Study of the Technical-Economic Feasibility of a Pyrolysis/Gasification Plant for the Generation of Liquid Gas Fuels from Plastic Waste

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Pyrolysis can offer a practical environmental solution for recycling plastic waste, converting it into liquid and gaseous fuels of high commercial value. This article proposed the simulation in Aspen Plus® of a pyrolysis/gasification plant, having plastic residues and residual soybean oils as raw material. The products generated in the gasifier are bio-oil and synthesis gas, which can be converted into ethylene and gasoline in reactors. To calculate the plant's cost of capital, the Lang Method was used. The economic indicators NPV, IRR, PI, and Payback determined the project's viability. The works show that the current scenario studied has economic viability, but better results can be achieved with increasing project maturity.

Keywords: Plastic Waste. Pyrolysis. Gasification. Simulation. Economic Evaluation.

Introduction

The dependence on energy in its many forms by society is high. Worldwide, energy demand is expected to increase by a third between 2015 - 2040, mainly in countries outside the Organization for Economic Co-Operation and Development [1]. Moreover, the rise in the standard of domestic consumption, industrial growth, and the increase in urbanization have brought the increase in fuel consumption and in pollution caused by solid waste, with plastics being one of the leading waste discarded.

Plastic is an organic synthetic polymer produced based on petroleum, which serves as a raw material for the manufacture of the most varied objects and with high durability. In 2020, around 367 million tons of plastics were produced worldwide [2]. However, this amount produced ends up generating an environmental liability. According to Plastic Europe (2017), around eight million tons of plastic waste are released annually into the oceans.

In Brazil, mechanical recycling is the most widespread for using plastic materials. However, in recent years, thermochemical conversion technologies have gained significant attention.

Pyrolysis offers a practical solution for recycling plastic waste, converting it into liquid fuel oil as the main product with high marketing value. Furthermore, the process generates by-products, such as reduced gases, due to the absence of O_2 in the process [3], in addition to carbon black as a solid material. Therefore, this technology adds environmental and economic benefits at the same time.

Pyrolysis

Pyrolysis is a thermochemical process in which organic chains undergo breakage in their original molecular structure, through a complex set of chemical reactions, due to the action of rapid heating in the absence of oxygen, reducing long-chain organic molecules into shorter molecules. The raw materials for pyrolysis is from many heterogeneous origin.

The pyrolysis of plastic material occurs in four stages: initiation, transfer, decomposition, and termination, resulting in the production of vapors and coal [4]. These pyrolysis vapors include condensable and non-condensable gases. The

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liquefaction of the condensable vapors forms the pyrolysis wax/oil, a complex combination of the thermal cracking products of each type of plastic. Interactions occur between the primary thermal cracking products to increase this complexity, producing secondary products [5]. Solid waste (coal) and non-condensable gases are also produced, but they are usually by-products of the pyrolysis process [6].

Three types of pyrolysis are classified by process duration and operating conditions: slow, fast, and flash (Table 1). In slow pyrolysis, which lasts longer, the reaction time is stipulated according to the raw material, which can vary from 10 min to 10 h. The low heating rates and temperatures are generally 5 to 10 K/min and 500 to 900 K, respectively [7]. Under these conditions, the percentage of carbonaceous solids is maximized; however, the yield and composition of the product are determined by the reaction parameters and the raw material. In fast pyrolysis, heating rates, and temperatures are higher, whereas gaseous products and oils tend to maximize.

This work investigates the technical-economic feasibility of obtaining combustible gases and liquids by developing and simulating a gasification/pyrolysis plant in Aspen Plus®, using plastic waste and residual soybean oil as raw material. We have been guided by economic indicators - Net Present Value (NPV), Internal Rate of Return (IRR), Profitability Index (PI) - to make the project viable.

Materials and Methods

Process Simulation of a Gasification/Pyrolysis Plant

We used a method adapted from the literature [8-10] for a simulated double-fluidized bed gasifier in Aspen Plus® v8.8 operating at 850 ºC and 1 atm. The raw materials for feeding the gasifier were plastic and residual soybean oil, both at a flow rate of 100 kg/h. The synthesis of two products, ethylene, and gasoline, is proposed from the gas produced (syngas). The criteria adopted for the gasification reactions was minimizing the Gibbs free energy coupled with the equilibrium constraint method.

For the synthesis of the final products, equilibrium reactors were used. The premises considered in this work were:

1. Steady state and isothermal operation;
2. Pressure and temperature are uniform in each reactor;
3. Load and heat losses are neglected;
4. Drying and pyrolysis stage are instantaneous;
5. Ash is inert;
6. All carbon in the biomass is gasified or converted to ash;
7. Purification steps represented by numerical separators.

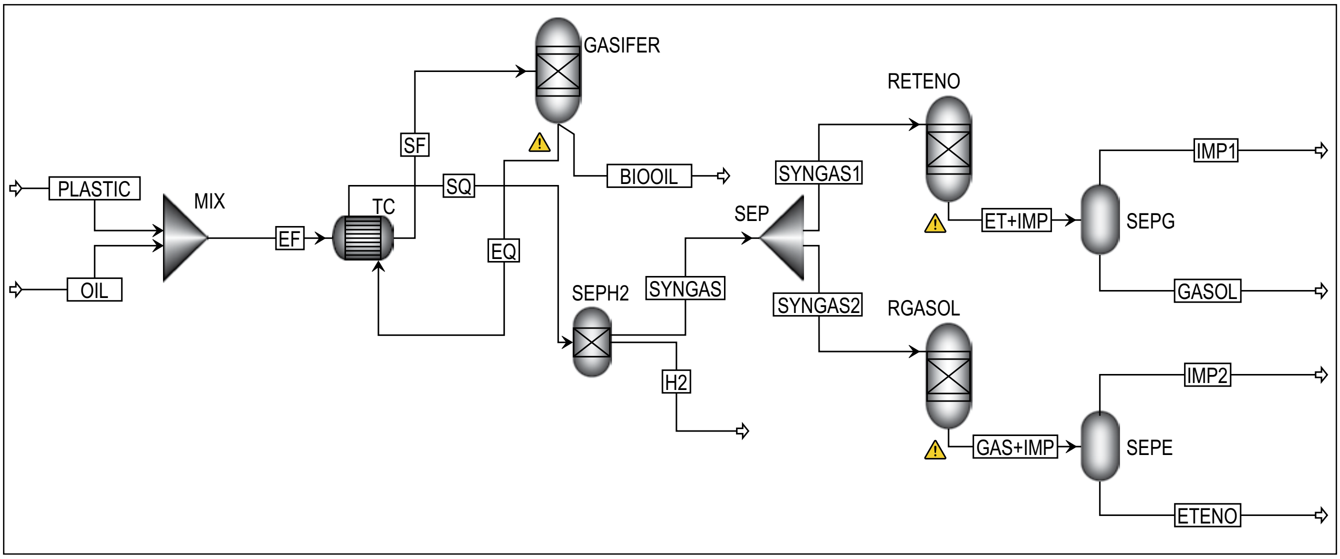
The thermodynamic package selected was the Peng-Robinson cubic equation of the state with the Boston-Mathias alpha function, which models the gas phase at medium and high pressures with good accuracy. The enthalpy model used was HCOALGEN with standard code options. Each number refers to a calculation method for obtaining the heat of combustion, standard heat of formation, heat capacity, and base enthalpy of coal. For density, the model was DCOALIGT.

Figure 1 presents the process simulation's scheme. The SF stream is the heated raw material that feeds the gasifier after passing through the exchanger (TC). The EQ stream that leaves the gasifier goes to the TC as a hot stream, and the other

Table 1. Typical technological parameters of different types of pyrolysis [7].

Pyrolysis	Process Time	Temperature (K)	Heat Rate (K/min)
Slow	10 min - 10 h	500 - 900	5 - 10
Fast	10 - 20 min	700 - 900	50 - 100
Flash	< 10 min	1000 – 1300	> 100

Figure 1. Flowchart of ethylene and fuel gas production from plastics and vegetable oils.



stream is the Bio-oil produced (Green Diesel - GD). The CT (SQ) output current goes to a separator (SEPH2), separating the syngas from the H_2. The SYNGAS current is divided into SYNGAS1 and SYNGAS2, where the separation percentage is defined. The currents SYNGAS1 and SYNGAS2 are sent to two different equilibrium reactors: one operating at 300 ºC and 10 bar and the other at 320 ºC and 40 bar, reaction conditions based on the literature [11]. The separator vessels (SEPG) and (SEPE) remove impurities from the final products in the streams (IMP1) and (IMP2), respectively, characterized by H_2, CO, O_2, and CO_2.

Economic Evaluation of the Gasification/Pyrolysis Plant

The Lang Method [12] was used to estimate the capital cost of the pyrolysis unit. This methodology has a degree of uncertainty of around 35 % but allows for comparing different procedural alternatives. The total investment capital (Total Capital Investment, TCI) is obtained by Equation 1:

$$C_{TCI} = 1.05\, f_L \sum i \left(\frac{PCI_i}{PCI_{b,i}}\right) C_i \qquad (1)$$

in which: CTCI is the total investment cost, including working capital; fL is the Lang Factor, which for a plant that processes solids and fluids is equal to 5.9; Ci is the cost of each of the sized equipment; PCIi and PCIb, i are the Plant Cost Index in the current year and the base year, respectively. The value of the Plant Cost Index for the year on which the correlations were based was 394. For the year 2021, this value is 680.5.

Using the data obtained in the simulation, the design was based on the equations proposed in the literature [12]. The flow rates (m^3/h), operating pressure (psig), and temperature (ºF) obtained from the ASPEN simulation data were used as input data. The quotient between inlet flow, residence time, and catalyst composition determined the reactor volume.

A scenario of 50 % hydrogen recovery and syngas separation to 25 % gasoline and 75 % ethylene was considered. The equipment was then dimensioned, and the costs were estimated for that scenario. Finally, production costs were calculated following the literature method [13], considering that the plant operates 24 hours a day and 334 days a year, totaling 8016 hours.

The base prices considered for the raw material, the products, and utilities, in addition to the catalysts, along with their composition and density, were taken from the COMEX STAT (portal for accessing Brazilian foreign trade statistics), obtained by the ratio between the f.o.b import value, in US dollars, and the net import kilogram value for 2022.

The price of electricity and water were obtained from the tariffs published by ANEEL - National Agency of Electric Energy - for the industrial sector in August 2020 and by ANA - National Agency of Water and Basic Sanitation for the same sector and period, the conversion currency was carried out using the August 2020 quotation according to the Central Bank of Brazil.

The economic indicators evaluated to propose the feasibility of the project were the Net Present Value (NPV), the Internal Rate of Return (IRR), the Profitability Index (PI), and Payback.

Results and Discussion

The operational cost (Operational Expenditure - OPEX) corresponds to the cost associated with the daily operation of the pyrolysis plant. Its calculation is a function of direct production costs, fixed production costs, and general expenses. Among the factors that affect the operational cost are:

1. Direct costs comprising raw materials, inputs, utilities, labor, preventive and corrective maintenance, and operational supplies, along with others;
2. Fixed costs comprising depreciation, taxes, plant overheads, and
3. Overheads comprising the cost of administration, distribution and sales and research and development [13].

Table 2 presents the estimates of the operational costs of the pyrolysis plant obtained through the models presented in this work. The total operating cost of the pyrolysis plant was close to US$ 640,000.00 per year.

The cost of capital (Capital Expenditure – CAPEX) includes investment costs in the pyrolysis plant to become operational. In addition, it includes the direct costs of acquiring equipment, indirect costs, contingency costs, and costs with auxiliary facilities [13]. Table 3 shows the estimates of the investment costs in the equipment of the pyrolysis plant, together with the indirect and auxiliary costs, added to the working capital necessary to keep the plant in operation. The total investment cost of the pyrolysis plant was in the order of US$ 3,145,000.00.

Table 4 shows the plant's revenue projection data, considering the formation of 4 main products based on the recovery scenario described in the methodology. Hydrogen generated the highest revenue return among products due to its higher selling price per kg (2.0 US$/kg).

A cash flow was prepared considering the estimated values of OPEX, starting operations in year 1, CAPEX, considering investment in year zero, and the projected revenue in year 1 of the project. To calculate the discounted cash flow (DCF), the net present value (NPV) formula was used, considering a minimum attractiveness rate (MAR) of 9.0 % per year and an average inflation rate (IR) of 6.0 % in the same period.

Figure 2 shows the discounted cash flow accumulated for 20 years of operation of the pyrolysis plant, considering the current economic scenario of the project and 2 additional scenarios: a pessimist with a 20 % lower revenue and an optimistic one with a revenue of 20 % higher. The results showed that the current scenario's calculated net present value (NPV) was positive, reporting a return of US$ 869,464.55. The internal rate of return (IRR) reported a return of 6 %, which is below the MAR (9.0 %). The profitability index (PI) reported a value of 1.28, which means that for every US$ 1.00 invested in the plant, US$ 1.28 is returned in present values. The payback, the time required to recover the initial investment, was 14.6 years. The economic indicators evaluated showed that the proposed implementation of a gasification plant could be economically viable under the conditions presented, except for the low value of the IRR. In a scenario where revenue is 20% lower, we found that the project is not viable within 20 years. However, in a scenario where revenue is 20% higher, the payback reduces considerably for 7.9 years, with an IRR of 13% (above MAR) and a positive NPV of US$ 3,605,316.42. Plant revenue and business

Table 2. Annual operating result of the economic evaluation of the pyrolysis plant.

Plant Operating Costs	
Direct Costs	
Raw material (CRM)	US$ 1,154.00
Plastic + Oil	US$ 1,154.00
Labor (CL)	US$ 35,456.11
Technical supervision (CTS)	US$ 5,318.42
Utilities (CUTIL)	US$ 119,701.04
Steam	US$ 0.00
Cooling water	US$ 63,854.40
Electricity	US$ 9,590.40
Catalysts	US$ 45,944.41
Adsorbents	US$ 311.83
Effluent disposal (CED)	US$ 0.00
Maintenance and repairs (CMR)	US$ 150,868.55
Operating supplies (COS)	US$ 22,630.28
Laboratory charges (CLAB)	US$ 5,318.42
Patents and royalties (CPR)	US$ 19,187.88
Indirect Costs	
Packaging and storage (CPS)	US$ 114,985.85
Local taxes (CLT)	US$ 27,717.14
Interest (CI)	US$ 12,572.38
Depreciation (non-accounting)	US$ 251,447.59
General Expenses	
Administrative costs (CADM)	US$ 28,746.46
Distribution and sale of products (CDSP)	US$ 63,959.59
Research and development (CR&D)	US$ 31,979.80
TOTAL OPERATING COST (OPEX)	**US$ 639,595.91/year**

profitability can be increased with greater project maturity.

Conclusion

This work proposed a study of using plastic and oily residues for synthesizing hydrogen, gasoline, and ethylene. The results of the simulation and economic evaluation point to a promising scenario. The total project investment was US$ 3,143,094.85 with an operating cost of US$ 639,595.91/year, and the plant generated 25 % of the products in hydrogen and 75 % of Syngas for the production of gasoline and ethylene. The economic indicators reported the feasibility of the project under the conditions presented. However, the payback time for the current scenario studied was 14.6 years, a reasonably long period with the IRR remaining below the MAR. In the optimistic scenario, the time to recover the initial investment was 7.9 years, with a positive NPV and an IRR of 13 % above the MAR.

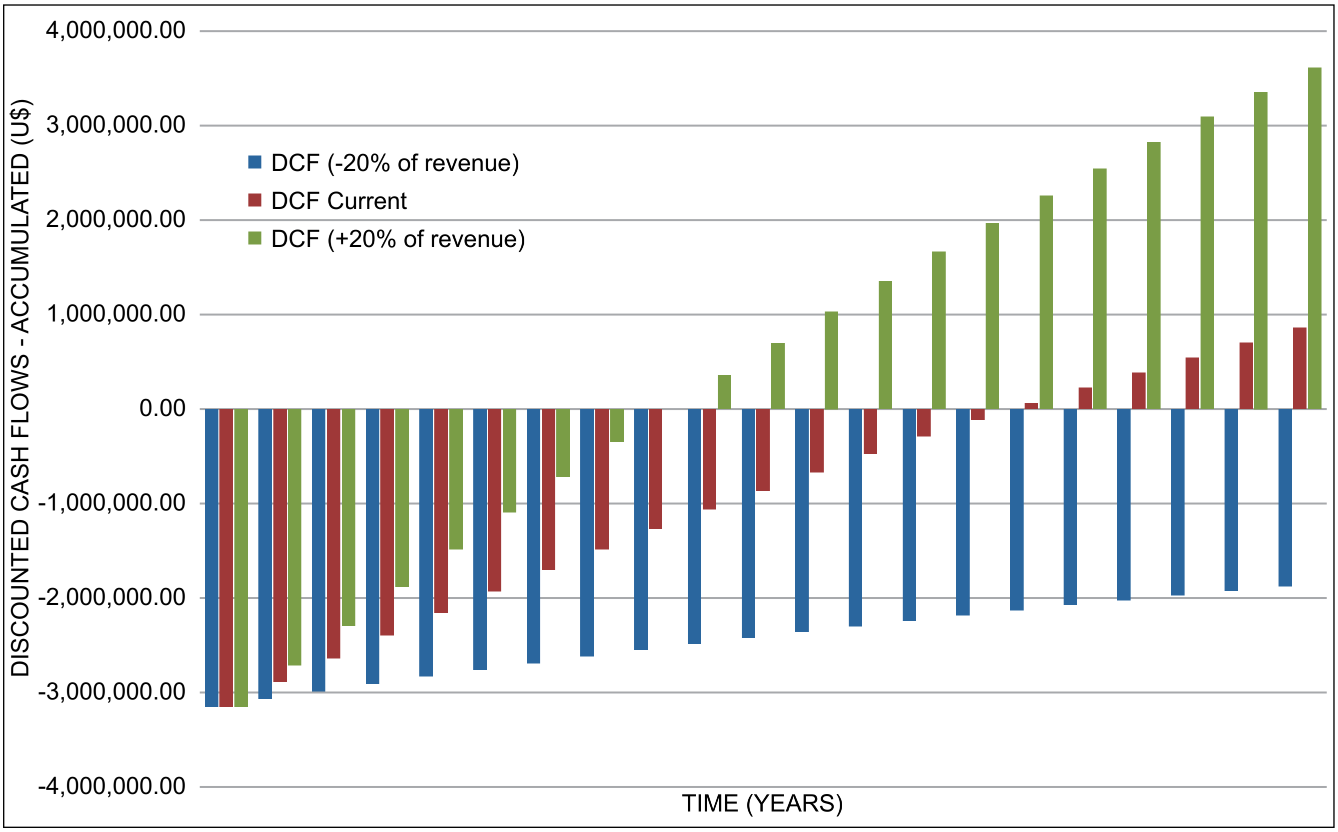
Table 3. Capital investment results for the pyrolysis plant.

Pyrolysis Plant Investiment	
Equipment cost (Separators, gasoline, and ethylene reactors, gasifiers, and heat exchangers)	US$ 997,807.89
Indirect and ancillary costs	US$ 1,516,667.99
Working capital	US$ 628,618.97
TOTAL CAPITAL COST (CAPEX)	**US$ 3,143,094.85**

Table 4. Results of the annual revenue projection for the pyrolysis plant.

Plant Revenue Projection	
Hydrogen (H_2)	US$ 577,186.91
Bio-oil (Green Diesel)	US$ 96,192.00
Ethene	US$ 139,601.45
Gasoline	US$ 92,106.00
TOTAL REVENUE PROJECTION	**US$ 905,086.36**

Figure 2. Cumulative cash flow scenarios for a change in revenue at a MAR of 9.0 % and an IR of 6.0 % on the economic viability of the pyrolysis plant projec.



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References

1. Energy Agency. International. World Energy Outlook 2016. Paris - France: [s. n.], 2016. Available at: www.iea.org/books.
2. Statista, Production of Plastics Worldwide from 1950 to 2018. 2020. Available at: www.statista.com/statistics/282732/global-production-of-plastics-since-1950/.
3. Fivga A, Dimitriou L. Pyrolysis of plastic waste for production of heavy fuel substitute: A techno-economic assessment. Energy 2018;149:865–874.
4. Faravelli T et al. Thermal degradation of polystyrene. Journal of Analytical and Applied Pyrolysis 2001;60(1):103–121.
5. Pinto F et al. Pyrolysis of plastic wastes. 1. Effect of plastic waste composition on product yield. Journal of Analytical and Applied Pyrolysis, v.51 (1–2), 39–55, 1999.
6. Young GC. Municipal solid waste to energy conversion processes. Economic, Technical, and Renewable Comparisons. New Jersey: John Wiley & Sons, Inc., Publication, 2010.
7. Pawelczyk E, Wysocka I, Gebicki J. Pyrolysis combined with the dry reforming of waste plastics as a potential method for resource recovery - A review of process Parameters and Catalysts. Catalysts 2022;12:362.
8. Doherty W, Reynolds A, Kennedy D. Aspen Plus simulation of biomass gasification in a steam blown dual fluidised bed. In: Materials and Process for Energy. Dublin: [s.n.]. 2013:212–220.
9. Puig-Gamero M et al. Three integrated process simulation using Aspen Plus®: Pine gasification, syngas cleaning and methanol synthesis. Energy Conversion and Management 2018;177:416–427.
10. Sikarwar VS, Zhao M. Biomass Gasification. Encyclopedia of Sustainable Technologies 2017;3:205-216.
11. Wang C et at. Investigation on hydrogen-rich syngas production from catalytic co-pyrolysis of polyvinyl chloride (PVC) and waste paper blends. Energy 2021;232:121005.
12. Seider WD, Seader JD, Lewin DR. Product and process design principles: Synthesis, analysis and evaluation. 2ª ed. New York: John Wiley & Sons, 2003, 786p.
13. Turton R, Bailie RC, Whiting WB, Joseph A, Shaeiwitz JA, Bhattacharyya D. Analysis, synthesis, and design of chemical processes. Prentice Hall - Pearson Education, Inc, 4° Ed., 2012.