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Title:

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

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ABSTRACT

In recent decades new recycling technologies for mixed plastic waste have emerged. In pyrolysis, the polymer chains are thermally broken (pyrolyzed) to obtain hydrocarbon materials of different molecular weights such as naphtha, oil or waxes, whose yields can be controlled by varying the reaction parameters. Naphtha represents a closed-loop recycling process as it is a feedstock for (poly)olefins; while the co-production of waxes, having several applications in e.g. the construction industry, exemplifies an open-loop recycling process. This paper compares the economic performance of the pyrolysis of mixed polyolefin waste in a closed-loop and open-loop scheme, including a probabilistic approach to the most important variables. From an economic perspective, open-loop pyrolysis as presented outperforms closed-loop recycling, due to the high prices of wax. However, the results present a high dispersion caused by the volatility of the prices of crude oil and its derivates. Considering the current oil price projections, our case study analysis showed that for open-loop recycling there is a future probability of almost a 98 % of observing positive results and around 57 % of probability in the case of closed-loop recycling, under the assumptions made. Yet, in a future scenario where decarbonized electricity would decrease oil prices, the probability of a positive outcome reduces to 57 % for the open-loop case and to less than 8 % in the case of closed-loop recycling. To make these pathways attractive to investors, the nameplate capacity should be at least 70 kt/year for open-loop recycling and 115 kt/year for closed-loop recycling. A 120 kt/year plant should operate minimally at 80 % of its capacity for open-loop recycling, while closed-loop recycling would demand running close to maximum capacity. Security of feedstock supply therefore is required.

KEYWORDS

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

HIGHLIGHTS

- Open-loop recycling has better economic performance than closed-loop recycling.
- Oil price variability and CAPEX estimation uncertainty affect the variance.
- Technology is profitable for 70 kt/year capacity plants or larger.
- Provision of plastic waste feedstock should be ensured.

1 Introduction

The use of plastic packaging has increased twenty-fold in the past half-century and is expected to double in the next 20 years. Additionally, 90 % of this industry's feedstock comes from finite stocks of oil and gas (Ellen MacArthur Foundation, 2017). These facts have increased the interest in the development of strategies that intend to keep the value of plastics as long as possible, aiming for the transition to a circular economy scheme.

Circular economy is an economic system that entails to decouple gradually the economic activity from the consumption of finite resources, reducing maximally the production of waste and the loss of value of materials and products throughout the value chain (European Commission, 2018).

Circular economy strategies can be applied to different stages of the value chain: design, production, use (and reuse) and end-of-life, which may include several recycling techniques. Recycling can be classified according to the technology that is used (mechanical recycling or (thermo)chemical recycling) and to the products aimed at (closed-loop recycling or open-loop recycling). In closed-loop recycling, the recycled material can substitute the original virgin material and can be used in the same type of products. In open-loop recycling, the properties of the recycled material differ from those of the virgin material, so it is used in other product applications, substituting other materials (Huysman et al., 2017).

Chemical recycling or feedstock recycling is a broad group of techniques that work by breaking up the polymer into smaller molecular fragments to produce oil, fuel, syngas, monomers or other by-products. Pyrolysis is a type of thermochemical recycling in which heating occurs in the absence of oxygen. In this process the organic compounds are decomposed, generating gaseous and liquid hydrocarbon products while keeping the inorganic material unchanged (Almeida and Marques, 2016).

In pyrolysis of plastic waste, the obtention of the desired products can be targeted by varying the process parameters (pressure, temperature, feedstock, etc.). Lopez et al. (2017), reviewed studies referring to the chemical recycling of polyolefins to produce light olefins, fuel, aromatics or waxes. They concluded that in pyrolysis, higher temperatures and short residence time favor the production of light olefins and mild temperatures favor the production of waxes. Likewise, Al-Salem et al. (2017) collected research regarding the effect of feedstock, temperature, residence time and pressure on the product distribution. They signaled that temperature is the factor with the highest influence on the product distribution that was more extensively studied thus far. However, they indicate that a high temperature or a long residence time may provoke secondary reactions potentially leading to unwanted products. Regarding the pressure, the aforementioned review refers to Murata et al. (2004), who compared the degradation rate and the product distribution of the thermal degradation of polyethylene (PE) under atmospheric and elevated pressure. Increasing the pressure allows shifting the product distribution to liquid hydrocarbons. Specifically, at high pressure the mass fractions of the products with carbon numbers between 1 and 12 increased (as shown indicatively in Figure 1). Although these studies indicate that in pyrolysis it is possible to target the process parameters to certain products, they do not evaluate which products are more desirable.

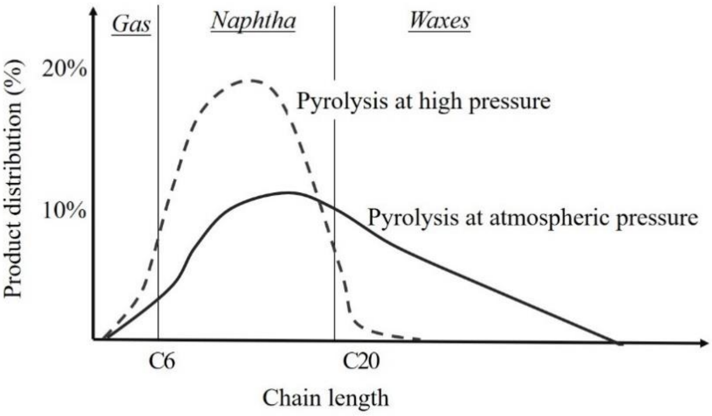

Figure 1: Carbon number distribution under different pressures. Illustration based on Murata et al. (2004)

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 obtained if 120 kt/year of waste plastics were treated by catalytic cracking to produce fuel oils. Together, these studies prove that the pyrolysis of plastic waste is profitable for large scale plants, but that capital costs and operating time have a critical role in the results.

With respect to the environmental assessment of plastic waste treatments, an early contribution was an LCA done by Perugini et al. (2005). They compared the impacts of landfilling, incineration, mechanical recycling, pyrolysis and hydrocracking and reported that the highest energy savings are observed with hydrocracking but that the lowest water consumption, CO_2 emissions, air emissions and waste generation is reached with mechanical recycling. A detailed examination of treatment options by Lazarevic et al. (2010) showed that mechanical recycling is preferred over feedstock recycling and incineration in case there is little organic contamination and there is a replacement virgin plastic ratio close to 1:1. In addition, Arafat et al. (2015) revealed that mechanical recycling is better than incineration and gasification from an energy recovery point of view. Huysman et al. (2017) developed a recyclability benefit rate indicator based on LCA and found that environmental benefits can be obtained with open-loop and closed-loop recycling when comparing them to landfilling or incineration. To our knowledge, no studies comparing the economic performance of open-loop vs closed-loop recycling of polyolefin waste have been published thus far.

Overall, there is much evidence that the environmental impact of recycling is lower than the environmental impact of landfilling and incineration, mainly because of the avoided impact of the recycled products. Furthermore, the reviewed studies support the notion that new plastic recycling technologies can realize economic benefits. Yet, very little attention has been paid to the role of the process parameters and product characteristics in the economic performance of a given technology. Therefore, it is not clear which products should be aimed at in the case of pyrolysis of plastic packaging waste, now that the technology is moving beyond recovery to fuels (Zhao et al., 2020).

Moreover, previous TEAs of chemical and thermal recycling, among which pyrolysis, have been deterministic in nature and therefore failing to deal with a crucial factor for investors: uncertainties related to oil prices and investment costs. The oil price is highly volatile and the forecasting of specialized energy agencies may present errors of almost 50 % in a 10 year horizon (Wachtmeister et al. 2018). Regarding the investment, preliminary cost studies can have accuracy ranges of -50 % to +100 % (Cheali et al., 2015) and most empirical analyses find a negative effect of uncertainty on investment (Koetse et al., 2006). Consequently, it is imperative to consider uncertainty in prospective economic assessments.

This paper compares the potential economic returns of closed-loop versus open-loop pyrolysis of mixed polyolefin waste, a contrast that so far has not been studied. Naphtha, used as a feedstock for ethylene and propylene and subsequently polyethylene (PE) and polypropylene (PP), is taken as a representative product of closed-loop recycling (Zhao et al., 2020), and wax is considered as a representative product for open-loop recycling. Both can be produced by changing the process parameters of pyrolysis of polyolefins, as shown before. Moreover, until now, TEAs that take into account the uncertainty of oil prices assume a certain variability or consider the observed past price variability (e.g. Li et al., 2015). Innovatively, this study uses forecasted oil prices and the uncertainty of the accuracy of these forecasts together with the uncertainty of projected investment costs. In doing so we capture the apprehensions of petrochemical industry investors.

2 Materials and Methods

To compare the economic performance of open-loop and closed-loop pyrolysis, a prospective TEA is applied to two case studies. TEA is used to calculate the profitability of a project by bringing all future costs and revenues to a net present value. It is an iterative process that consists of four phases: market study, process flow diagrams and mass and energy balances, economic assessment and sensitivity analysis (Thomassen et al., 2016).

Prospective TEA is applied when the technology is still in an early stage of development and there is a need to study it at a future stage (Thomassen et al., 2019). Pyrolysis of plastic waste into naphtha and waxes is in technology readiness level 6 out of 9 with pilot plants in Norway (BASF, 2019), Germany (Recenso

Germany, 2019) and the UK (Recycling Technologies, 2018), and this research intends to study the installation of a commercial scale plant.

2.1 Description of the case studies

The circular plastic packaging value chain involves several steps, as depicted in Figure 2. This research is focused only on the processes that are directly related to the pyrolysis of mixed polyolefins (MPO). MPO is a plastic waste fraction composed of mainly low-density PE and PP residue. The origin of this waste fraction could be a source separated bag containing other recyclable waste, for example the *plastics, cans and drink cartons* bag as collected in Flanders, Belgium. To separate the MPO, tetra-brick packaging, PET bottles, PP and PE bottles should be sorted by several specialized equipment. Then, to be used as feedstock for the pyrolysis process, the remaining fraction should be compressed into MPO pellets. The pyrolysis process delivers a hydrocarbon mix that is later separated and processed. For the production of new plastics the naphtha is subsequently cracked and the resulting ethylene and propylene monomers polymerized to obtain polyethylene and polypropylene. In this research, the recycled naphtha is assumed to be of equivalent quality and characteristics as the naphtha derived from crude oil, and thereby the naphtha cracking and polymerization processes will not be accounted for. Open-loop recycling in this study corresponds to the production of a naphtha only, whereas in closed-loop recycling the crude pyrolysis oil, with heavier hydrocarbons because of the lower pressure, is separated into a wax and a naphtha product.

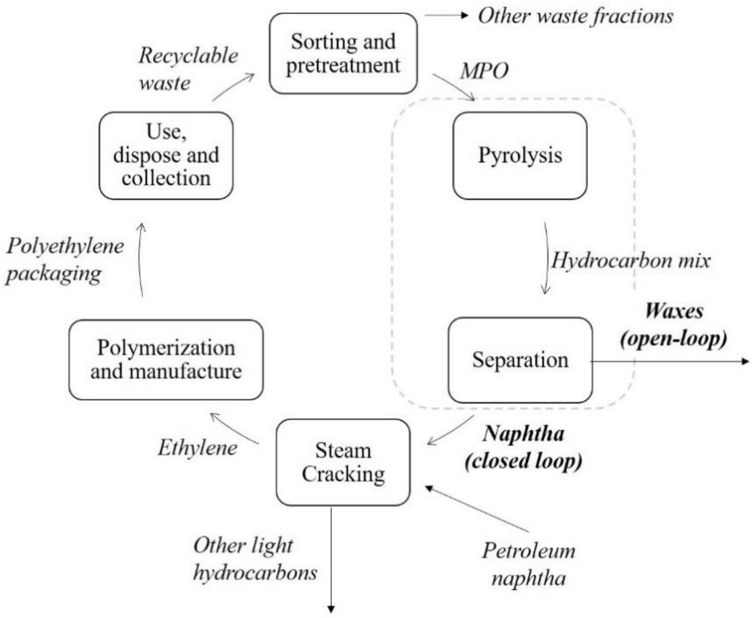

Figure 2: Polyolefin packaging value chain in the case of closed-loop and open-loop recycling.

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).

In a strict sense, case 1 does not exactly represent an open-loop process because also naphtha is produced. Similarly, case 2 is not a completely closed-loop process because of the losses occurring in the process. Therefore, the terms open-loop and closed-loop should be understood as a representation and not as an exact description of the material flows.

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

The cracking occurs at atmospheric pressure and a temperature of 460 ºC to 500 ºC, delivering a hydrocarbon mix in a molecular weight distribution covering non-condensable gases, naphtha and waxes. By condensing the mix, the non-condensable gaseous fraction is separated from the liquid fraction. The gaseous fraction is fed into a co-combustion engine to generate electric and thermal energy required for the process. The production of thermal energy is fully supplied by the engine, and the lacking electric energy is taken from the electric network. The liquid fraction follows a two-step steam distillation process where the naphtha is separated from the waxes. The products finally pass through a hydrogenation process, to eliminate impurities and increment the content of paraffins by saturating the hydrocarbon molecules under high pressure of hydrogen and relatively high temperature.

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

To obtain a larger proportion of naphtha, high pressure is applied to the pyrolysis process at the same temperature as for case 1. This cracking process yields a hydrocarbon mix composed mainly by molecules in the naphtha range. As in case 1, the gaseous fraction is separated from the liquid fraction by a condensation process and then fed into a co-combustion engine to generate electric and thermal energy. The remaining electric energy generated in this case is plugged into the network and accounted as an additional product. A distillation step is not necessary for the liquid fraction because naphtha is the only non-gaseous product obtained. This product passes through a hydrogenation process, to eliminate impurities and increase the content paraffin contents.

2.2 Techno - economic assessment

Following the TEA phases (Thomassen et al., 2016), expert market studies are used to project naphtha and slack wax prices. Then, the process flows and mass and energy balances are built based on product yields, residue yields, energy and consumable requirements. These values are retrieved from industrial references and are shown in Table 1. Because of confidentially reasons, specific process parameters are not disclosed in this paper. Following the guidelines of Van Dael et al. (2015), with the market study and the mass and energy balances we calculate the yearly revenues and operational costs. The net present value[1] (NPV), NPV per metric ton of plastic treated (NPVt), the IRR over a 15-year period and the discounted payback period (DPP) are calculated with the software Analytica, including the investment costs and considering the assumptions presented in Table 1.

The one-at-a-time sensitivity analysis exposes the variables that need a more thorough estimation because they have a dominant effect on the results. To perform it, the expected value of the NPVt is calculated after varying each one of the parameters independently to a low scenario and a high scenario. The low and high scenario correspond to 90 % and 110 % of the median values.

To incorporate uncertainty in the evaluation, some of the most important variables detected with the one-at-a-time sensitivity analysis are defined as probabilistic rather than deterministic numbers. With these probability density functions (PDFs) we calculate a PDF for the NPV with a Monte Carlo simulation. The PDFs of the variables are derived from observed data and constructed using 10 000 samples with median Latin Hypercube sampling. This sampling technique spreads the sample points by selecting the median values of intervals of equal probability instead of generating a random sample of points (Chrisman, 2014). In addition, the PDFs of the resulting Monte Carlo simulations are smoothed using Kernel Density

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[1]

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

Estimation, that replaces each sample point with a Gaussian kernel and then obtains the resulting estimate for the density by adding up these Gaussians (Analytica, n.d.).

A global sensitivity analysis is performed to determine the contribution of each probabilistic variable *"i"* to the total variance of the NPVt. We first calculate the Spearman's rank correlation coefficient (ρ_i), that corresponds to the correlation of the ranking of each input sample with the ranking of its respective NPVt. Then, using the formula $\rho_i / \sum \rho_i$ we calculate the contribution to the variance of each variable. To avoid double accounting for the uncertainty of the oil prices, for this analysis we leave naphtha and wax prices as a function of oil prices.

A parametric sensitivity analysis is done for those variables who have an important effect on the results (detected with the one-at-a-time sensitivity analysis) but that is not possible to derive a realistic PDF. These variables include the feedstock price (gate fee), oil price, nameplate capacity and feedstock availability.

Finally, to test the robustness of the results, four alternative scenarios related with the product prices are analyzed. In the *sustainable development scenario* (SDS) the oil prices are expected to decrease instead of increase, and in the *wax decoupling scenario* the wax price is assumed to be decoupled from the oil price.

2.3 Economic assumptions and cost modelling

The general economic assumptions are similar for both case studies and are summarized in Table 1. The initial year is 2019 and all prices are calculated on EUR 2019. The discount rate is set at 15 %, as commonly used for the expansion of new technologies (Van Dael et al., 2015). The feedstock input is 120 kt/year, representing an equilibrium between economies of scale as observed by Fivga and Dimitriou(2018) and Sahu et al. (2012) and considering sourcing capabilities. In fact, it is equivalent to the recycling of the 6.7

kg per capita of MPO waste[2] generated by people living 120 km around in an area with a density[3] of 394 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	Sinnott and Towler, 2019
	Maintenance	4 % of E&I	
	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

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

2.3.1 Revenues

We consider that the recycled naphtha and wax are of similar quality than naphtha and slack wax traded in the market. Thus, market prices for naphtha and slack wax are used as a reference. We collect the mean value of the projected price for naphtha and crude oil from the “Future of Petrochemicals” report developed by the International Energy Agency (International Energy Agency, 2018a). The model of this report estimates the future prices of naphtha based on its historical relationship with oil prices, using the long-term oil prices defined in the “World Energy Outlook” 2017 as a basis. The price for slack wax was 680 EUR/t on January 2018 (Argus Media, 2018), being 68 % higher than the average crude oil price. We calculate the future price of waxes considering this relationship constant. The International Energy Agency (2018a) presents forecasted values for 2020, 2025, 2030 and 2040 for crude oil and naphtha, these values are linearly interpolated.

It is well known that oil prices and those of its derivates are highly volatile and usually subject to a large estimation error. Hence, to have a better overview of the incentives to invest, it is crucial to acknowledge these uncertainties. Empirical density forecasting methods, based on forecasting errors, are a valuable approach for including an estimate of uncertainty with a forecast (Kaack et al., 2017). Following this, we take the standard deviation of the normal distribution of the forecasted values equivalent to the observed mean of forecasted errors of the “World energy outlook” from 2000 to 2016, as presented by Wachtmeister et al. (2018). The mean absolute percentage error of forecasted price for oil of the “World energy outlook” on a five year horizon is 37 % and on a 10 year horizon is 46 % (Wachtmeister et al., 2018).

For the electricity supply price, the average electricity EPEX price of 2017 in an annual contract (51 EUR/MWh) (CREG, 2018) is used and it is assumed to be normally distributed with a standard deviation of 16 % (Ruibal and Mazumdar 2008).

2.3.2 Capital Expenditure (CAPEX)

The investment cost for the 120 kt/year plant is the result of an engineering project of Indaver NV (Indaver, 2019). The equipment cost and infrastructure cost (E&I) were provided by this company and are not disclosed in this paper. For the sensitivity analysis, to calculate the CAPEX of plants of lower nameplate capacity (B), we use the equation presented by Sinnott and Towler (2019), with an exponent for pyrolysis plants of 0.69 (Kuppens et al., 2015) and the CAPEX for a 120 kt/year plant: $CAPEX_B = CAPEX_{120} * (Capacity_B/120)\exp(0.69)$.

Engineering and project management costs and contingency charges are calculated according to commonly observed ratios and are shown on Table 1.

For the uncertainty analysis, the CAPEX was modelled with a negatively skewed PERT distribution, commonly used in modelling cost with expert opinion (VOSE, 2000). The accuracy range was set between -22.5 % and +35 %, corresponding to expected values for a technology readiness level 6 (Tsagkari et al., 2016). Figure 3 shows the probability density function of the CAPEX.

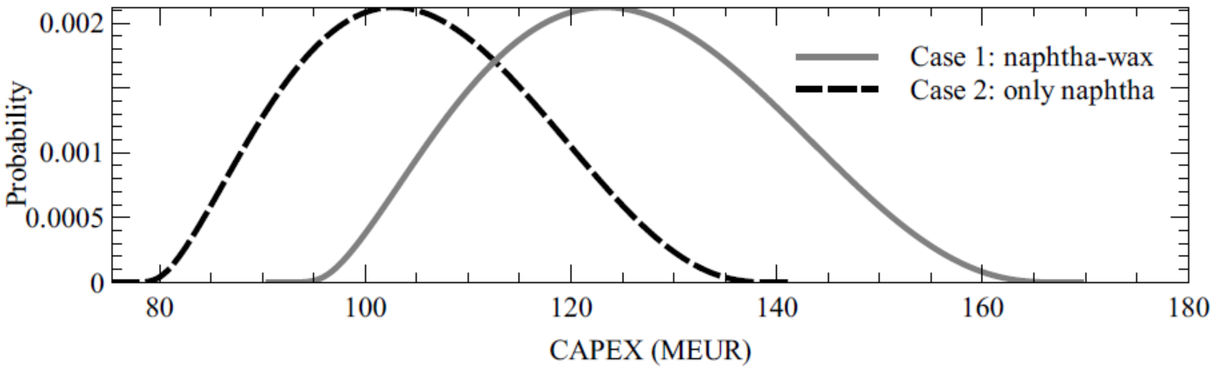

Figure 3: Probability density function of CAPEX.

2.3.3 Operational Cost (OPEX)

Table 1 shows the prices and ratios used to calculate the fixed operational costs, that do not depend on the amount of input treated, but may depend on the nameplate capacity; and the variable operational costs, that are directly proportional to the amount of feedstock processed.

For the uncertainty analysis and the global sensitivity analysis, the feedstock cost was modelled with a triangular distribution. The range of this distribution (+/- 10 EUR/t) is equivalent to the observed ranges of plastic fractions traded by the Belgian organization Fost Plus (RDC, 2018). The hydrogen price is assumed to distribute normally with a 10 % standard deviation.

3 Results and Discussion

3.1 Market Study

Figure 4 shows the forecast of the naphtha (a) and slack wax (b) price with the 50 % and 95 % probability bands (interquartile ranges), represented by the different shades of grey in the base case scenario or *Stated Policies Scenario (STEPS)*. The mean value of the naphtha and crude oil prices was obtained from the "Future of Petrochemicals"(International Energy Agency, 2018a). The standard deviation was calculated with the forecasting errors of the "World energy outlook" presented by Wachtmeister et al. (2018). For waxes, a constant relationship between the price of slack wax and crude oil was assumed.

The International Energy Agency presents an alternative scenario with different price forecasts for the oil derivates. The *sustainable development scenario* (SDS) estimates the future oil prices assuming the fulfillment of the sustainable development goals (International Energy Agency, 2018a). It is constructed considering a decarbonization of the energy production that would lead to a decrease in the demand for oil products, reflected in a decline of their price (International Energy Agency, 2018b). The standard deviation of the normal distribution is assumed to be equivalent to the one in the STEPS and the relationship between naphtha and wax prices is also assumed constant. In this scenario, naphtha and wax prices, slowly decrease (Figure 4.c and 4.d), whereas in the STEPS they show a constant increase (Figure 4.a and 4.b). The SDS prices are only used in the section *3.6.*

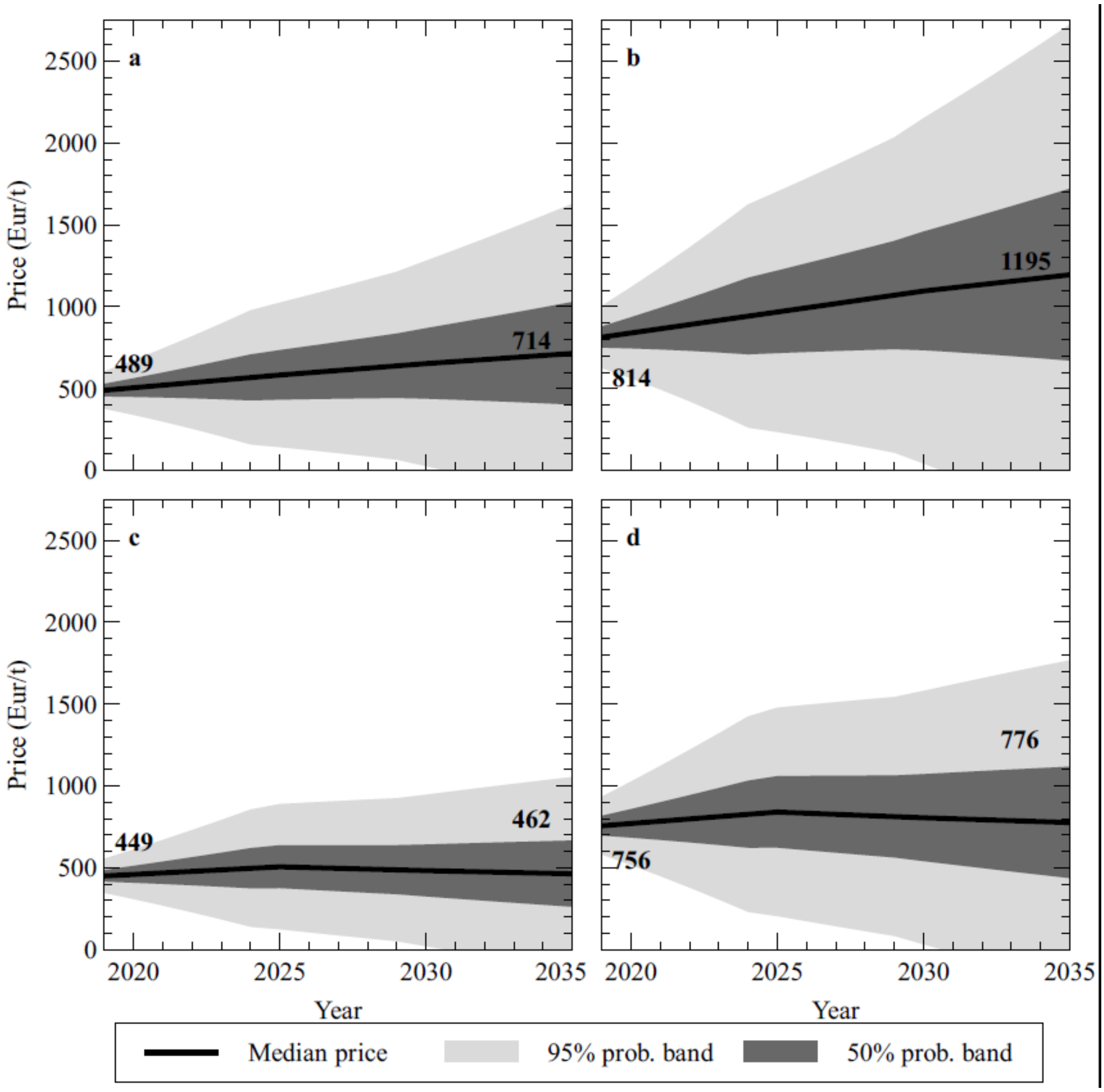

Figure 4: Naphtha (a) and slack wax (b) price forecast in STEPS. Naphtha (c) and slack wax (d) price forecast in the SDS.

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 the increased heat requirement for the distillations process in the open-loop recycling of case 1 and to the higher production of gas for case 2, given the shifted product distribution as schematically shown in Figure 1.

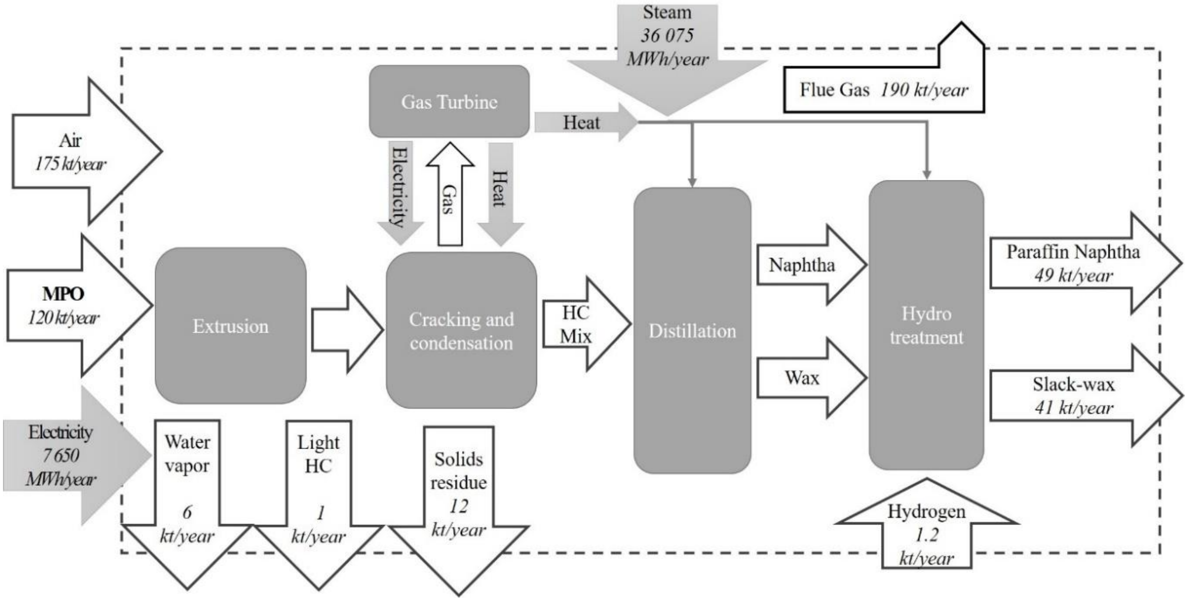

Figure 5: Process flow diagram case 1: naphtha-wax

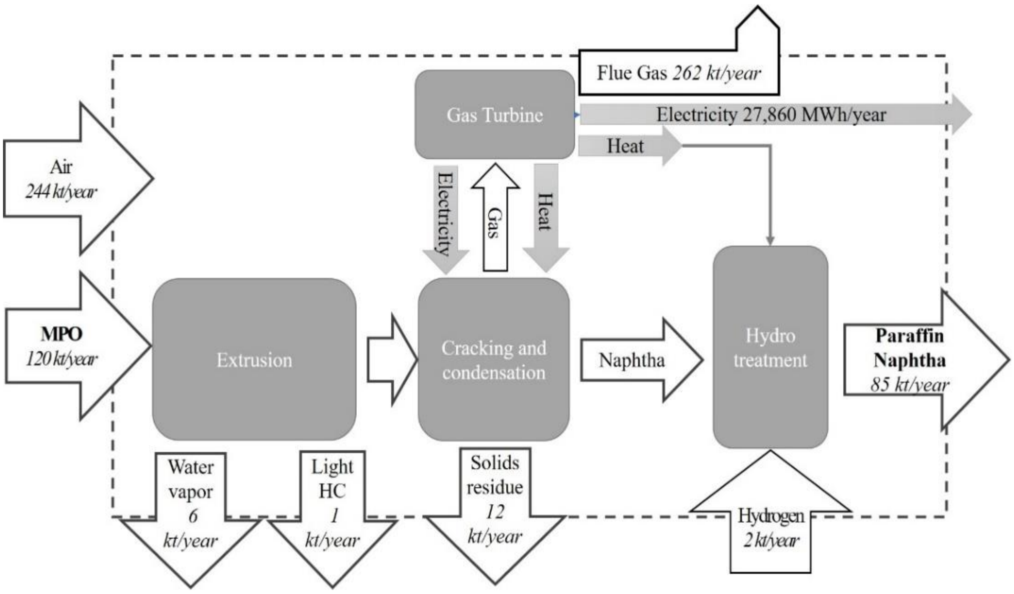

Figure 6: Process flow diagram case 2: only naphtha

3.3 Economic Results

Table 2 shows the results of the baseline deterministic economic analysis considering the assumptions presented in Table 1 and the yearly product prices of Figure 4.a and Figure 4.b. All results are better for case 1 (open-loop) than for case 2 (closed-loop), mainly because of the large price difference between naphtha and waxes that makes the income of case 1 a 34 % larger than the income of case 2. This gap outweighs the OPEX (4 %) and CAPEX (106 %) gaps between both cases.

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

As commonly observed in studies at this level of technology readiness, results presented in Table 2 are not generally valid because they are based on industry specific assumptions. To analyze the outcome if the underlying parameters change, a sensitivity analysis, uncertainty analysis and alternative scenario analysis are presented in the following sections.

3.4 Sensitivity and uncertainty analysis

3.4.1 One-at-the-time sensitivity analysis

In this step, the expected value of the NPVt is calculated after varying each one of the parameters in an independent way to a low scenario (-10 %) and a high scenario (+10 %). The tested parameters are producer electricity price, water disposal price, land expenses, solid residue disposal price, consumer electricity price, gas price, steam requirement, insurance fee, thermal energy requirement, electric energy requirement, hydrogen-to-product ratio, general plant overhead, cost of labor, hydrogen price, electric energy requirement, low heating value gas, maintenance expenses, feedstock price, total investment, naphtha price and slack wax price. Figure 7 shows that the feedstock availability, slack wax price, naphtha price, naphtha yield, wax yield, discount rate and CAPEX have a greater impact on the NPVt than maintenance, feedstock price and hydrogen price. The remaining variables have an influence of less than the 10 % on the overall value of the NPVt for both cases. The variables who had an impact lower than 1 % were excluded from the graph.

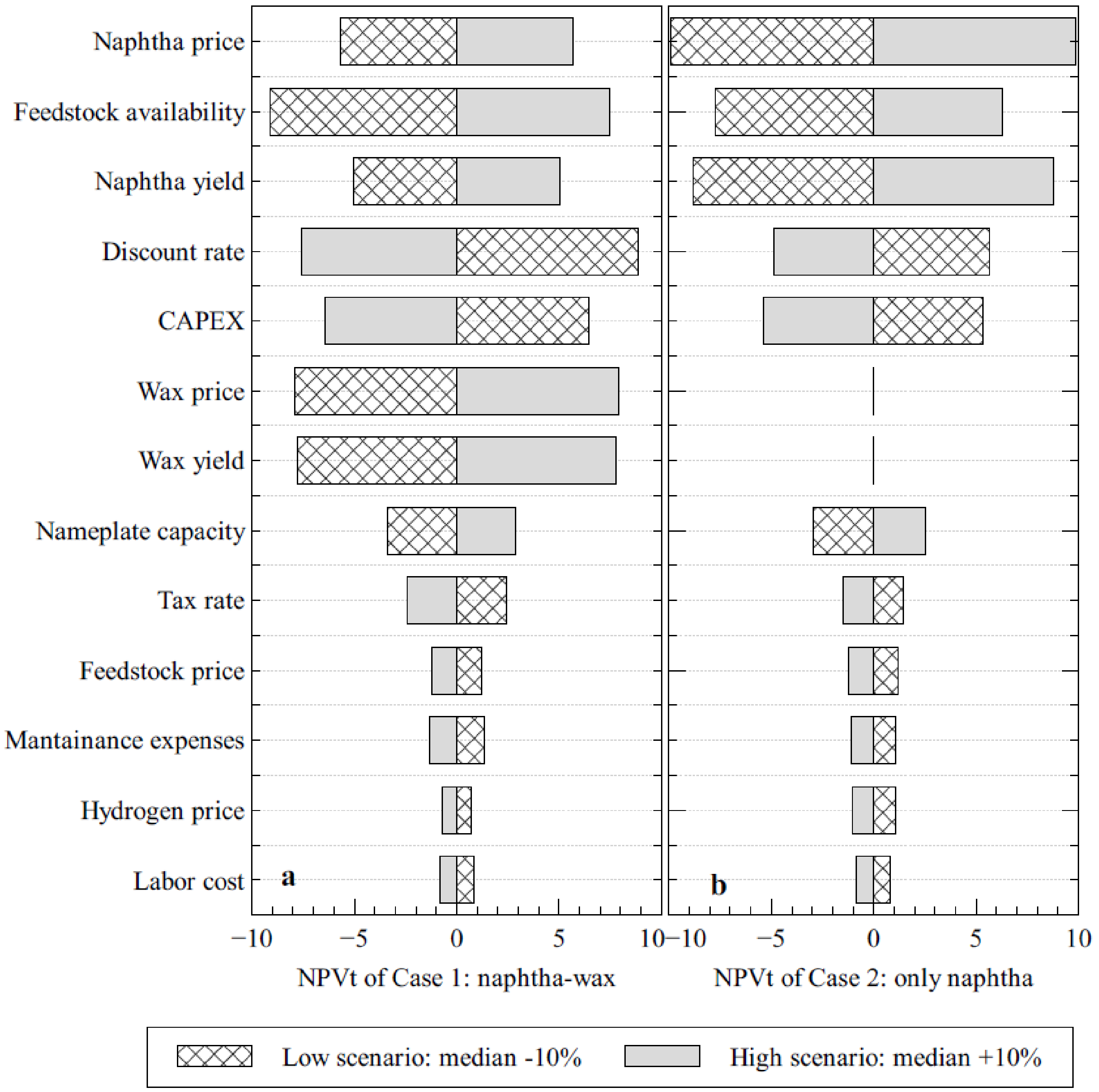

Figure 7: One-at-a-time sensitivity analysis for case 1 (a) and case 2 (b).

3.4.2 *Uncertainty analysis*

The one-at-a-time sensitivity analysis (Figure 7) shows that the products prices, CAPEX and feedstock availability are the variables with a higher influence on the results. For a broader view of the expected results product prices, CAPEX, feedstock and hydrogen price are modelled as probabilistic variables. Naphtha and slack wax price projections were previously shown in Figure 4, whereas the CAPEX estimation was shown in Figure 3. Feedstock availability and nameplate capacity are modelled as deterministic because no probabilistic function could accurately describe the supply uncertainty in this non-existing market. Instead, a parametric sensitivity analysis is performed for these variables. Additionally, as the product yields can be controlled and the discount rate is a parameter chosen by the investors, they are also modelled as deterministic.

The results of the combined Monte Carlo simulation after varying CAPEX, naphtha price, slack wax price and feedstock price together for the four price level scenarios are presented in Figure 8. From the PDF we can deduce that given the assumptions presented above, open-loop recycling surpasses closed-loop recycling. However, although the median values of the NPVt are positive, there is a probability of negative NPVt of around 2 % for case 1 and 43 % for case 2, under the given assumptions. This means that for open-loop pyrolysis there are relatively high chances of observing negative results.

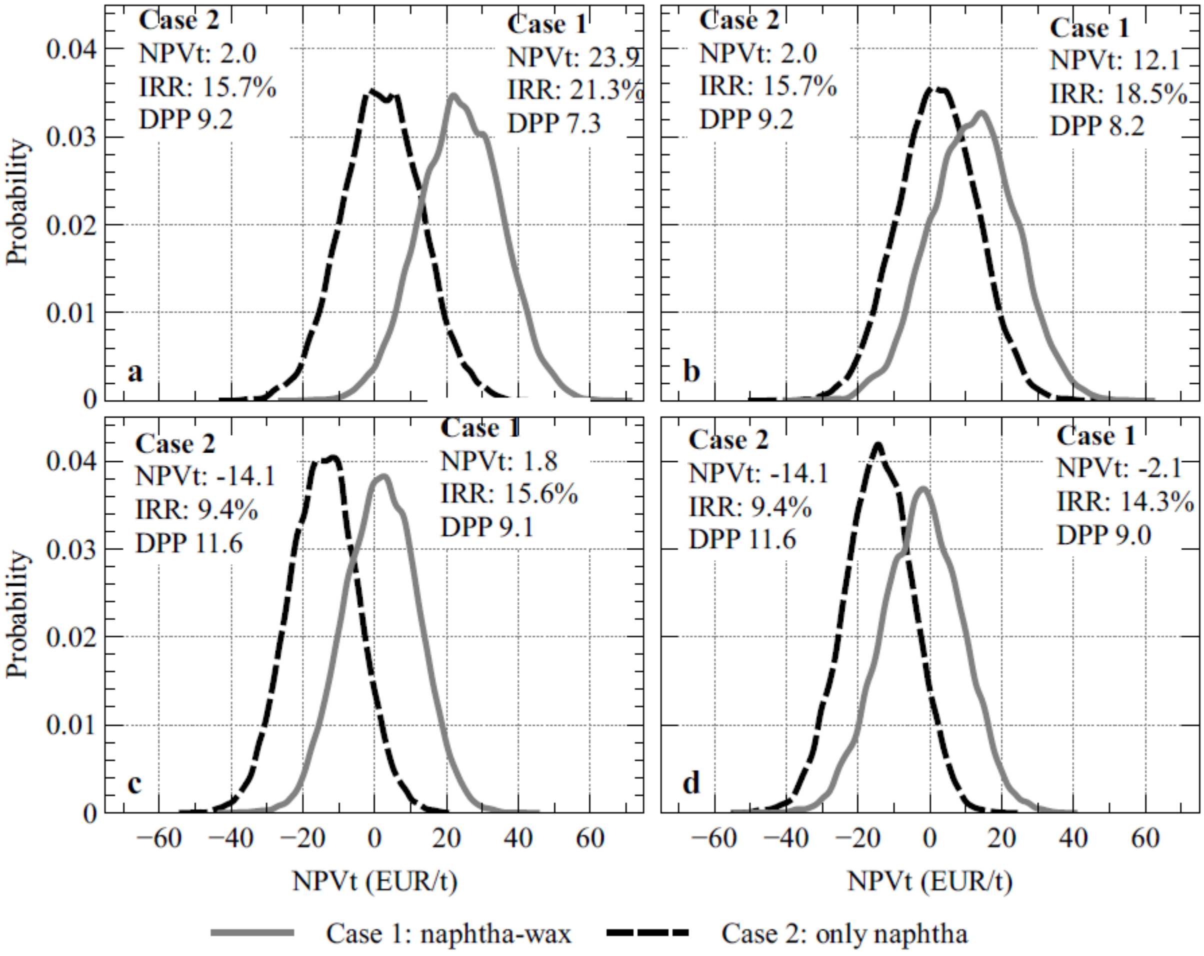

Figure 8: PDFs for the STEPS and coupled wax-oil prices scenario (a), STEPS and decoupled wax-oil prices scenario (b), SDS and coupled wax- oil prices scenario (c), SDS and decoupled wax-oil prices scenario (d).

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).

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 %

3.5 Parametric sensitivity analysis

3.5.1 Feedstock and product price

Supply of feedstock and demand of products are critical for the successful implementation of the circular value chain. Furthermore, as the partial sensitivity study suggests (Figure 7), product prices and feedstock prices have an impact on the results larger than 10 %. Thus, it is particularly interesting to analyze under which of these prices, that are given mostly by exogenous factors, the project would deliver positive results.

Assuming that feedstock prices remain constant at 50 EUR/t, that the slack wax price will always be 68 % higher than the oil price (coupled wax-oil price), and that the naphtha price will always be 10 % lower than the oil price, the mean value of oil must be over 575 EUR/t (78 EUR/barrel) to observe positive results. When looking at case 2, for profitable results the oil price must be over 550 EUR/t (75 EUR/barrel).

On the other hand, taking naphtha and wax prices presented in Figure 4.a and 4.b, the maximum price of feedstock that shows positive results is 150 EUR/t for case 1 and 50 EUR/t for case 2. These prices should be acknowledged if a waste management organization would like to convey their MPO waste to a pyrolysis plant. Moreover, they are in the range presented in Cipman et. al (2016) for PE foils.

As intuition suggests, when analyzing the variations of the feedstock price and the product prices jointly and assuming that they vary independently, it can be seen that for higher prices of feedstock, higher prices of oil are required (Figure 9). If the price of the feedstock doubles that of the base case (reaching 100 EUR/t), the minimum price of oil that would generate profits is 525 EUR/t (72 EUR/barrel) for case 1 and

625 EUR/t (85 EUR/barrel) for case 2. Moreover, in case the price for a ton of MPO would be zero, a minimum price of 425 EUR/t (58 EUR/barrel) for case 1 and 475 EUR/t (65 EUR/barrel) for case 2 will be necessary to obtain profits (Figure 9).

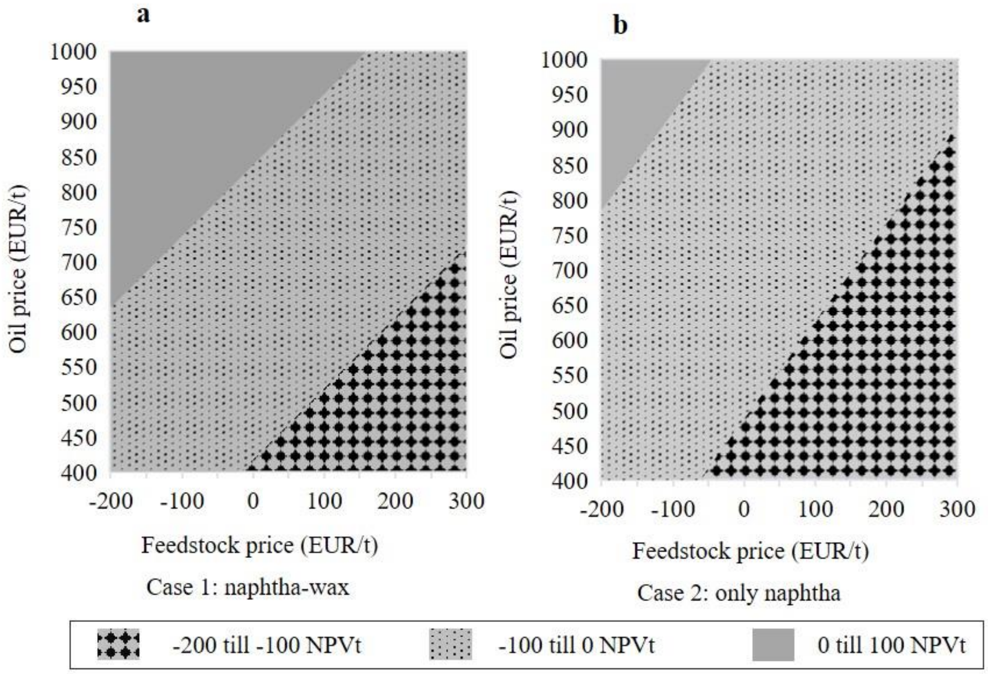

Figure 9: Sensitivity of NPVt over variations in oil and feedstock prices assuming coupled prices from naphtha and waxes to oil for case 1 (a) and case 2 (b).

3.5.2 Nameplate capacity

When calculating the NPVt for lower capacity plants it is found that for case 1 the break-even nameplate capacity is 70 kt/year while for case 2 this value ascends to 115 kt/year, assuming a discount rate of 15 % (Figure 10.a). Besides, for a discount rate over 20 % the plant must at least treat 115 kt/year in case 1 and 170 kt/year in case 2. This can be explained by the high proportion of the CAPEX over the total costs (around 50 %).

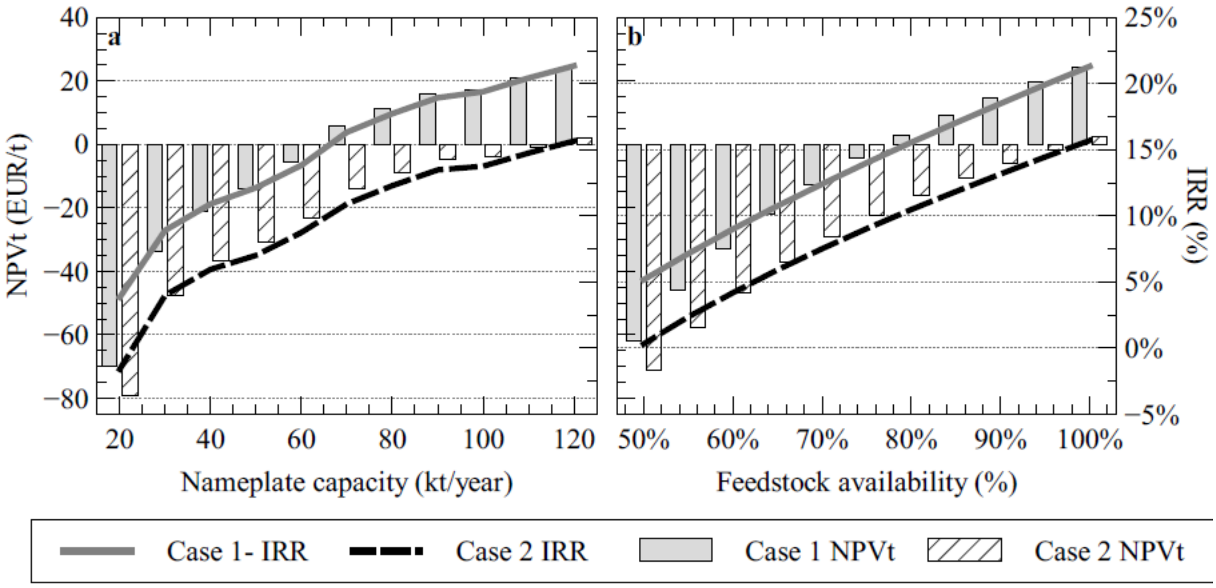

Figure 10: NPVt and IRR for lower nameplate capacities (a) and feedstock availability (b).

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.

3.6.1 Sustainable development scenario:

Figure 8 shows the results of the Monte Carlo simulation for the STEPS and SDS expressed as NPVt. The probability of observing negative results for case 1 increases from 2 % in the STEPS (a) to 43 % in the SDS (c). For case 2 this probability increases from 43 % in the STEPS (a) to 93 % in the SDS (c), with a negative median value in the last case. It is possible, therefore, that if oil prices decrease because of the implementation of policies to reduce global warming or because of a reduction in oil demand, pyrolysis would be less attractive to investors.

3.6.2 Wax – oil price decoupling scenario:

Waxes, in contrast to many naphtha products that are predominantly produced from crude oil, can be produced synthetically. Because of this, we analyzed what would happen in case wax prices decouple from the crude oil price and follow an independent trajectory. For the decoupled wax-oil price scenarios, prices of wax are assumed to remain constant at 760 EUR/t.

Figure 8 shows that for case 1 the probability of observing negative results increases from 2 % (a) to 17 % (b) in the STEPS. Likewise, in the SDS the probability of perceiving negative results increases from 43 % (c) to 58 % (d) in case wax prices follow an independent trajectory from oil prices.

The most striking of these results is that for every price scenario analyzed case 1 seems better than case 2, being this in line with the deterministic baseline. Only a price of slack wax lower to 690 EUR/t in STEPS and lower than 600 EUR/t in the SDS would make closed-loop recycling more profitable than open-loop recycling.

4 CONCLUSIONS

From an economic perspective, open-loop pyrolysis (case 1) as presented in this paper outperforms closed-loop pyrolysis (case 2) because of the higher price of waxes when compared to naphtha. This price gap is high enough to overcome the required extra separation processes of case 1 when compared to case 2. In our deterministic analysis and under several industry specific assumptions, a positive NPVt is observed for both cases. Nevertheless, these results heavily rely on the volatile oil price, the feedstock availability, the uncertain investment costs and on specific assumptions such as the discount rate. Separating the recycled products market from the oil-derived products market would reduce the reliance of recycling on oil prices and therefore increase its economic robustness. Related to feedstock availability, for a successful business case, the provision of plastic waste should be somehow secured. The minimum plant sizes are 70 kt/year for case 1 and 115 kt/year for case 2. In a 120 kt/year nameplate capacity plant, a positive NPV is obtained upon a minimum feedstock availability of 96 kt/year in case 1 recycling and almost 120 kt/year for case 2 recycling. This again makes open-loop (case 1) recycling more robust.

Moreover, if a higher discount rate would be required by the investors the results of the NPV will vary significantly. As the IRR result show, a maximum discount rate of 21. 3 % for case 1 and 15.7 % for case 2 could be tolerated.

When accounting for uncertainty of the product, feedstock and hydrogen prices, together with the uncertainty of the investment estimations, we observe a probability of 2 % for case 1 and of 43 % for case 2 of negative results. Lower naphtha and wax prices, higher CAPEX, lower feedstock availability or higher feedstock price all may increase the probability of observing negative results. The current study did not take into account the correlations in the auxiliaries (hydrogen, energy, etc.) and product market prices for the Monte Carlo evaluation, that could affect the overall uncertainty of the results.

Results suggest that to enable the transition to a circular economy, policy incentives should focus on the security of the value chain. On the upstream sector, mechanisms to ensure the provision of plastic feedstock to the pyrolysis companies would increase the attractiveness of this recovery alternative. On the downstream sector, separating the recycled products market from the oil market would increase the confidence of investors towards this type of technology. This could be enabled by for example, further development of secondary raw material markets.

5 ACKNOWLEDGMENTS

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6 ABBREVIATION LIST

DPP	Discounted Payback Period
E&I	Equipment and Infrastructure
IRR	Internal Rate of Return
LCA	Life Cycle Assessment
MPO	Mixed Polyolefins
NPV	Net Present Value
NPVt	NPV per ton of plastic treated
PDF	Probability Density Fucntion
PE	Polyethylene
PMD	Plastic, metal and drink cartons
PP	Polypropylene
SDS	Sustainable Development Scenario
STEPS	Stated Policies Scenario
TEA	Techno-economic Assessment

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