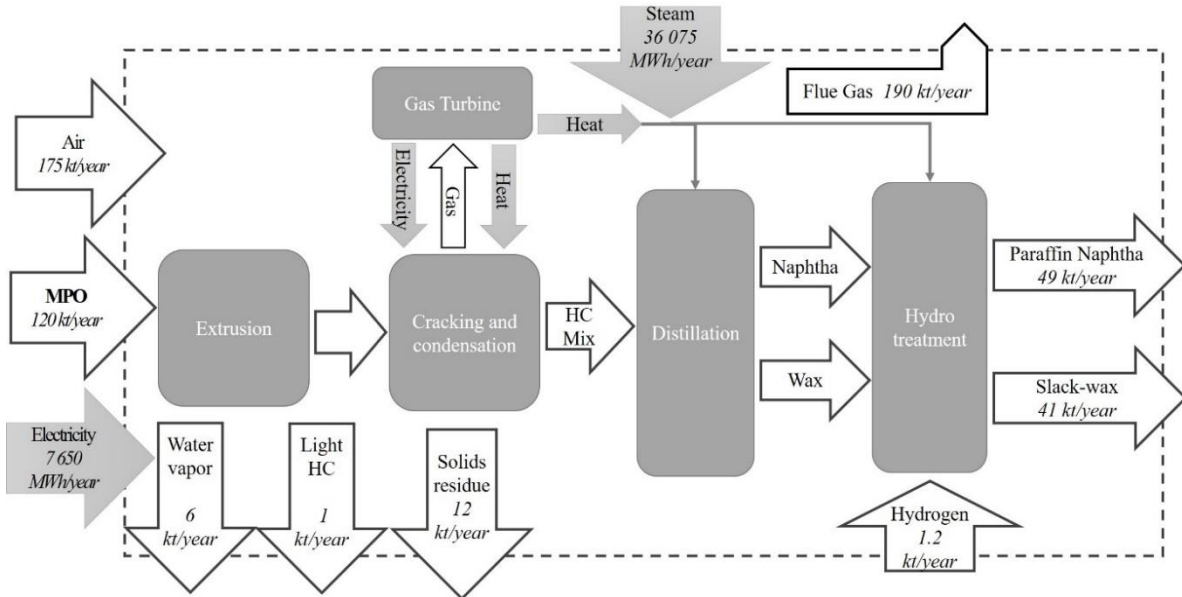
334

335   Figure 5: Process flow diagram case 1: naphtha-wax

336

337   Figure 6: Process flow diagram case 2: only naphtha
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339 *3.3   Economic Results*

340 Table 2 shows the results of the baseline deterministic economic analysis considering the assumptions

341 presented in Table 1 and the yearly product prices of Figure 4.a and Figure 4.b. All results are better for

342 case 1 (open-loop) than for case 2 (closed-loop), mainly because of the large price difference between

343 naphtha and waxes that makes the income of case 1 a 34 % larger than the income of case 2. This gap

344 outweighs the OPEX (4 %) and CAPEX (106 %) gaps between both cases.

345

| Table 2: Median results for case 1 and case 2		
	Case 1: naphtha-wax	Case 2: only naphtha
NPV	56.5 MEUR	4.3 MEUR
IRR	21.3 %	15.7 %
DPP	7.3 years	9.2 years
NPVt	23.9 EUR/t	2 EUR/t

346

347 As commonly observed in studies at this level of technology readiness, results presented in Table 2 are not

348 generally valid because they are based on industry specific assumptions. To analyze the outcome if the

349 underlying parameters change, a sensitivity analysis, uncertainty analysis and alternative scenario analysis

350 are presented in the following sections.

351 *3.4   Sensitivity and uncertainty analysis*

352 *3.4.1   One-at-the-time sensitivity analysis*

353 In this step, the expected value of the NPVt is calculated after varying each one of the parameters in an

354 independent way to a low scenario (-10 %) and a high scenario (+10 %). The tested parameters are

355 producer electricity price, water disposal price, land expenses, solid residue disposal price, consumer

356 electricity price, gas price, steam requirement, insurance fee, thermal energy requirement, electric energy

357 requirement, hydrogen-to-product ratio, general plant overhead, cost of labor, hydrogen price, electric

358 energy requirement, low heating value gas, maintenance expenses, feedstock price, total investment,

359 naphtha price and slack wax price. Figure 7 shows that the feedstock availability, slack wax price, naphtha

360 price, naphtha yield, wax yield, discount rate and CAPEX have a greater impact on the NPVt than

20

361   maintenance, feedstock price and hydrogen price. The remaining variables have an influence of less than

362   the 10 % on the overall value of the NPVt for both cases. The variables who had an impact lower than 1 %

363   were excluded from the graph.
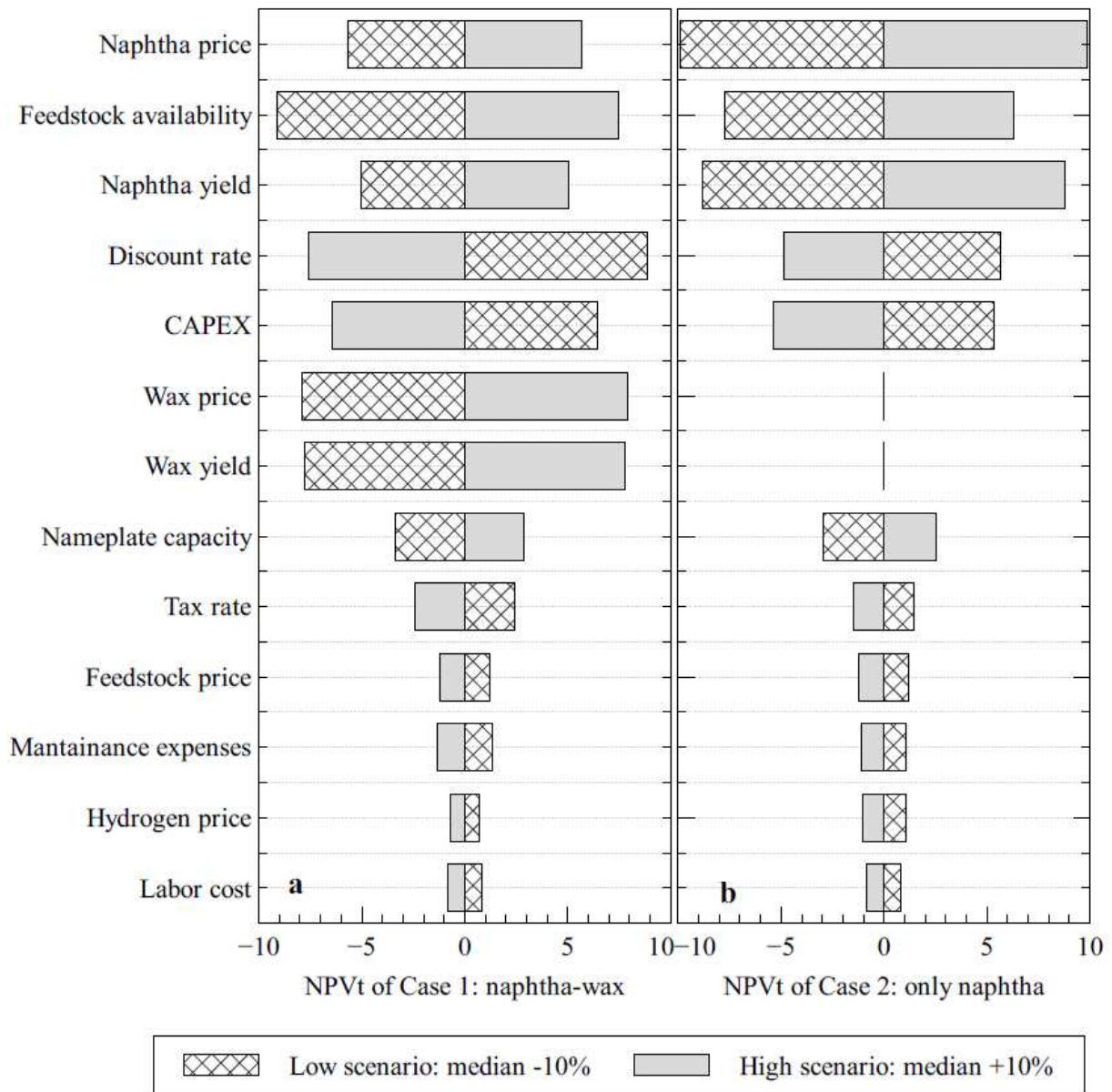
Figure 7: One-at-a-time sensitivity analysis for case 1 (a) and case 2 (b).

3.4.2   Uncertainty analysis

368   The one-at-a-time sensitivity analysis (Figure 7) shows that the products prices, CAPEX and feedstock

369   availability are the variables with a higher influence on the results. For a broader view of the expected

21

370   results product prices, CAPEX, feedstock and hydrogen price are modelled as probabilistic variables.

371   Naphtha and slack wax price projections were previously shown in Figure 4, whereas the CAPEX estimation

372   was shown in Figure 3. Feedstock availability and nameplate capacity are modelled as deterministic

373   because no probabilistic function could accurately describe the supply uncertainty in this non-existing

374   market. Instead, a parametric sensitivity analysis is performed for these variables. Additionally, as the

375   product yields can be controlled and the discount rate is a parameter chosen by the investors, they are

376   also modelled as deterministic.

377   The results of the combined Monte Carlo simulation after varying CAPEX, naphtha price, slack wax price

378   and feedstock price together for the four price level scenarios are presented in Figure 8. From the PDF we

379   can deduce that given the assumptions presented above, open-loop recycling surpasses closed-loop

380   recycling. However, although the median values of the NPVt are positive, there is a probability of negative

381   NPVt of around 2 % for case 1 and 43 % for case 2, under the given assumptions. This means that for open-

382   loop pyrolysis there are relatively high chances of observing negative results.
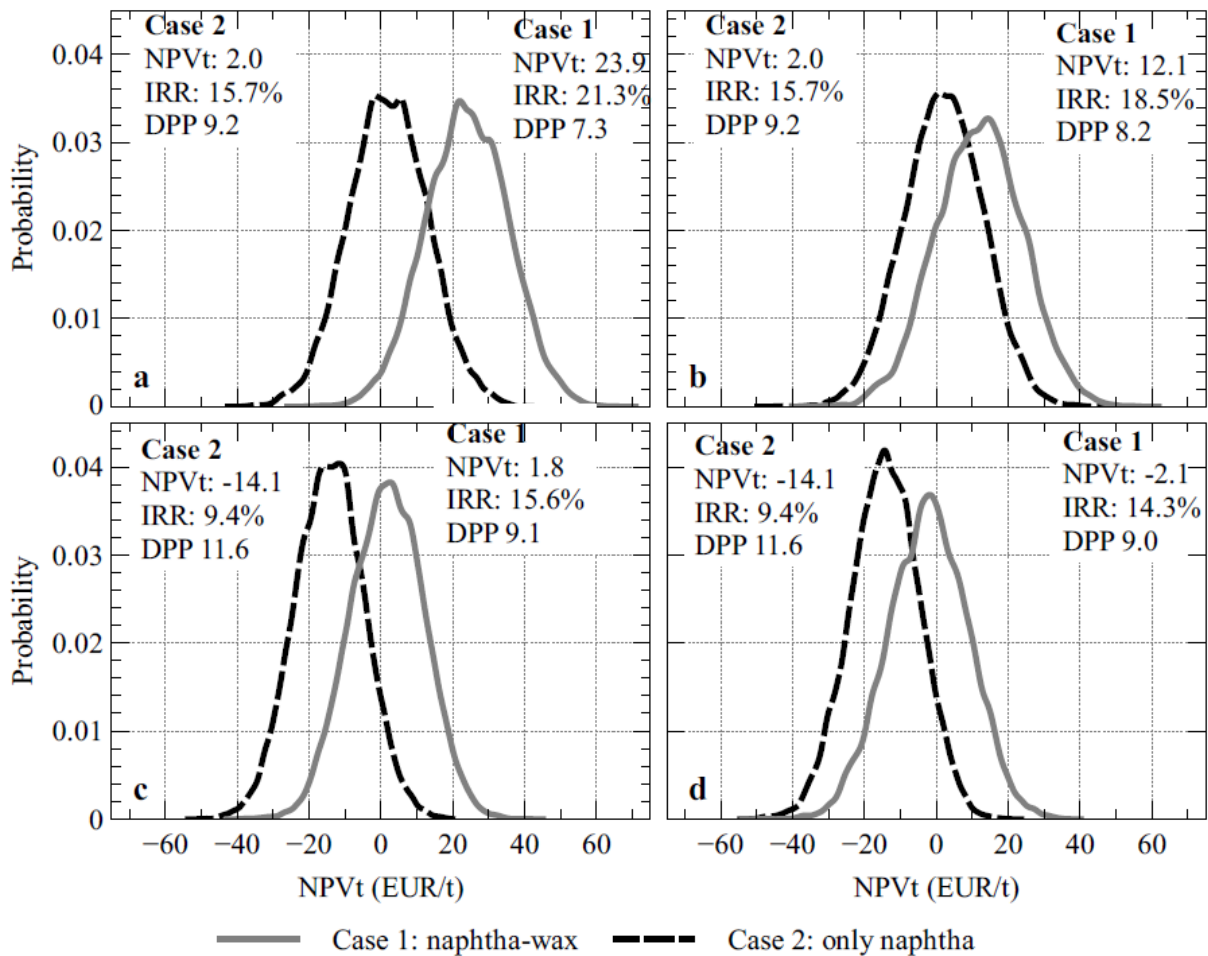
Figure 8: PDFs for the STEPS and coupled wax-oil prices scenario (a), STEPS and decoupled wax-oil prices scenario (b), SDS and coupled wax- oil prices scenario (c), SDS and decoupled wax-oil prices scenario (d).

3.4.3   Global sensitivity analysis:

The contribution to the variance exposed in Table 3, indicates that the variables whose uncertainties have a higher impact on the variance of the results are the oil price and the CAPEX. This can be explained by the high influence of these variables on the expected NPVt (Figure 7) and by the high uncertainty of these variables (Figure 3 and Figure 4.a and Figure 4.b).

23

393

Table 3: Global sensitivity analysis: contribution to the variance		
	Case 1: naphtha-wax	Case 2: only naphtha
CAPEX	12.5 %	12.7 %
Hydrogen price	1.2 %	2.2 %
Feedstock price	1.7 %	1.7 %
Total oil price	84.2 %	74.6 %
Electricity price	0.4 %	8.9 %

394

3.5   Parametric sensitivity analysis

395

*3.5.1   Feedstock and product price*

396

Supply of feedstock and demand of products are critical for the successful implementation of the circular

397

value chain. Furthermore, as the partial sensitivity study suggests (Figure 7), product prices and feedstock

398

prices have an impact on the results larger than 10 %. Thus, it is particularly interesting to analyze under

399

which of these prices, that are given mostly by exogenous factors, the project would deliver positive

400

results.

401

Assuming that feedstock prices remain constant at 50 EUR/t, that the slack wax price will always be 68 %

402

higher than the oil price (coupled wax-oil price), and that the naphtha price will always be 10 % lower than

403

the oil price, the mean value of oil must be over 575 EUR/t (78 EUR/barrel) to observe positive results.

404

When looking at case 2, for profitable results the oil price must be over 550 EUR/t (75 EUR/barrel).

405

On the other hand, taking naphtha and wax prices presented in Figure 4.a and 4.b, the maximum price of

406

feedstock that shows positive results is 150 EUR/t for case 1 and 50 EUR/t for case 2. These prices should

407

be acknowledged if a waste management organization would like to convey their MPO waste to a pyrolysis

408

plant. Moreover, they are in the range presented in Cipman et. al (2016) for PE foils.

409

As intuition suggests, when analyzing the variations of the feedstock price and the product prices jointly

410

and assuming that they vary independently, it can be seen that for higher prices of feedstock, higher prices

411

of oil are required (Figure 9). If the price of the feedstock doubles that of the base case (reaching 100

412

EUR/t), the minimum price of oil that would generate profits is 525 EUR/t (72 EUR/barrel) for case 1 and

413

24

414 625 EUR/t (85 EUR/barrel) for case 2. Moreover, in case the price for a ton of MPO would be zero, a

415 minimum price of 425 EUR/t (58 EUR/barrel) for case 1 and 475 EUR/t (65 EUR/barrel) for case 2 will be

416 necessary to obtain profits (Figure 9).
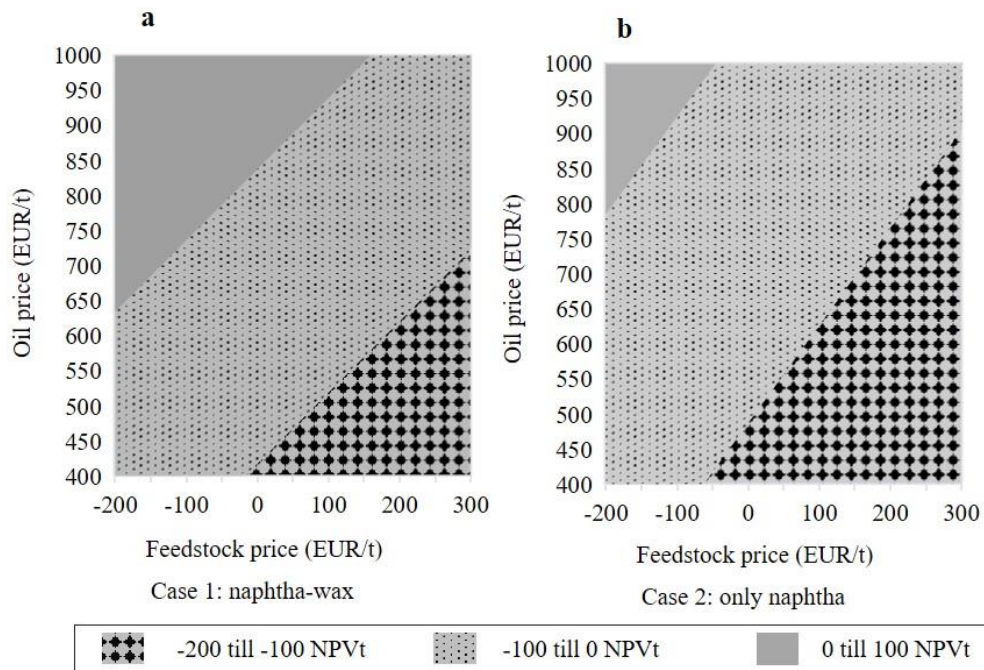
417
418 Figure 9: Sensitivity of NPVt over variations in oil and feedstock prices assuming coupled prices from naphtha
419 and waxes to oil for case 1 (a) and case 2 (b).
420

421 *3.5.2   Nameplate capacity*

422 When calculating the NPVt for lower capacity plants it is found that for case 1 the break-even nameplate

423 capacity is 70 kt/year while for case 2 this value ascends to 115 kt/year, assuming a discount rate of 15 %

424 (Figure 10.a). Besides, for a discount rate over 20 % the plant must at least treat 115 kt/year in case 1 and

425 170 kt/year in case 2. This can be explained by the high proportion of the CAPEX over the total costs
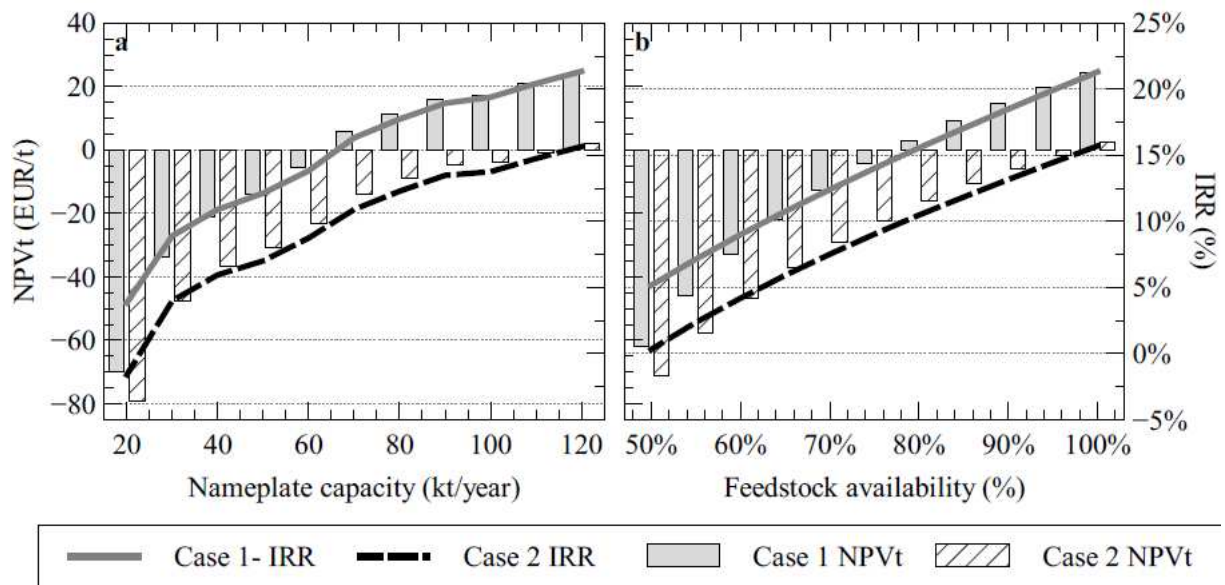
426 (around 50 %).

Figure 10: NPVt and IRR for lower nameplate capacities (a) and feedstock availability (b).

3.5.3 Feedstock availability:

If the demand for the plastic waste fraction increases by other recyclers, there is a risk of feedstock shortage (next to feedstock price variations) after construction of the 120 kt/year plant.

Figure 10.b shows the NPVt and IRR when changing the feedstock availability, assuming the already installed 120 kt/year capacity and baseline feedstock cost. These values are calculated by varying the variable costs and leaving the fixed cost unchanged. The figure depicts that case 1 shows positive results already for 80 % of feedstock availability, whereas for case 2 a full operative plant is necessary to obtain profits.

3.6 Alternative scenario analysis

To test the representativeness of our result we develop three alternative scenarios: one assuming that oil prices are the ones projected in the SDS scenario described in section 3.1, a second one considering that wax prices are decoupled from oil prices and a third one considering the second and third scenario simultaneously.

443 *3.6.1   Sustainable development scenario:*

444 Figure 8 shows the results of the Monte Carlo simulation for the STEPS and SDS expressed as NPVt. The

445 probability of observing negative results for case 1 increases from 2 % in the STEPS (a) to 43 % in the SDS

446 (c). For case 2 this probability increases from 43 % in the STEPS (a) to 93 % in the SDS (c), with a negative

447 median value in the last case. It is possible, therefore, that if oil prices decrease because of the

448 implementation of policies to reduce global warming or because of a reduction in oil demand, pyrolysis

449 would be less attractive to investors.

450 *3.6.2   Wax – oil price decoupling scenario:*

451 Waxes, in contrast to many naphtha products that are predominantly produced from crude oil, can be

452 produced synthetically. Because of this, we analyzed what would happen in case wax prices decouple from

453 the crude oil price and follow an independent trajectory. For the decoupled wax-oil price scenarios, prices

454 of wax are assumed to remain constant at 760 EUR/t.

455 Figure 8 shows that for case 1 the probability of observing negative results increases from 2 % (a) to 17 %

456 (b) in the STEPS. Likewise, in the SDS the probability of perceiving negative results increases from 43 % (c)

457 to 58 % (d) in case wax prices follow an independent trajectory from oil prices.

458 The most striking of these results is that for every price scenario analyzed case 1 seems better than case

459 2, being this in line with the deterministic baseline. Only a price of slack wax lower to 690 EUR/t in STEPS

460 and lower than 600 EUR/t in the SDS would make closed-loop recycling more profitable than open-loop

461 recycling.

462 **4   CONCLUSIONS**

463 From an economic perspective, open-loop pyrolysis (case 1) as presented in this paper outperforms

464 closed-loop pyrolysis (case 2) because of the higher price of waxes when compared to naphtha. This price

465 gap is high enough to overcome the required extra separation processes of case 1 when compared to case

466 2. In our deterministic analysis and under several industry specific assumptions, a positive NPVt is observed

27

467   for both cases. Nevertheless, these results heavily rely on the volatile oil price, the feedstock availability,

468   the uncertain investment costs and on specific assumptions such as the discount rate. Separating the

469   recycled products market from the oil-derived products market would reduce the reliance of recycling on

470   oil prices and therefore increase its economic robustness. Related to feedstock availability, for a successful

471   business case, the provision of plastic waste should be somehow secured. The minimum plant sizes are 70

472   kt/year for case 1 and 115 kt/year for case 2. In a 120 kt/year nameplate capacity plant, a positive NPV is

473   obtained upon a minimum feedstock availability of 96 kt/year in case 1 recycling and almost 120 kt/year

474   for case 2 recycling. This again makes open-loop (case 1) recycling more robust.

475   Moreover, if a higher discount rate would be required by the investors the results of the NPV will vary

476   significantly. As the IRR result show, a maximum discount rate of 21. 3 % for case 1 and 15.7 % for case 2

477   could be tolerated.

478   When accounting for uncertainty of the product, feedstock and hydrogen prices, together with the

479   uncertainty of the investment estimations, we observe a probability of 2 % for case 1 and of 43 % for case

480   2 of negative results. Lower naphtha and wax prices, higher CAPEX, lower feedstock availability or higher

481   feedstock price all may increase the probability of observing negative results. The current study did not

482   take into account the correlations in the auxiliaries (hydrogen, energy, etc.) and product market prices for

483   the Monte Carlo evaluation, that could affect the overall uncertainty of the results.

484   Results suggest that to enable the transition to a circular economy, policy incentives should focus on the

485   security of the value chain. On the upstream sector, mechanisms to ensure the provision of plastic

486   feedstock to the pyrolysis companies would increase the attractiveness of this recovery alternative. On

487   the downstream sector, separating the recycled products market from the oil market would increase the

488   confidence of investors towards this type of technology. This could be enabled by for example, further

489   development of secondary raw material markets.

28

493 **6   ABBREVIATION LIST**

494 DPP   Discounted Payback Period

495 E&I   Equipment and Infrastructure

496 IRR   Internal Rate of Return

497 LCA   Life Cycle Assessment

498 MPO   Mixed Polyolefins

499 NPV   Net Present Value

500 NPVt   NPV per ton of plastic treated

501 PDF   Probability Density Fucntion

502 PE   Polyethylene

503 PMD   Plastic, metal and drink cartons

504 PP   Polypropylene

505 SDS   Sustainable Development Scenario

506 STEPS   Stated Policies Scenario

507 TEA   Techno-economic Assessment

508

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509   **7   REFERENCES**

510   Al-Salem, S.M., Antelava, A., Constantinou, A., Manos, G., Dutta, A., 2017. A review on thermal

511   and catalytic pyrolysis of plastic solid waste (PSW). J. Environ. Manage. 197, 177–198.

512   https://doi.org/10.1016/j.jenvman.2017.03.084

513   Almeida, D., Marques, M. de F., 2016. Thermal and catalytic pyrolysis of plastic waste. Polímeros

514   26, 44–51. https://doi.org/10.1590/0104-1428.2100

515   Analytica,   n.d.   Kernel   Density   Smoothing   [WWW   Document].   URL

516   https://wiki.analytica.com/index.php/Kernel_Density_Smoothing#Kernel_Density_Smooth

517   ing (accessed 12.16.19).

518   Arafat, H.A., Jijakli, K., Ahsan, A., 2015. Environmental performance and energy recovery

519   potential of five processes for municipal solid waste treatment. J. Clean. Prod. 105, 233–

520   240. https://doi.org/10.1016/j.jclepro.2013.11.071

521   Arena, U., Di Gregorio, F., Amorese, C., Mastellone, M.L., 2011. A techno-economic comparison

522   of fluidized bed gasification of two mixed plastic wastes. Waste Manag. 31, 1494–1504.

523   https://doi.org/10.1016/j.wasman.2011.02.004

524   Argus Media, 2018. Global Waxes Market Summary.

525   Athanassiou, M., Zabaniotou, A., 2007. Techno-economic assessment of recycling practices of

526   municipal   solid   wastes   in   Cyprus.   J.   Clean.   Prod.

527   https://doi.org/10.1016/j.jclepro.2007.09.001

528   BASF, 2019. Chemical recycling of plastic waste [WWW Document]. URL

529   https://www.basf.com/global/en/who-we-are/sustainability/we-drive-sustainable-

30

530   solutions/circular-economy/chemcycling.html

531 Channiwala, S.A., Parikh, P.P., 2002. A unifieed correlation for estimating HHV of solid, liquid and

532   gaseous fuels. Fuel 81, 1051–1063.

533 Cheali, P., Gernaey, K. V, Sin, G., 2015. Uncertainties in early-stage capital cost estimation of

534   process design – a case study on biorefinery design.

535   https://doi.org/10.3389/fenrg.2015.00003

536 Chrisman, L., 2014. Latin Hypercube vs. Monte Carlo Sampling [WWW Document]. Anal. Lumina

537   Blog. URL http://www.lumina.com/blog/latin-hypercube-vs.-monte-carlo-sampling#7

538   (accessed 4.9.19).

539 Cimpan, C., Maul, A., Wenzel, H., Pretz, T., 2016. Techno-economic assessment of central sorting

540   at material recovery facilities e the case of lightweight packaging waste. J. Clean. Prod. 112,

541   4387–4397. https://doi.org/10.1016/j.jclepro.2015.09.011

542 CREG, 2018. Annual report, Commission for Electricity and Gas Regulation Annual Report.

543 Ellen MacArthur Foundation, 2017. The New Plastics Economy: Catalysing Action. Ellen

544   MacArthur Found. 1–68.

545 European Commission, 2018. A European Strategy for Plastics in a Circular Economy.

546 Fivga, A., Dimitriou, I., 2018. Pyrolysis of plastic waste for production of heavy fuel substitute : A

547   techno-economic assessment. Energy 149, 865–874.

548   https://doi.org/10.1016/j.energy.2018.02.094

549 Ghisellini, P., Cialani, C., Ulgiati, S., 2016. A review on circular economy : the expected transition

31

550   to a balanced interplay of environmental and economic systems. J. Clean. Prod. 114, 11–32.

551   https://doi.org/10.1016/j.jclepro.2015.09.007

552   Ghodrat, M., Rhamdhani, M.A., Brooks, G., Masood, S., Corder, G., 2016. Techno economic

553   analysis of electronic waste processing through black copper smelting route. J. Clean. Prod.

554   126, 178–190. https://doi.org/10.1016/j.jclepro.2016.03.033

555   Huysman, S., Dewulf, J., De Schaepmeester, J., Ragaert, K., De Meester, S., 2017. Performance

556   indicators for a circular economy: A case study on post-industrial plastic waste. Resour.

557   Conserv. Recycl. 120, 46–54. https://doi.org/10.1016/j.resconrec.2017.01.013

558   Indaver, 2019. Press release: Indaver receives permit to build a new plant for the chemical

559   recycling   of   end-of-life   plastics   [WWW   Document].   URL

560   https://www.indaver.com/en/news-media/news-detail/press-release-indaver-receives-

561   permit-to-build-a-new-plant-for-the-chemical-recycling-of-end-of-lif/ (accessed 12.20.19).

562   International Energy Agency, 2018a. The Future of Petrochemicals:Towards more sustainable

563   plastics and fertilisers.

564   International Energy Agency, 2018b. Sustainable Development Scenario [WWW Document].

565   2019. URL https://www.iea.org/weo/weomodel/sds/

566   Kaack, L.H., Apt, J., Morgan, M.G., Mcsharry, P., 2017. Empirical prediction intervals improve

567   energy   forecasting.   Proceeding   Natl.   Acad.   Sci.   United   Stated   Am.

568   https://doi.org/10.1073/pnas.1619938114/-/DC

569   Koetse, M.J., de Groot, H.L.F., Florax, R.J.G.M., 2006. The Impact of Uncertainty on Investment: A

570   Meta-Analysis, Tinbergen Institute discussion papers. https://doi.org/10.2139/ssrn.917095

571   Kuppens, T., Van Dael, M., Vanreppelen, K., Thewys, T., Yperman, J., Carleer, R., Schreurs, S., Van

572   Passel, S., 2015. Techno-economic assessment of fast pyrolysis for the valorization of short

573   rotation coppice cultivated for phytoextraction. J. Clean. Prod. 88, 336–344.

574   https://doi.org/10.1016/j.jclepro.2014.07.023

575   Lazarevic, D., Aoustin, E., Buclet, N., Brandt, N., 2010. Plastic waste management in the context

576   of a European recycling society: Comparing results and uncertainties in a life cycle

577   perspective.   Resour.   Conserv.   Recycl.   55,   246–259.

578   https://doi.org/10.1016/j.resconrec.2010.09.014

579   Li, B., Ou, L., Dang, Q., Meyer, P., Jones, S., Brown, R., Wright, M., 2015. Bioresource Technology

580   Techno-economic and uncertainty analysis of in situ and ex situ fast pyrolysis for biofuel

581   production.   Bioresour.   Technol.   196,   49–56.

582   https://doi.org/10.1016/j.biortech.2015.07.073

583   Lopez, G., Artetxe, M., Amutio, M., Bilbao, J., Olazar, M., 2017. Thermochemical routes for the

584   valorization of waste polyolefinic plastics to produce fuels and chemicals. A review. Renew.

585   Sustain. Energy Rev. 73, 346–368. https://doi.org/10.1016/j.rser.2017.01.142

586   Mellouk, H., Meullemiestre, A., Maache-rezzoug, Z., Bejjani, B., Dani, A., Rezzoug, S., 2016.

587   Valorization of industrial wastes from French maritime pine bark by solvent free microwave

588   extraction   of   volatiles.   J.   Clean.   Prod.   112,   4398–4405.

589   https://doi.org/10.1016/j.jclepro.2015.06.129

590   Murata, K., Sato, K., Sakata, Y., 2004. Effect of pressure on thermal degradation of polyethylene.

591   J. Anal. Appl. Pyrolysis 71, 569–589. https://doi.org/10.1016/j.jaap.2003.08.010

33

592   OVAM, 2019. Tarieven en capaciteiten voor storten en verbranden actualisatie tot 2018.

593   Perugini, F., Mastellone, M.L., Arena, U., 2005. A life cycle assessment of mechanical and

594   feedstock recycling options for management of plastic packaging wastes. Environ. Prog. 24,

595   137–154. https://doi.org/10.1002/ep.10078

596   PWC, 2019. A European comparison of electricity and gas prices for large industrial consumers.

597   RDC, 2018. Milieu , economische en sociale beoordeling van verschillende scenario ' s voor de

598   inzameling van huishoudelijke verpakkingen Studie voor Fost Plus.

599   Recenso   Germany,   2019.   Plastic   Conversion   [WWW   Document].   URL

600   https://www.recenso.eu/en/plastic-conversion.html (accessed 1.6.20).

601   Recycling   Technologies,   2018.   Lodestar   project   [WWW   Document].   URL

602   https://recyclingtechnologies.co.uk/what-we-do/project-lodestar/ (accessed 1.5.20).

603   Ruibal, C.M., Mazumdar, M., 2008. Forecasting the mean and the variance of electricity prices in

604   deregulated   markets.   IEEE   Trans.   Power   Syst.   23,   25–32.

605   https://doi.org/10.1109/TPWRS.2007.913195

606   Sahu, J., Mahalik, K., Kim Nam, H., Yee Ling, T., Swee Woon, T., Shahimi bin Abdul Rahman, M.,

607   Mohanty, Y., Jayakumar, N., Jamuar, S., 2012a. Feasibility Study for Catalytic Cracking of

608   Waste Plastic to Produce Fuel Oil with Reference to Malaysia and Simulation using ASPEN

609   Plus. Environ. Prog. Sustain. Energy. https://doi.org/10.1002/ep.11748

610   Sahu, J., Mahalik, K., Kim Nam, H., Yee Ling, T., Swee Woon, T., Shahimi bin Abdul Rahman, M.,

611   Mohanty, Y., Jayakumar, N., Jamuar, S., 2012b. Feasibility Study for Catalytic Cracking of

612   Waste Plastic to Produce Fuel Oil with Reference to Malaysia and Simulation using ASPEN

34

613   Plus. Environ. Prog. Sustain. energy. https://doi.org/10.1002/ep.11748

614   Schultmann, F., Engels, B., Rentz, O., 2004. Flowsheeting-based simulation of recycling concepts

615   in the metal industry 12, 737–751. https://doi.org/10.1016/S0959-6526(03)00050-7

616   Sinnott, R., Towler, G., 2019. Chemical Engineering Design, 6th Editio. ed. Elsevier, Oxford.

617   STATBEL, 2019. An overview of Belgian wages and salaries- Gemiddelde bruto maandlonen voor

618   voltijds tewerkgestelde werknemers volgens anciёniteit [WWW Document]. URL

619   https://statbel.fgov.be/en/themes/work-training/wages-and-labourcost/overview-

620   belgian-wages-and-salaries#figures (accessed 3.30.19).

621   Thomas, D., Mertens, D., Meeus, M., Van der Laak, W., Francois, I., 2016. Power To Gas: Roadmap

622   for Flanders report.

623   Thomassen, G., Egiguren Vila, U., Van Dael, M., Lemmens, B., Van Passel, S., 2016. A techno-

624   economic assessment of an algal-based biorefinery. Clean Technol. Environ. Policy 18, 1849–

625   1862. https://doi.org/10.1007/s10098-016-1159-2

626   Thomassen, G., Van Dael, M., Van Passel, S., You, F., 2019. How to assess the potential of

627   emerging green technologies ? Towards a prospective environmental and techno-economic

628   assessment framework. Green Chem. https://doi.org/10.1039/c9gc02223f

629   Tsagkari, M., Couturier, J.L., Kokossis, A., Dubois, J.L., 2016. Early-Stage Capital Cost Estimation of

630   Biorefinery Processes: A Comparative Study of Heuristic Techniques. ChemSusChem 9,

631   2284–2297. https://doi.org/10.1002/cssc.201600309

632   Van Dael, M., Kuppens, T., Lizin, S., Passel, S. Van, 2015. Techno-economic Assessment

633   Methodology for Ultrasonic Production of Biofuels, in: Production of Biofuels and Chemicals

35

634   with Ultrasound. https://doi.org/10.1007/978-94-017-9624-8

635   VOSE, 2000. Modified PERT distribution [WWW Document]. Modif. PERT Distrib. URL

636   https://www.vosesoftware.com/riskwiki/ModifiedPERTdistribution.php   (accessed

637   7.31.19).

638   Wachtmeister, H., Henke, P., Höök, M., 2018. Oil projections in retrospect: Revisions, accuracy

639   and   current   uncertainty.   Appl.   Energy   220,   138–153.

640   https://doi.org/10.1016/j.apenergy.2018.03.013

641   Werner International, 2014. LABOR COST COMPARISONS 2014.

642   Yong, Y.S., Lim, Y.A., Ilankoon, I.M.S.K., 2019. An analysis of electronic waste management

643   strategies and recycling operations in Malaysia : Challenges and future prospects. J. Clean.

644   Prod. 224, 151–166. https://doi.org/10.1016/j.jclepro.2019.03.205

645   Zhao, D., Wang, X., Miller, J.B., Huber, G.W., 2020. The Chemistry and Kinetics of Polyethylene

646   Pyrolysis : A Process to Produce Fuels and Chemicals. ChemSusChem 1764–1774.

647   https://doi.org/10.1002/cssc.201903434

648