

# **Decentralized Plastic Waste Recycling Through Pyrolysis—a Techno-economic Feasibility Study**

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## **Abstract**

Plastic waste is a major societal issue in large parts of the world. The role of plastics in a circular economy have seen increased interest from policy makers due to oceanic pollution and inherent GHG emissions when incinerated, and because of the large part plastic materials constitute in modern society. In this work recycling of three plastic waste flows have been investigated from a techno-economic perspective. Process models for recycling of PS, PVC and mixed plastics have been developed with the purpose of comparing recycling of mixed plastics to pure waste fractions. Furthermore, the economic possibilities of local plastic waste recycling have been compared to centralized concepts. Results indicate that there are no economic incentives for local plastic waste recycling through pyrolysis, the payback period exceeds to economic life time of the plants for all considered processes. At a centralized scale, the mixed plastic process reaches payback 8 years faster than the PS processes and the PVC process does not reach payback at all.

**Keywords:** Plastics recycling, Techno-economic assessment, Process modelling

## **1. Introduction**

Plastic materials play a major role in society but pose certain challenges. Accumulation in nature has adverse effects on wildlife, and most plastics are currently produced from fossil resources which contradicts the demands on climate change mitigation stated by the UN (T.U. Nations, Editor. 2015). Legislators are raising the bar for recycling rates, with the EU setting a target of 50 % recycling of plastic packages by 2025 (E. Union, Editor. 2018). It is unlikely that plastic will disappear as a material in modern society, and thus crucial to define options for how plastic materials can constitute a part in a future circular economy (Material Economics, 2019).

In Sweden, plastic waste is recycled by companies and individuals through a statutory plastic waste sorting system. The recycled plastic waste is mechanically sorted into different plastic types and colours, cleaned and made into granulates for production of new plastics. However, it is not possible to sort out all plastic fractions and therefore approximately 30% is incinerated for energy recovery (How plastic recycling works. 2019). There are also several limits to mechanical recycling, comprising e.g. mechanical degradation, issues related to aged or contaminated plastics, and fibre-reinforced plastics. Furthermore, about 58% of plastics are not recycled at all in Sweden and thus end up in mixed waste fractions where they are incinerated for energy recovery (Plastics recycling and handling of plastic waste, 2019). Thus, there

is a need for more technical solutions to improve plastics waste recycling, especially with the aim of decreasing plastic waste incineration, since it contributes to net positive GHG (green-house gas) emissions. Solutions are likely to include better mechanical recycling, utilization of biological feedstock (e.g. forest residues), but also thermo-chemical recycling of plastic fractions for production of poly-olefins. The need for multiple technical solutions for plastics in a circular economy was emphasised in a report by Material Economics on Industrial Transformation 2050. The report highlights that “chemical recycling will play an indispensable role in a future net-zero emissions plastic system” (Material Economics, 2019).

Pyrolysis is a thermochemical process where plastics are decomposed into their basic monomers. The main positive aspects of pyrolysis are the robustness of the process, low demand on feed purity and the fact that decomposing plastics into its basic monomers does not lead to deterioration of mechanical properties. It is a subject which has been widely researched on an experimental level, both using mixed plastic (MP) fractions (Kaminsky, W., B. Schlesselmann, and C. Simon, 1995) and pure plastic fractions (Yuan, G., et al., 2014). Process modelling and techno-economic and environmental evaluation studies have also been reported, especially on mixed plastic processes (Al-Salem, S., P. Lettieri, and J. Baeyens, 2009). This research has demonstrated the technical feasibility of plastic pyrolysis processes. However, the environmental- and economic potential for pyrolysis of pure plastic streams requires further research, especially with respect to the respective plant capacities. Currently, mechanical recycling of plastic waste in Sweden is done in centralized facilities. However, the plastic sorting and gathering befalls on local waste disposal companies. An incentive, therefore, exists to evaluate whether local plastic waste recycling through pyrolysis can be an economical valid option.

The purpose of this study is to investigate the economic incentives for decentralized recycling of plastic waste, both in pure and mixed plastic fractions. The Gothenburg region in Sweden is used as reference regarding waste flows. Three different plastic fractions are evaluated: pure Polystyrene (PS), for production of Styrene and Toluene, pure PVC, for production of HCl and Benzene and a mixed plastic case consisting of PS (26%<sub>weight</sub>), PVC (1%) and PE/PP (73%) for production of different alkenes and pyrolysis diesel.

## **2. Methodology**

A literature study on plastics pyrolysis and a review of plastic waste flows in the Gothenburg region were similarly conducted. Those results were used to identify the plastic fractions suitable for further evaluation. A flow sheeting software (Aspen Plus V10.0) was used to construct process models and those models were the basis for subsequent economic evaluation.

### **2.1. Plastic Waste Review**

The most recent data at Statistics Sweden is from 2016, and states that 316 130 tons of plastic waste was collected in Sweden that year. Even though plastic waste often is sorted by recycling companies, composition of different polymers in the plastic waste is rarely reported. To estimate the composition of the plastic waste, data on plastics sold in the EU were therefore used.

Table 1. Share of total plastic supply in the EU and total estimated waste flow in the Gothenburg Region (GR) for the two types of considered plastic.

Polymer	EU 2017 [%]	GR waste [t/a]
Polystyrene (PS)	3.7	1200
Expanded PS	2.9	900
Polyvinyl chloride (PVC)	10.2	3300
Mixed plastics PE+PP (73% <sub>weight</sub> ), PS (26% <sub>weight</sub> ), PVC (1% <sub>weight</sub> )	-	32000

As displayed in Table 1, two types of polymers were selected for further evaluation, PS and PVC. PS can be converted to its monomer, Styrene, with a high yield. Additionally, PS is used for packaging and is relatively simple to sort out in a clean fraction, particularly from industries. PVC is used in construction and it, therefore, stays in the system for extended periods of time before it is discarded. Previously, it often contained additives that are currently banned, which means that it is not possible to recycle PVC mechanically from a legal perspective. Due to the high chloride content, PVC waste is also hard to handle through incineration for energy recovery. Furthermore, PVC is available in relatively large quantities (10.2%). Part of the objective of this work was to evaluate the potential benefits of sorting plastic waste. Therefore, the PVC and PS cases were compared to a mixed plastics case.

## 2.2. Process Models and Economic Evaluation

For the pyrolysis reactor conditions and product composition data were gathered from experimental studies. All other parts of the processes were modelled using Aspen Plus V10.0. The Peng-Robinson equation of state was used to describe all thermodynamic properties. Figure 1 presents simplified flowsheets of the four considered processes.

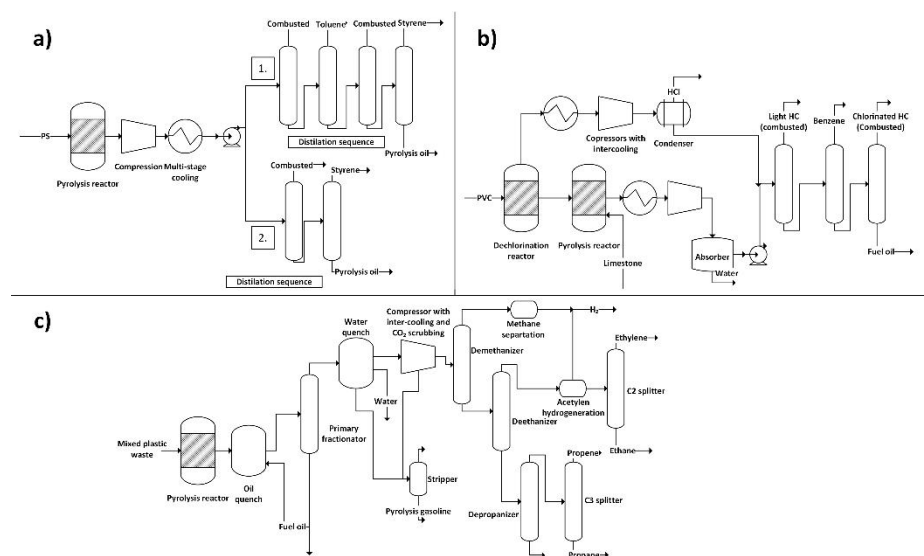


Fig. 1 Simplified flowsheets of all considered processes. a) Option 1 is the original PS process and Option 2 is the simplified PS process, b) is the PVC process and c) is the mixed plastic process.

The PS process was based on the experiments published by Liu, Qian (Liu, Y., J. Qian, and J. Wang, 2000). Pyrolysis occur in a fluidized bed reactor at 600°C using nitrogen as fluidization medium. Sand is removed in a cyclone and then the gas is cooled and

compressed. The compressed gas eventually goes to a distillation train with four columns where Toluene, Styrene and Pyrolysis oil are the products and remaining hydrocarbons are combusted to generate the heat required to sustain the pyrolysis reaction. A second PS process was also investigated, where the distillation train is smaller. This entails that toluene is omitted as a product.

To avoid corrosion problems in the downstream separation, the PVC process was based on a dual reactor concept presented by Miranda et al. (Miranda, R., et al., 1999). In the first reactor the PVC is dechlorinated at 320°C. Chloride forms HCl and leaves together with some chlorinated hydrocarbons. The stream is compressed, and the hydrocarbons (HC) are separated, leaving a pure HCl stream. Polymers remaining after the first reactor step are pyrolyzed in the subsequent reactor. To avoid corrosion issues related to the remaining chloride, limestone is added to the reactor and thus remaining Cl is converted to CaCl<sub>2</sub>. The pyrolysis gas is cooled and mixed with the condensed HC from the first reactor. In the subsequent distillation train, Benzene and fuel oil are separated out, these two together with HCl constitute the products. Remaining HC are combusted.

The pyrolysis product produced in the mixed plastic process is similar in composition to what is achieved when cracking Naphtha for production of Ethylene. Therefore the mixed plastic process was based on a fossil Naphtha plant (Chadwick, S.S., 1988). To avoid spontaneous polymerization of the pyrolysis product, the mixture is cooled immediately after the reactor, first through heat exchanging and then by quenching with oil from the first fractionation column and with water. Fuel oil and pyrolysis diesel is separated out and the remaining product mix is compressed with intercooling and dried before a distillation train. The first part of the separation occurs at cryogenic conditions to separate out methane and hydrogen from remaining products and subsequently to separate methane from hydrogen. The main products Ethylene and Propene are separated out in 4 following columns. Acetylene is present in small amounts and to avoid further separation it is selectively hydrogenated into ethylene over a catalyst.

The OPEX and revenues of each process were estimated based on the energy and mass balance results generated through the flow sheeting models. The inbuilt cost estimation tool of Aspen Plus v10.0 was used to determine CAPEX for all parts of the process except the pyrolysis reactors, for which literature data was used (Thunman, H., et al., 2019). All four plant types are investigated at both a local scale and a centralized scale (10 times larger) to investigate the economic incentive for local plastic waste recycling through pyrolysis.

Due to uncertainties in the price/revenue of plastic waste and the price of different monomers, sensitivity analysis was performed using the Monte Carlo (MC) method. The price of commodities and products, the electricity price and the investment cost were randomly varied within a specified range for 1 000 000 calculations of the NPV. The economic results are presented as an average NPV of these calculations. For all economic calculations it is assumed that the economic investment is made during the first three years, and that production and OPEX is gradually ramped up during the first four years. The plant life time is specified to 30 years.

## **5. Results**

The decomposed results from the base case of the economic evaluation are presented in Figure 2. As shown in Figure 2, the revenues are highest for the two PS processes,

with the original process reaching a slightly higher revenue. This implies that the value of separating out toluene as an additional product is low.

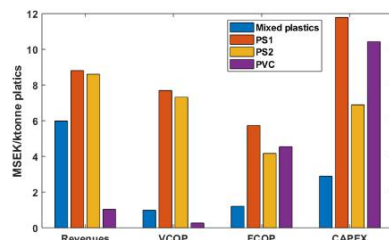


Fig. 2 The decomposed results of the base economic analysis.

The mixed plastic process reaches a relatively high revenue, where as the revenue of the PVC process is very low, which is explained by the low value of benzene and HCl. Looking at the variable and fixed costs of production, it is clear that the MP process outperforms both the PVC and PS processes. The same trend is also observed for the CAPEX, where it is also shown that the additional cost of separating out the toluene has a severe impact on the CAPEX of the PS process. The NPV of each process is presented as the cumulative value per year of operation in Figure 3.

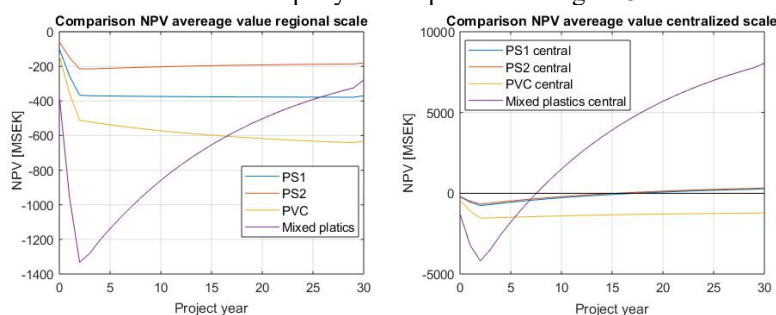


Fig. 3 Cumulative NPV for the mean values from the Monte Carlo sensitivity analysis, for both the regional scale (left) and the centralized scale (right).

When translating the economic results into the cumulative NPV, it becomes obvious that there is no economic gain in the regionally scaled pyrolysis processes, regardless of the type of plastic. All four considered processes have a large decrease in NPV during the first three years due to the investment, however, that loss is never made up for. In the case of the MP and PS processes there is positive revenue although small in the latter case. The PVC process has a negative revenue and will never reach the PBP regardless of how long the plant can operate.

When scaling up the process to a centralized scale (10 times larger), the economic performance improves. The MP process reaches payback after 7 years and the PS processes after approximately 17 and 15 years, implying that the additional CAPEX to separate out the toluene is not made up for by the increased revenue. The PVC process has a slight economic revenue in the centralized case, but it does not reach payback within the plant lifetime. The results indicate that economy of scale is the most important parameter in reaching a fast payback period. Hence, the PS process is penalized even though the revenues from the products are higher than both the other cases.

## 5. Conclusions

The two main questions that this paper aimed to answer were whether it can be economically feasible to recycle via pyrolysis PS, PVC or MP at local scale in Sweden and if there is an economic incentive in separating out pure plastic fractions before recycling. The results clearly indicate that the amount of plastic waste in the Gothenburg region is too low to justify an investment in a pyrolysis unit. The PS case reaches higher revenues than the mixed plastics case, but without a profit at regional scale because of high specific investment costs. Even at centralized scale, the MP case reaches its payback period 8 years earlier than the best performing PS case. Regarding recycling of PVC, it is hard to see that pyrolysis could constitute a valid option, at least not from an economic perspective. It should be mentioned that for a centralized recycling plant careful localization of the plant must be performed and the costs related to logistics for transferring plastics will be higher, something that has not been accounted for in this work.

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