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Producing hydrocarbon fuel from the plastic waste: Techno-economic analysis

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Abstract−Dumping plastic waste into landfills can lead to severe health and environmental problems. Plastic waste can be treated by the pyrolysis process to produce fuel. A techno-economic and feasibility assessment was performed for plastic-waste pyrolysis followed by hydrodeoxygenation to upgrade the fuel using the software Aspen Plus. A simulation was conducted using Aspen Plus to estimate the plant's mass and energy balance; it is assumed that 1,000 dry metric tons of plastic waste is processed per day. Plastic waste contains 40% polystyrene (PS), 20% polyethylene (PE), 20% polypropylene (PP), and 20% polyethylene terephthalate (PET). The process is simulated in five steps: pretreatment, pyrolysis, hydrogen production, and hydrodeoxygenation of oil and energy generation. The mass and the energy yields of this process are 36% and 42%, respectively. The capital investment of the plant and the production cost were calculated based on the Aspen Plus model. Based on the economic estimation, the capital investment of this process is $118 million and the production cost is $27 million. For the 20-year project, the minimum selling price (MSP) of the fuel was calculated to be $0.60/gal. Sensitivity analysis was performed to verify the economic assumptions on the MSP. The MSP is highly sensitive to the feedstock cost, plant capacity, and product yield. As the plant capacity or product yield increases, the MSP decreases significantly.

Keywords: Plastic, Aspen Plus, Process Modelling, Fast Pyrolysis, Techno-economic Assessment, Waste Management

INTRODUCTION

During the last decades, plastic has played an important role in enhancing the lives of human beings. The demand for commodity plastics has been increasing, since they are used in several sectors such as healthcare, electronics, automotive, and packaging. Furthermore, the demand for plastic is increasing with the growth of the world population. In 2013, around 300 million tons of plastic were produced around the world, a 4% increase compared to 2012 [1]. The rise of plastic production and use has led to increases in municipal plastic waste (MPW) every year. For example, in 2012, more than 25 million tons of plastic were dumped at landfill sites. Worldwide, the rate of population growth has been recorded as 1.05% in 2020, which has led to increasing amounts of MPW. For instance, in the Kingdom of Saudi Arabia (KSA), about 15 million tons of municipal solid waste (MSW) is generated every year, and around 20% of it is MPW [2]. Municipal plastic waste contains various plastic types, such as polyethylene (PE), high polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), and polyethylene terephthalate (PET); PE and PS represent more than 50% of all MPW.

Recycling, conversion to energy, and disposal at landfill sites are techniques that have been used to manage plastic waste [3]. In Europe, mechanical recycling techniques recycle 26% of the plastic waste, and a further 36% is converted to energy, which leads to 38% of the plastic waste ending up in landfill sites [1]. Plastic waste is contaminated by other materials such as soil, dirt, and food waste, decreasing the efficiency of mechanical recycling [2]. Thus, most plastic waste dumped at landfill sites occupies huge areas and causes environmental problems, since plastics take billions of years to be naturally degraded [4]. One of the environmental problems is air, water, and land pollution, since the dumped waste contains bacteria and insects [5]. Furthermore, landfill dumping systems cost money for maintenance, labor, land, and transportation. Therefore, in recent decades, technologies that convert MPW to energy, such as gasification, pyrolysis, and plasma arc gasification, have gained increasing attention in an attempt to manage MPW [1,3].

Among thermal processes for MPW, pyrolysis is adopted to produce fuel since it has a high energy-recovery efficiency and produces

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high liquid yields at low temperatures of 425 to 600 °C with short residence times (less than 3 s) [6]. Moreover, it is the most environmentally friendly process, since it produces fewer emissions compared to gasification and incineration. Pyrolysis is divided into three types: fast, slow, and microwave-assisted. Fast pyrolysis is the most efficient process for producing fuel, since the primary product of this process is liquid oil [6,7]. Moreover, the pyrolysis process is flexible, as the yield of the products can be optimized by manipulating the operating parameters. The liquid oil from pyrolysis of MPW can be utilized for various applications such as turbines and diesel engines, without upgrading or further treatment [8].

Many studies and research papers have investigated the production of oil from different types of plastic using pyrolysis. Different types of plastics have various compositions that influence the yield of the products of the process. For instance, Miandad et al. [9] investigated the effect of plastic type on the yield and quality of liquid oil. They used PS and PP as the feedstock for the pyrolysis reactor at 450 °C and found that PS produced more liquid oil (81%) and less gas (13%) compared to PE, which produced 42% liquid oil and 55% gases. Moreover, they introduced mixtures of PS, PP, PE, and PET, with a weight percentage of 40 : 20 : 20 : 20 wt%, respectively, to the pyrolysis rector under the same condition. The oil, gas, and char yields were 40%, 42%, and 18%, respectively. The authors stated that the type of plastic has a major impact on liquid yield and quality. In addition, Rehan et al. [10] used disposable plastic plates as feedstock for the fast pyrolysis process at 450 °C, and the yields of the products were liquid oil (80.8%), gases (13.0%), and char (6.2%). Syamsiro et al. [11] also pyrolyzed a mixture of MWP at 450 °C. The products of their experiment were 58% liquid oil, 28% gases, and 14% char.

Besides the feedstock, the temperature of the pyrolysis rector also has a significant impact on the product yields. Donaj et al. [12] introduced a plastic mixture that contained 75 wt% PE and 25 wt% PP to the pyrolysis reactor at 650 and 730 °C. The liquid-oil yield at lower temperatures (650 °C) was 48 wt%, which was higher than that obtained (44%) at 730 °C. However, the liquid oil obtained at low temperatures was very heavy and contained wax and black carbon. They observed that, at a higher temperature, the liquid yield decreased, while the gas yield increased. Ahmad et al. [13] investigated the pyrolysis of high-density polyethylene (HDPE) using a steel micro reactor. The reactor temperature varied between 300 to 400 °C, with a heating rate of 5-10 °C/min. Solid residue was very high at 300 °C, and it decreased as the temperature increased, until it reached 0.54 wt% at 400 °C. The researchers obtained the highest liquid-oil yield at 350 °C, which was 81wt% of the total products. Furthermore, Onwudili et al. [14] conducted a pyrolysis study of PS using a batch autoclave reactor at 300-500 °C with a heating rate of 5-10 °C/min. From the results of the experiment, 97 wt% liquid oil and 2.5 wt% gases were obtained at 425 °C. As temperature increased, the liquid yield decreased and the gas yield increased. Even though the pyrolysis process produces a large amount of liquid oil, there are certain limitations, since the liquid oil is very heavy and contains impurities and residues [1]. Moreover, thermal plastic pyrolysis requires a large amount of energy, since the pyrolysis reactions occur at high temperatures. Thus, catalytic pyrolysis has been developed to overcome the limitations of thermal pyrolysis [15].

Adding a catalyst to the pyrolysis reactor decreases energy input and enhances the quality of the liquid oil obtained. Several catalysts have been utilized in the pyrolysis of plastic waste, including FCC silica-alumina, MCM-41, and zeolites such as Y-zeolite, HZSM, and ZSM-5. Miskolczi [16] reported that adding FCC microporous catalyst enhanced the liquid-oil yield from plastic pyrolysis, whereas ZSM-5 decreased the liquid yield and increased the gas yield. Marcilla et al. [17] investigated the effect of adding HZSM-5 and HUSY for pyrolyzing low-density polyethylene (LDPE) at 550 °C. They reported that HUSY produced a higher liquid-oil yield 62 wt% compared to HZSM-5, which produced 18 wt% [17].

Although plastic pyrolysis has been investigated extensively in the literature, technical feasibility and economic viability of hydrocarbon fuel production via this process should be more thoroughly analyzed and investigated. A techno-economic assessment for the production of fuel from plastic pyrolysis was done by Fivga and Dimitirou [18]. The study was conducted in the UK, and the authors reported that the production cost for fuel from MPW is ten times lower than the market fuel prices for a plant with a capacity of 240 metric tons of plastic per day [18]. Furthermore, Sahu et al. [19] investigated the technical and economic feasibility of producing hydrocarbon fuel from plastic waste via catalytic pyrolysis in Malaysia. Their study reveals that an internal rate of return (IRR) of 36% may be gained for a plant capacity of 330 metric tons per day [19]. These studies show that the pyrolysis of MPW is a profitable process for large-scale plant, but capital costs, feedstock, and operating conditions play a critical role in the results. Thus, these results cannot be generalized to all MPW plastic-waste pyrolysis.

The overarching objective of this paper is, therefore, to evaluate the feasibility and economic viability of producing hydrocarbon fuel from MPW pyrolysis. Process models of MPW pyrolysis and hydrodeoxygenation were developed. The model was validated with experimental data for plastic-waste pyrolysis. Mass and energy balances of the process were calculated using Aspen Plus, and capital and operating costs were estimated based on these calculations. A discounted cash analysis method was used to determine the minimum selling price (MSP) of hydrocarbon fuel. Finally, the MSP sensitivity to financial and process-related assumptions is measured for a ±33.3% change in the assumptions. This percentage selected to match the sensitivity analysis for previously published studies [20,21].

PROCESS DESCRIPTION

Fig. 1 presents a block flow diagram illustrating the production of hydrocarbon fuel from plastic waste via the pyrolysis process. The plant in this study is assumed to process 1,000 metric tons of plastic waste per day that contains 40 wt% PS, 20 wt% PP, 20 wt% PE, and 20 wt% PET. Table 1 presents the elemental analysis and the higher heating value of the plastic waste. The higher heating value (HHV) of the MPW is estimated by using the following formula [22]:

$$\mathrm{HHV\ dry}\left(\frac{\mathrm{MJ}}{\mathrm{kg}}\right) = 0.3491\mathrm{C} + 1.1783\mathrm{H} + 0.1005\mathrm{S} - 0.1034\mathrm{O} - 0.015\mathrm{N} - 0.0211\mathrm{A} \quad (1)$$

where C, H, S, O, N, and A represent mass percentages on a dry basis of carbon, hydrogen, sulfur, oxygen, nitrogen, and ash con-

Table 1. Elemental analysis and higher heating value of MPW

Elemental analysis	Wt % (dry basis)
C	80.4
H	13
O	6.6
N	Trace
S	0
LHV (MJ/kg)	39

tents in feedstock, respectively. The lower heating value of MPW is estimated using the following formula [22]:

$$\text{LHV dry}\left(\frac{\text{MJ}}{\text{kg}}\right) = \text{HHV dry} - 2.442 * \frac{8.936\text{H}}{100} \quad (2)$$

The process takes place in five steps: plastic pretreatment, pyrolysis, hydrogen production, hydrodeoxygenation, and energy generation. The processes are explained below in detail.

1. Plastic Pretreatment

First, the MPW is washed to remove unwanted components that may affect performance. The MPW is then fed into the dryer so as to decrease the moisture content to less than 10%. A superheater steam dryer is used for the drying process, because it is safer than hot flue gas. Finally, the MPW is ground by a hammer mill to reduce the size of the particles to less than 2 mm. The grading step consumes 10 kWh per MT of MPW [21].

2. Pyrolysis

After pretreatment, the MPW is fed into the pyrolysis process. A circulating fluidized bed reactor pyrolyzes the MPW to produce the gases and char. Hot sand is used as a fluidizing medium and heat carrier. The reaction occurs at 450 °C and 1 atm. The product is then fed into a cyclone to separate the solid products from the sand and char. The char and sand are placed in the char combustor, which combusts the char to increase the sand temperature. The sand is subsequently circulated into the pyrolysis reactor. The gases and vapor are condensed to separate the oil from the non-condensable gases. The oil is sent to the hydrodeoxygenation process for upgrading, and the non-condensable gases are fed into the hydrogen production process. The products of plastic pyrolysis vary depending on the plastic type, as reported by Miandad et al. [9]. The product yield for the plastic waste containing 40% PS, 20% PE, 20% PP, and 20% PET is reported as 40% oil, 42% gases, and 18% char, and these product yields are used in this study, as shown in Table 2.

3. Hydrogen Production

Non-condensable gases produce hydrogen using a steam reforming process, carried out using a commercial nickel-based catalyst at 850 °C and 37 bar with GHSV 2,500 h^{-1} [21,23]. During the steam reforming process, 70% of the light hydrocarbon is assumed to be converted into H_2 and CO, which agrees with experimental results [23] for the same catalyst and reaction conditions. CO_2 is removed by the amine scrubbing process, and hydrogen is separated by pressure swing adsorption (PSA), which has an assumed recovery efficiency of the hydrogen production of 80% [23]. Hydrogen is sent to the hydrodeoxygenation process, and fuel gases are sent to the power generation unit.

Table 2. Pyrolysis product

	Product (wt%)	C (wt%)	H (wt%)	O (wt%)
Oil	40	83	7	10
Char	18	97	3	0
Gas	42	73	20	7

4. Oil Hydrodeoxygenation

Hydrodeoxygenation is employed to convert the oil to hydrocarbon fuel that contains 87.5 wt% carbon and 12.5 wt% hydrogen. Only a single-stage trickle bed reactor is required for this conversion, since the oil has a low oxygen content (10 wt%) [24,25]. Hydrogen from the hydrogen production unit is fed into the reactor with the oil from the plastic along with a Ni/SiO_2-Al_2O_3 catalyst, under conditions of 350 °C and 52 bar pressure with WHSV 0.21 h^{-1} [24]. Eaton et al. [24] reported that Ni/SiO_2-Al_2O_3 is an active and stable catalyst that converts the oil produced from the thermal deoxygenation of levulinate and format salt into hydrocarbon fuel. The authors found a hydrocarbon fuel yield in the range of 85-94% [24]. The process of upgrading the bio-oil or oil from the plastic using hydrodeoxygenation is under investigation and development at a bench scale. This study assumes a hydrocarbon fuel yield of 85% and 15% non-condensable gases, which agrees with Eaton et al's results [24]. Sensitivity analysis is performed to evaluate the fuel yield and the assumptions on the catalyst life. For economic modeling, the life of the catalyst is assumed to be one year. The fuel gas and extra hydrogen from the hydrodeoxygenation process are sent to the power generation unit.

5. Power Generation

Fuel gases from the hydrogen and hydrodeoxygenation processes are combusted to generate power. The energy produced can be utilized for several applications, such as feedstock drying and power for compressors.

PROCESS SIMULATION AND ECONOMIC MODELING

Hydrocarbon fuel production via pyrolysis using MPW was simulated using the Aspen Plus software, where UNIQUAC is selected as a thermodynamic package [20,26]. The model estimated the mass and energy balance of the process. Pyrolysis and hydrodeoxygenation reactors were simulated using a reactor yield model in Aspen Plus. The conversion and selectivity of the reactions were based on the experimental results [9,24]. The remaining unit processes were simulated as modeled in previous studies [18,21,23,25]. Table 3 presents the operational parameters and design specifications used for modelling the process in Aspen Plus. Figs. S1-3 show the process models in Aspen Plus. Municipal plastic waste and char are not available in the Aspen Plus databanks, so they are treated as nonconventional components [20]. The oil contains several components, as reported by Miandad et al. [9] Table 4 presents the model components of the oil from the plastic and their mass fractions to match the elemental analysis of the oil and the HHV of the oil. The final product of the process is assumed to be the hydrocarbon fuel, which contains C (87.5 wt%) and H (12.5 wt%). The hydrocarbon fuel

Table 3. Process model

Equipment	Description	Aspen Model
Gridding	Temp 25 °C	General Crusher
	Pressure 1 bar	
	Reduce the size of MPW to less than 2 mm	
Pyrolysis	Temp 450 °C	RYield (Reactor)
	Pressure 1 bar	
	MPW flow rate 11.57 kg/sec	
	Moisture content less than 10%	
	Oil yield 40%	
Char combustor	Temp 1,120 °C	RStoic (Reactor)
	Pressure 1 bar	
	Char flow rate 2.1 kg/sec	
	Excess air 20%	
Steam Reforming	Temp 850 °C	RGibbs (Reactor)
	Pressure 37 bar	
	Natural gas flow rate 0.46 kg/sec	
	H_2O/Natural gas ratio=3.7	
	Nickel based catalyst	
Hydrodeoxygenation	Temp 850 °C	RYield (Reactor)
	Pressure 52 bar	
	Oil flow rate 4.63 kg/sec	
	H_2 flow rate 0.38 kg/sec	
	Fuel yield 83%	
	Ni/SiO_2-Al_2O_3 catalyst	
Power generation	Combustion Temp 1,300 °C	RStoic (Reactor)
	Excess air 20%	Compressor
	Turbine efficiency 85%	

Table 4. Aspen Plus model compounds and mass fractions to represent MPW's oil

Compound	Formula	Wt%
Azulene	$C_{10}H_8$	17
Phenanthrene	$C_{14}H_{10}$	9
Phenol	C_6H_6O	10
O-terphenyl	$C_{18}H_{14}$	9
Biphenyl	$C_{12}H_{10}$	7
Benzenedicarboxylic acid	$C_8H_6O_4$	19
Stigmasta	$C_{29}H_{48}O$	29

simulated by Aspen Plus comprises cycloheptane (29 wt%), octane (23 wt%), and 1,3,5-trimethylbenzene (48 wt%).

ESTIMATED CAPITAL AND OPERATING COSTS

The capital and operating cost estimates in this work are based on the USD in 2020. The cost was updated to 2020 USD using the chemical engineering plant cost indices (CEPCI). The estimation of the equipment size of the process was based on the material and energy balance. The cost of the process-related equipment was estimated via published cost estimates of similar equipment [18,21, 23,25] and calculated based on the equipment size, which was adjusted by the rule of six-tenths. The *n*-th plant design assumption was used to estimate the capital cost. Variable and fixed operating costs as well as the MSP were estimated based on the assumptions presented in Table 5. The MSP of hydrocarbon fuel was estimated using a discounted cash flow analysis with a return rate of 10% and a plant life of 20 years.

Table 5. Economic assumptions

Parameters	Value
Plant size	1000 DMTPD
Annual interest rate	10%
MACRS depreciation	7 years
Taxation rate	40%
Stream factor	90%
Cost of land	3% of Purchased Equipment Cost
Salvage value	10% of Capital cost
Project life	20 years
Construction period	2 years
Working capital	5% of Total Capital Investment

RESULTS AND DISCUSSION

1. Mass and Energy Balances

Fig. 1 and Tables 6-8 present the energy and mass yields for the process. The higher heating value was used as the basis for calcu-

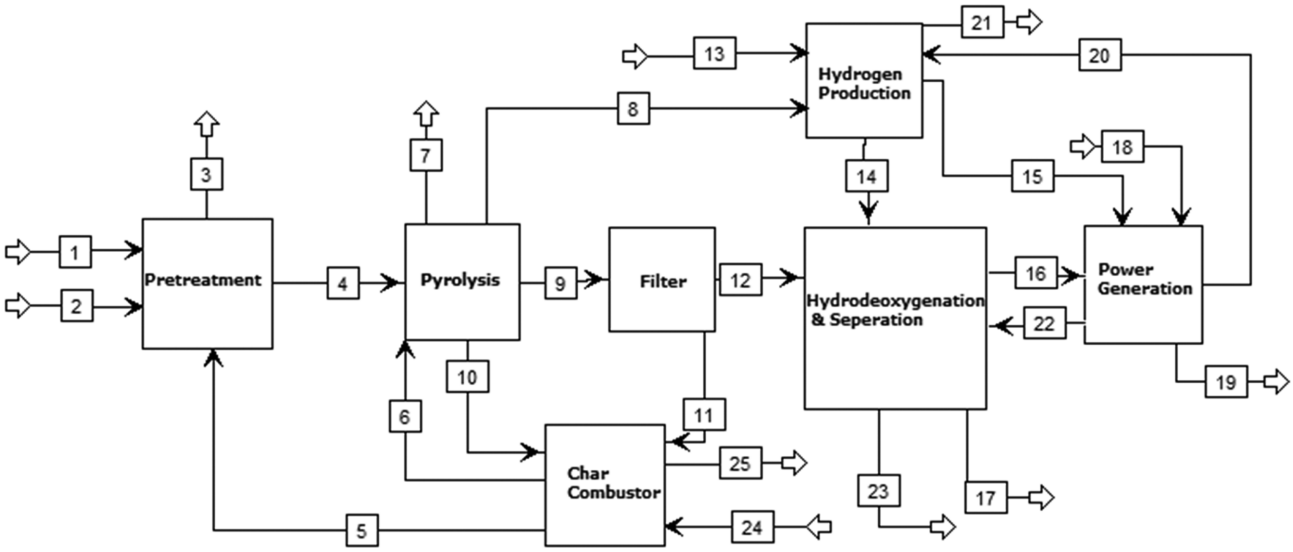

Fig. 1. Overall block flow diagram.

Table 6. Inputs stream the process (mass and energy flow)

Inputs	1	2	13	18	24	Total
	MWP	Water	Water	Air	Air	
Temperature (°C)	25	25	25	25	25	
Pressure (bar)	1	1	1	1	1	
Mass [MT/d]	1,000	1,000	125	11,000	3,000	16,125
Energy [MW]	451	0	0	0	0	451

Table 7. Outputs stream the process (mass and energy flow)

Inputs	3	7	17	19	21	23	25	Total
	Water (vapor)	Cooling	Fuel	Fuel gas	Cooling	Cooling	Fuel Gas	
Temperature (°C)	100	450	25	1,300	850	850	1,170	
Pressure (bar)	1	1	1	1	37	23	1	
Mass [MT/d]	1,000	0	360	11,585	0	0	3,180	16,125
Energy [MW]	8	16	190	115	32	28	62	451

Table 8. Internals stream the process (mass and energy flow)

Stream	4	5	6	8	9	10	11	12	14	15	16	20	22
	MWP/ water	Energy to Dryer and crusher	Energy to Pyrolysis	NCG	Oil/ char	Char	Char	Oil	H_2	Gases	Cracking gases	Energy to H_2 Production	Energy to oil upgrade
Temperature (°C)	100	1,170	1,170	100	100	450	100	31	870	25	25	1,300	1,300
Pressure (bar)	1	1	1	1	1	1	1	52	52	1	1	1	1
Mass [MT/d]	1,000	0	0	420	405	180	5	400	33	512	73	0	0
Energy [MW]	451	8	16	192	174	85	1	173	54	134	38	28	29

lating the energy yield and demands of the process. The simulation was based on processing 1,000 metric tons of MPW per day, producing 451 MW. As shown in Table 7 (stream 17), the overall mass yield of the process is 36% and the energy yield is 38%. The hydrocarbon fuel yield from MPW is meager compared to polystyrene (80%), since the plastic waste feedstock contains PET, which

is not suitable for the pyrolysis process [1,27]. Fivga and Dimitriou [18] conducted a techno-economic study to produce fuel from plastic waste by assuming that the feedstock contains 85% C and 15% H. The hydrocarbon fuel yield from their simulation was 85%, with the other 15% as non-condensable gases [18]. Their model was based on experiments on polystyrene [28]. As per their model, they reported the HHV for plastic calculated as 43 MJ/kg, and the energy yield of their process was 86%. Sahu et al. [19] performed a study producing hydrocarbon fuel from mixed plastic comprising 40% PP, 40% PE, and 20% PS. They reported a hydrocarbon fuel yield of 95%. Their model was based on experiments on catalytic pyrolysis with an alumina-silica catalyst [4]. The study found that 7 kg of hydrogen was required to upgrade 100 kg of plastic-produced oil to hydrocarbon fuel, which is lower than the amount of hydrogen (13 kg) required to upgrade 100 kg of the bio-oil, as reported by Wright et al. [25]. Char combustion produces energy which is used for pretreatment and pyrolysis. The pretreatment step consumes 8 MW, while the drying step consumes 7 MW, and the grading step consumes 1 MW. Comparing the pretreatment of plastic waste with biomass treatment for the same plant capacity (1,000 DMT), the latter (drying and grading) consumes 12 MW for the total energy of the process to dry the biomass, as reported by Carrasco et al. [21]. The amount of energy required to pyrolyze 1 kg of MPW is 1.3 MJ, based on the data reported in the literature [29]. Thus, the pyrolysis reactor consumes 15 MW, which represents 3.5% of the total energy of the feed, in agreement with Fivga and Dimitriou's findings [18]. According to these authors, rector pyrolysis consume just 3.3% of the total energy [18]. The hydrogen production and hydrodeoxygenation processes consume 7% and 6% of total energy, respectively.

In the Aspen Plus simulation, 1,000 DMT per day of MPW was processed by the pyrolysis reactor, followed by the hydrodeoxygenation process, producing 36 wt% hydrocarbon fuel, 41 wt% gas, 5 wt% water, and 18wt% char (Fig. 2). Hydrocarbon fuel production is 360 MT per day, which equals 66 gallons per DMT of MPW. The carbon efficiencies of hydrocarbon fuel and gas products are 41% and 37%, respectively. The mass yield of hydrocarbon fuel produced from plastic waste is higher than that using the biomass, since the plastic has a low oxygen content [1]. Wright et al. [25] conducted a techno-economic study to produce biofuel from corn stover using pyrolysis followed by hydro-processing (upgrading the bio-oil). They reported that the plant produced 36 gallons of hydrocarbon fuel per DMT of corn stover, which is lower than the yield from plastic waste [25]. In this study, the hydrocarbon fuel yield is low due to the high yield of gases and char, which are used to provide energy and heat for the process. Thus, the on-site power production met the power demand for the process, and no excess power was purchased from the grid.

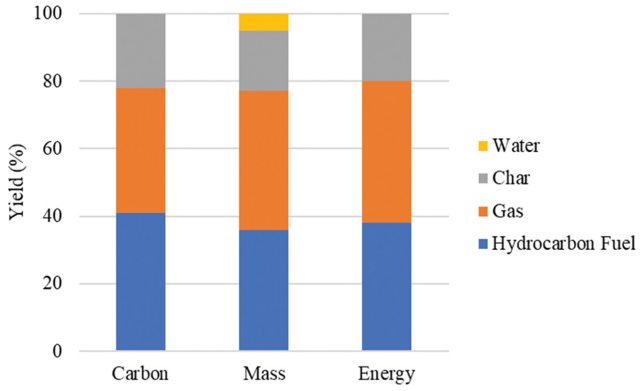

Fig. 2. Mass, energy and carbon yields for pyrolysis plastic waste.

Table 9. Capital investment

Process	Value ($MM)	Contribution [%]
Pretreatment	8.5	13
Pyrolysis	13	19
Hydrodeoxygenation and separation	24	38
Hydrogen production	7	11
Energy generation	6	9.5
Storage and water cooling	6	9.5
Total installed equipment (TIE)	64.5	100
Land (3% of TIE)	1.9	
Site development (5% of TIE)	3.2	
Indirect cost and project contingency (66% of TIE)	42.6	
Fixed capital (FCI)	112.2	
Working capital (5 % of FCI)	5.6	
Total capital investment (TCI)	118	

2. Economic Analysis

The total capital costs of hydrocarbon fuel production from MPW via pyrolysis and hydrodeoxygenation processes are presented in Table 9. The estimated total installed equipment (TIE) cost is $64.5 million, and the total capital investment (TCI) is $118 million. Pyrolysis and hydrodeoxygenation with separation significantly contribute to the TCI of the plant, which represents 57% of the TIE. The TCI of this process is higher than that for producing hydrocarbon fuel from polystyrene, as Fivga and Dimitriou [18] reported. According to their report, the capital investment for processing 2,400 DMT of polystyrene per day to produce fuel is $57 million [18]. Even though their model has a higher capacity, their TCI is lower than that of this study, as the oil produced from polystyrene does not require further treatment and upgrading [18,28]. However, the TCI for producing fuel from plastic waste is lower than that from corn stover for the same process, as reported by Wright et al. [25]. Their reported TCI for producing biofuel from corn stover is $285 million [25]. Production of hydrocarbon fuel from MPW via the pyrolysis process followed by hydro-processing to improve fuel quality is at lab-scale development. It is not well established, which means that the TCI required is expected to decrease over time.

The operation and production costs of producing fuel from MPW using this process total to $27 million, as presented in Table 10. The feedstock cost is assumed to be free, since MPW is garbage. Waste treatment includes ash disposal and water treatment. The annual expense is significantly affected by distribution and sales, which accounts for 22% of the total amount. The other expense, such as catalysts, utilities, and labor cost, contributes in the same range of 7-12% of the total expense. The operating cost estimated

Table 10. Annual expense

Annual expenses	Value $MM
Feedstock	0
Catalysts	3
Utilities	2
Waste treatment	2
Operating labor	3
Maintenance and overheads	3
Distribution and selling	6
Capital depreciation	2
Average income tax	2
Average ROI	3
Total Cost of production	27

Table 11. Minimum selling price (MSP) breakdown

	Cost ($/gal)	Contribution (%)
Feedstock	0.000	0.00
Catalyst	0.068	11.33
Maintenance and overheads	0.071	11.85
Utilities	0.051	8.47
Distribution & selling	0.130	21.64
Operating labor	0.074	12.30
Waste treatment	0.047	7.78
Capital depreciation	0.055	9.19
Average income tax	0.043	7.11
Average ROI	0.062	10.34
MSP	0.602	

for this study is lower than what Alvarez et al. [30] reported for fuel production from HDPE waste. According to their report, the cost of producing fuel via pyrolysis (by processing 500 DMT of HDPE) is $41.4 million [30]. The difference between their study and the present study is that the former assumed the cost of feedstock to be $22 per ton [30]. Moreover, the cost of fuel production from plastic waste is lower than that using biomass as feedstock. For instance, Carrasco et al. [21] reported that the annual cost of producing hydrocarbon fuel from hog fuel is $154 million for a plant capacity of 2,000 DMT of hog fuel per day [21]. The feedstock and catalyst for their study had higher contributions of 45%, and 22%, respectively [21]. The high cost of feedstock is due to the price assumption of $70 per DMT [21], and the estimated cost of the catalyst is $22 million per year; the latter is very high, as the biofuel needs to be upgraded in two steps: stabilization and hydrotreating [21]. From these results, it can be concluded feedstock and catalyst costs have a significant impact on production cost.

The MSP of hydrocarbon fuel produced by pyrolysis followed by the hydrodeoxygenation process was calculated to be $0.60/gal. Table 11 presents the contribution of each cost component to the MSP. Distribution and sales have a significant impact on the MSP, while operating labor, maintenance, overhead, and catalyst costs are contributed equally. Feedstock does not contribute to the MSP, since it is assumed to be free. Fivga and Dimitirou [18] estimated the MSP for fuel production from plastic waste via pyrolysis with a plant capacity of 213 DMT per day, which comes to $0.55/gal [18]. This MSP is lower than that of this study. Meanwhile, Alvarez et al. [30] reported an MSP of $1.32/gal for fuel production from HDPE via the pyrolysis process with a plant capacity of 500 DMT per day. Their price is higher than the MSP of this study because they assumed that HDPE waste is not free, and their fuel yield obtained was 43% [30]. Although waste plastic is assumed to contribute to the MSP for fuel production, the MSP is lower than using biomass, as reported by Carrasco et al. [21]. The authors reported an MSP of $6.25/gal for hydrocarbon fuel production by pyrolyzing hog fuel biomass, and the cost of feedstock contributed to the MSP by 21% [21]. The case of buying hydrogen from suppliers was investigated, and the results are presented in Table S1-3. For this

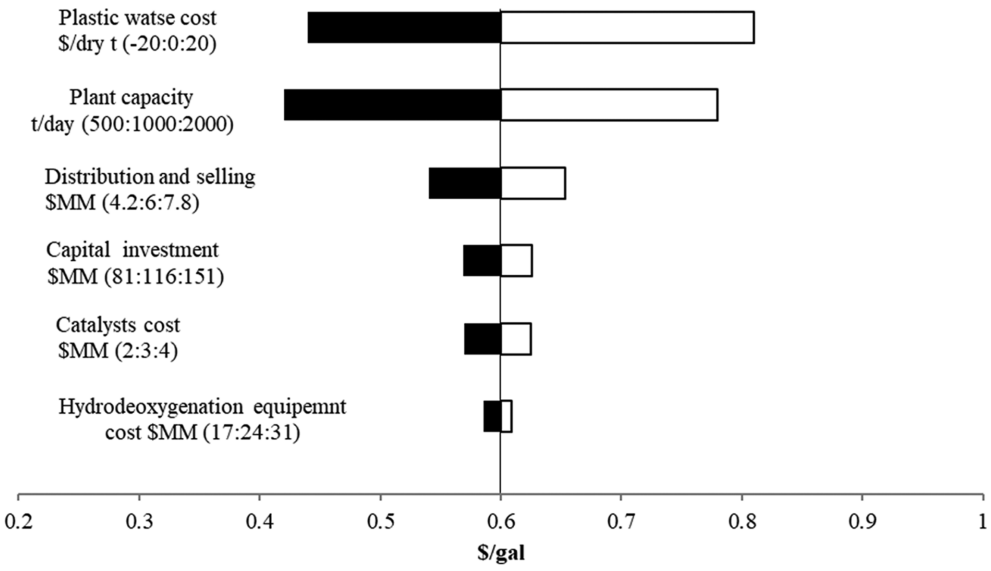

Fig. 3. Economic sensitivity.

case, the MSP is \$0.79/gal, which is higher than producing the hydrogen in the plant since producing the hydrogen in the plant uses the steam reforming of the light hydrocarbon pyrolysis process. From these results, it is clear that the economic assumptions significantly impact the MSP, and a sensitivity analysis is essential for verifying these assumptions.

Sensitivity analysis was performed to ascertain the effect of the economic assumptions on the MSP. They were carried out by varying one variable at a time, while all the other variables remained at the base values, as shown in Fig. 3. Sensitivity was determined for a ±30% variation in all the variable values except for plant capacity and feedstock cost. The sensitivity results show that the MPW cost and plant capacity significantly impact the MSP of the hydrocarbon fuel produced. On these assumptions, the cost of MPW was set to 0 DMT, since the local authorities would not pay any disposal fees to the plant owners. The cost of MPW would be \$-20 per DMT if the local authorities paid \$20 per DMT to the plant owner, decreasing the MSP of hydrocarbon fuel to \$0.44/gal. On the other hand, the MSP would be \$0.81/gal if the plant owner paid \$20 per DMT of MPW. Fivga and Dimitriou [18] reported the same effect of the feedstock on the MSP. They found that, if the feedstock costs \$-17 per DMT of plastic waste, the MSP would decrease by 40% [18]. In contrast, if the feedstock cost is \$17 per DMT of plastic waste, the MSP would increase by 40%.

Moreover, the plant capacity has a major impact on the MSP. As the former increases to 2,000 DMT per day, the latter decreases to \$0.42/gal, since the production cost has decreased. The MSP increases to \$0.78/gal when the plant capacity decreases to 500 DMT per day. These results agree with Sauh's findings [19], which indicate that, as the plant capacity decreases from 165 to 27 DMT, the MSP increases from \$1.40/gal to \$1.60/gal [19]. Furthermore, distribution and sales are assumed to cost \$0.13/gal [20]; if this amount increased by 30%, the MSP would increase by 8%, whereas if it decreased by 30%, the MSP would decrease by 9%.

The MSP is not affected by capital investment, catalyst, or hydrodeoxygenation equipment costs, as Fig. 3 illustrates. For instance, if the life cycle of the catalysts increased by 30%, the MSP would decrease by just \$0.03/gal. However, if the former decreased by 30%, the latter would increase by \$0.03/gal. These results agree with Almohamadi et al. [20], who found that the cost of the catalyst does not have a high impact on the MSP of hydrocarbon fuel production from formate-assisted pyrolysis and hydro-processing, since the bio-oil is stable and has a low oxygen content (>15 wt%) [20]. Also, sensitivity analysis was conducted by changing two factors, as shown in Fig. S4. If the cost of the feedstock decreased to be \$-20\$ per ton and the plant capacity increased to be 2,000 DMTPD, the MSP would be \$0.28/gal. In contrast, if the cost of feedstock increased to be \$20 per DMT and the plant capacity decreased to be 500 DMTPD, the MSP would be \$1.33/gal. Moreover, if the plant capacity increased to be 2,000 DMTPD and capital investment decreased to be \$77MM, the MSP would be \$0.4/gal. If the plant capacity decreased and capital investment increased, the MSP would be \$0.83/gal. From these results, it can be concluded that the economic assumptions have a significant impact on the MSP, and they must be realistic in order to obtain a realistic MSP.

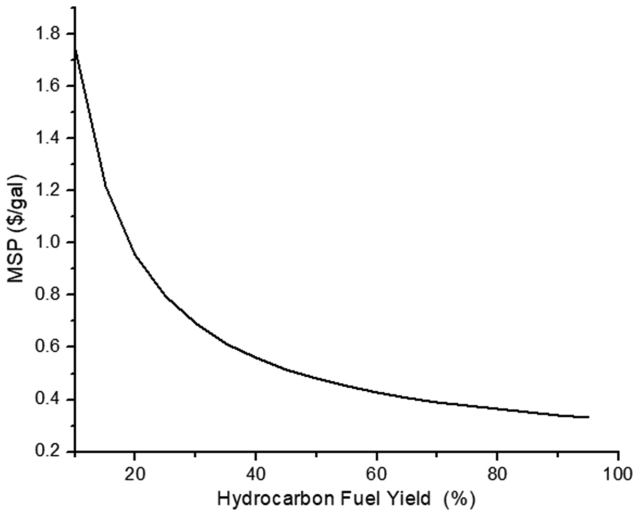

Fig. 4. Effect of hydrocarbon fuel yield on the MSP.

The hydrocarbon-fuel yield significantly impacts the MSP, as shown in Fig. 4. This yield varies based on the type of plastic. As the hydrocarbon-fuel yield increases, the MSP decreases sharply. If the fuel yield was 95%, as considered by Sauh et al. [19], the MSP of this study would be \$0.33/gal, which is lower than the value (\$1.32/gal) reported by Sauh et al. [19]. If the plastic waste only contained PS, the hydrocarbon-fuel yield would be more than 80%, as reported by Miandad et al. [9]. Thus, the MSP would be \$0.37/gal (Fig. 4). If the hydrocarbon-fuel yield was 85%, the MSP would be \$0.35/gal, which is lower than the MSP (\$0.54/gal) reported by Fivga and Dimitriou [18] for the same yield. The MSP difference is due to the plant capacity, which was assumed by Fivga and Dimitriou [18] to be 200 DMT per day; for this study, it was taken to be 1,000 DMT per day. If the plastic waste contained 50% PS and 50% PE, the hydrocarbon-fuel yield would be 54% [9], and the MSP would be \$0.45/gal. When the feedstock comprises only PVC, which is unsuitable for pyrolysis, the yield will be 13%, as reported by Miranda et al. [27], and the MSP \$1.74/gal. From these results, it can be concluded that the type of plastic has a significant impact on the hydrocarbon-fuel yield and the MSP of the product.

CONCLUSION

The economic feasibility of producing fuel from plastic waste via the pyrolysis process was determined by conducting a techno-economic assessment. The plant was assumed to process 1,000 DMT of MPW composed of 40% PS, 20% PE, 20% PP, and 20% PET. The mass and energy yields of the process were 36% and 42%, respectively. The low mass yield compared to other studies is due to the types of plastic waste. The process is integrated and does not need a source of external energy or heat supply; the energy requirement of the pyrolysis and pretreatment processes were fulfilled through char combustion. The TCI of the process is \$118 million and the production cost is \$27 million. The MSP of hydrocarbon fuel produced by this process will be \$0.60/gal for 20-year project. The analysis shows that the MSP is highly sensitive to the cost of the plastic waste, plant capacity, and plastic type (hydrocarbon fuel

yield).When the fuel yield increases to 70-85%, the MSP will be in range of $0.39-0.35/gal. Further research and development on plastic waste pyrolysis would improve the fuel yield.

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DECLARATION OF INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

SUPPORTING INFORMATION

Additional information as noted in the text. This information is available via the Internet at http://www.springer.com/chemistry/journal/11814.

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Supporting Information

Producing hydrocarbon fuel from the plastic waste: Techno-economic analysis

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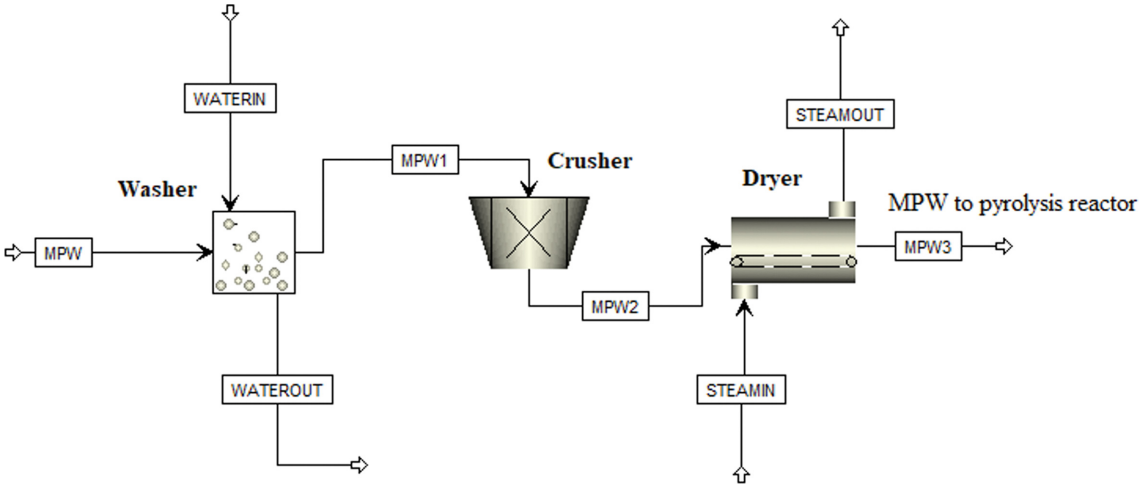

Fig. S1. Pretreatment process model in Aspen Plus®.

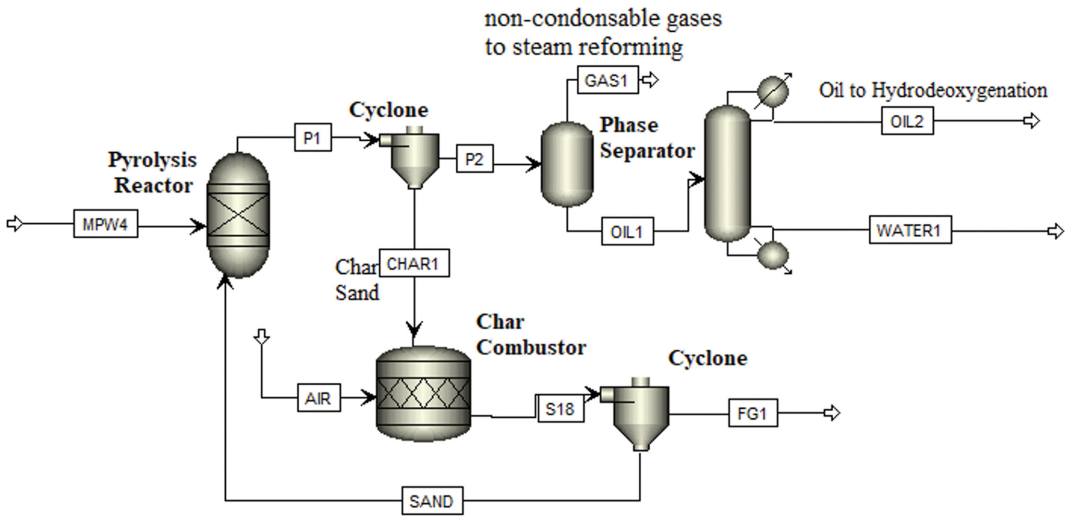

Fig. S2. Pyrolysis process model on Aspen Plus®.

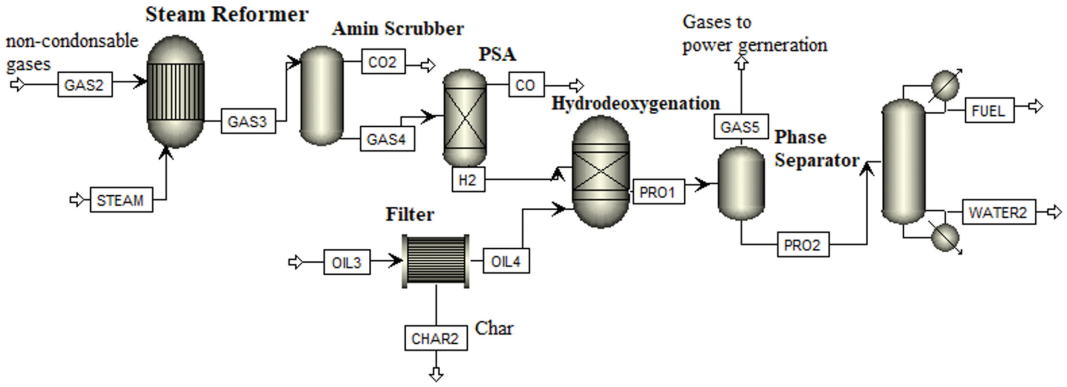

Fig. S3. Steam reforming and Hydrodexoghenation process model in Aspen Plus®.

Table S1. Capital investment for H_2 case

Process	Value ($MM)	Contribution (%)
Pretreatment	8.5	15
Pyrolysis	13	23
Hydrodeoxygenation and separation	24	42
Energy generation	6	10
Storage and water cooling	6	10
Total installed equipment (TIE)	57.5	100
Land (3% of TIE)	1.7	
Site development (5% of TIE)	2.9	
Indirect cost and project contingency (66% of TIE)	38.0	
Fixed capital (FCI)	100.1	
Working capital (5% of FCI)	5.0	
Total capital investment (TCI)	105.1	

Table S2. Annual expense for H_2 case

Annual expenses	Value $MM
Hydrogen cost	9
Catalysts	2
Utilities	2
Waste treatment	2
Operating labor	3
Maintenance and overheads	3
Distribution and selling	6
Capital depreciation	2
Average income tax	2
Average ROI	3
Total cost of production	34

Table S3. Minimum selling price (MSP) breakdown for H_2 case

	Cost ($/gal)	Contribution (%)
Hydrogen	0.200	25.21
Catalyst	0.050	6.30
Maintenance and overheads	0.065	8.24
Utilities	0.046	5.81
Distribution & selling	0.138	17.44
Operating labor	0.058	7.27
Waste treatment	0.047	5.90
Capital depreciation	0.055	6.98
Average income tax	0.055	6.96
Average ROI	0.078	9.88
MSP	0.793	

Calculating the cost of hydrogen per year:

The Plastic's oil production per day=400 ton

Hydrogen required to upgraded the plastic oil=7 ton of H_2/100 ton of plastic's oil

Hydrogen consumption per day=(7 ton of H_2/100 ton of oil)*400 ton of oil*1.1[a]=31 ton of H_2

The cost of Hydrogen per day=28 ton * ($873/ton)[b]=$27,063

The cost of Hydrogen per year=$24,444*365 days/year*0.9[c]= $9MM

[a]extra 10%

[b]Mondal, K.C.; Ramesh Chandran, S. Evaluation of the economic impact of hydrogen production by methane decomposition with steam reforming of methane process. Int. J. Hydrogen Energy 2014, 39, 9670-9674.

[c]Stream factor

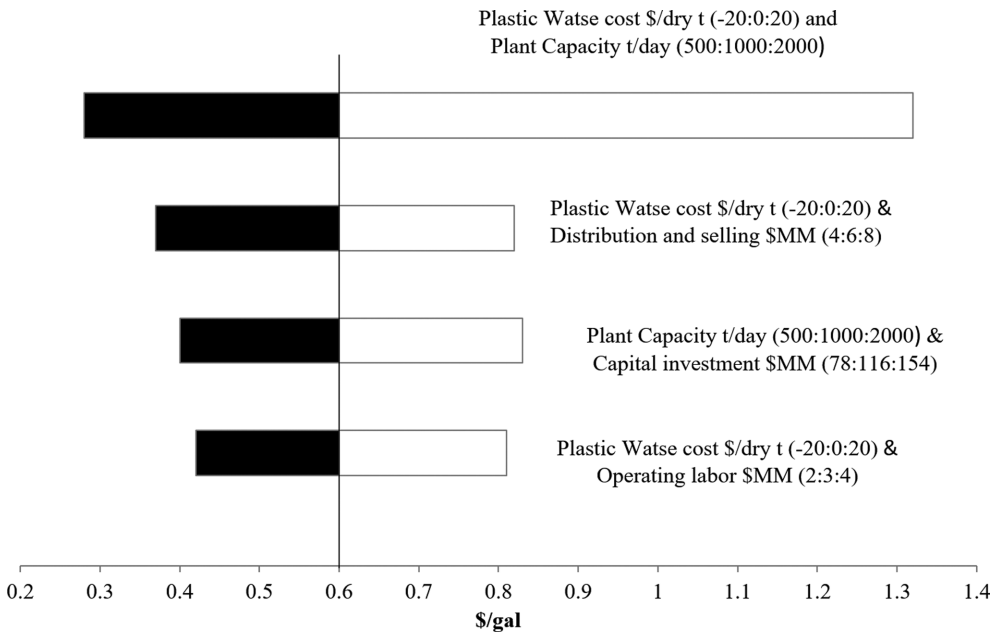

Fig. S4. Economic sensitivities with changing two factors.