TereCycle

Mixed PET Waste to Dimethyl Terephthalate & Ethylene Glycol

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Executive Summary

Despite extensive greenwashing by the plastics industry, less than 10% of plastic ever produced has been recycled. This fact has come to light in recent years, against the backdrop of the climate crisis, and consumers and corporations have begun to demand more widespread use of recycled plastics as a result.

One such recyclable plastic is polyethylene terephthalate (PET), a versatile polymer mainly used in packaging and textiles. Our senior design project targets PET recycling through the construction of TereCycle, a US-based plant to depolymerize 100,000 metric tons of contaminated PET per year. TereCycle will produce ethylene glycol (EG) and dimethyl terephthalate (DMT) as well as a diethylene glycol (DEG) byproduct, using methanolysis, a novel chemical reaction pathway. Though our process has a 248% higher GHG burden than mechanical recycling, it is important to note that mechanical recycling is not an option to produce infinitely recyclable PET, and that our process is not entirely comparable with virgin PET production due to the final step of repolymerization. Thus, further analysis is necessary to determine whether TereCycle is a better alternative.

This plant will cost $176 million to construct. With rPET trading at a 16% premium compared to virgin PET (vPET), TereCycle is projected to have an NPV of -$198 million. However, there is significant opportunity to break even, depending on future pricing trends for rPET. By structuring TereCycle as a joint venture with a major specialty chemical company (referred to as Company X), we can utilize their proprietary catalyst and capitalize on their brand recognition and existing supplier/customer relationships to fund the construction of the project and obtain contracts. This joint venture can also outcompete Loop Industries, our main competitor in the methanolysis space. Our senior design team will add value to Company X through our novel design of the pre-processing and separation blocks before and after the depolymerization reactor.

TereCycle's main customers will be manufacturers in the packaging and textile industries (the largest users of PET resin). The construction of this plant will solve two major pain points at either end of the PET lifecycle: a supply shortage of high quality rPET and an impending overflow of PET waste. Beyond this, companies and consumers have shown that they care about sustainability; TereCycle will help companies meet their ESG goals, gaining them market share in the process, and protect the planet for future generations.

Overview of Problem

To date, humans have created over 8.3 billion metric tons of plastic (1). It is commonly believed that much of this plastic finds a second life as recycled material, but in actuality, less than 10% of all plastic ever produced has been recycled (2). There are several reasons why plastic is not easily recyclable. First, there are many varieties of plastic; plastics are broadly categorized into one of seven resin codes. In addition, during the manufacturing process, dyes and additives can be added to plastics to change their inherent properties (3). Many plastics contain other contaminants as well, such as moisture, organic material, adhesives, and the like. The process to sort resin from its additives and contaminants is difficult, energy intensive, and expensive, so oftentimes, buying virgin feedstock is much cheaper than producing feedstock from recycled materials. Finally, even after the previous difficulties are addressed, plastics often degrade in the recycling process, and most plastic can only be recycled once, into lower-grade products.

Taken together, these factors make plastics some of the most prolific waste materials in our landfills and oceans. Once dumped, plastics may take up to 1000 years to decompose, all the while leaching toxic compounds like phthalates and BPA. Additionally, plastics decompose into nanoparticles that enter the food chain, and these particles have shown the ability to cross the blood-brain barrier and alter the behavior of affected organisms (4). Meanwhile, incineration of plastics for energy generation releases carcinogenic compounds, neurotoxins, and air pollutants (5). Not only does plastic cause disposal issues at the end of its lifecycle, but it also poses environmental harms at the very start. Plastics are produced from crude oil and natural gas, raw materials that are produced via fracking (a dangerous and destabilizing process) and liberate carbon deposits as they are extracted. These petrochemicals need to be refined and cracked to produce the correct size of polymers. Refining and cracking both use massive amounts of heating and release toxic compounds into the environment. The harms of plastic production and disposal are so great that environmental advocates have termed it the "plastic death cycle," and immediate action is necessary to remediate these ill effects (6).

Polyethylene terephthalate (PET), also known as No. 1 plastic (per its resin code), is one of the more common types of plastics in use, accounting for 3.1 million tons produced annually in North America (7). PET is strong and highly resistant to moisture, gas permeability, and solvation by organic and inorganic compounds, making it an ideal candidate for use in food and beverage packaging and textiles (polyester) (8). PET is also one of the more recyclable plastics currently in use (9), with a recycling rate of 26.6% (10).

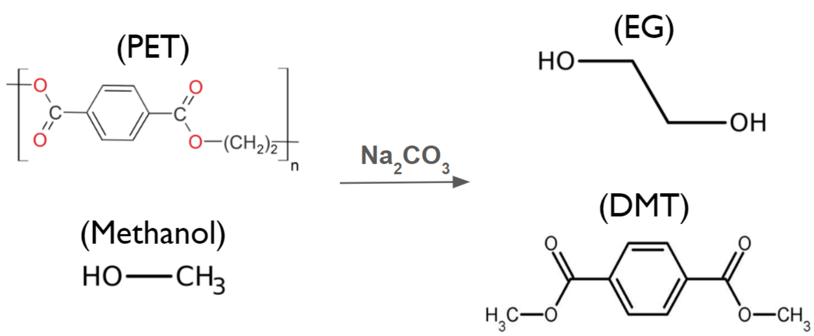


Figure 1: Methanolysis depolymerization pathway of polyethylene terephthalate.

As PET is a polymer (a large molecule of repeating subunits), it can be chemically recycled into its constituent monomers through various reaction pathways. The pathway investigated in this senior design project is a transesterification of PET with methanol to form ethylene glycol (EG) and dimethyl terephthalate (DMT), shown above. The EG and DMT may be reacted in the future to reform recycled PET (rPET), or used for other applications, such as the production of antifreeze. For the purposes of this senior design project and due to market tailwinds elaborated upon later, we focus on the use of EG and DMT for rPET production.

Value Proposition

Packaging and textile manufacturers have increased their demand for rPET, in response to consumer attitudes towards the growing climate and pollution crisis. However, they are facing a bottleneck in rPET supply and quality. In a joint venture with Company X, we will construct a US-based plant to depolymerize 100,000 metric tons of contaminated PET per year to produce EG and DMT, using a novel chemical reaction pathway. This will alleviate the supply constraints that the above manufacturers face and allow them to use eco-friendly high-quality PET to improve public perception of their products.

Stakeholders

PET stakeholders can be grouped into several large categories:

1. Providers of post-consumer PET feedstock, such as municipal waste management and recycling facilities and post-consumer reclaimers.
2. Landfills, incinerators, and other final destinations for PET waste.
3. Virgin PET, DMT, and EG producers, such as Plastipak and Indorama.
4. Petrochemical companies, such as Royal Dutch Shell and Exxonmobil, that provide crude oil and natural gas, key components of virgin PET, DMT, and EG production. There may be significant overlap between the third and fourth categories of PET stakeholders; for example, Exxonmobil owns a PET plant in Beaumont, TX.
5. Plastic processing companies, such as textile, pellet, bottle, and packaging manufacturers.
6. End users:
    a. Businesses mainly in the food and beverage and textile industries.
    b. Individuals who buy items that contain or are packaged with PET.

Market Opportunity, Size, and Growth

As of 2020, the global **PET market** was valued at **$27 billion**, and is expected to surpass $40 billion by 2028, with a CAGR of 3.69% (11). The **rPET market** comprises a large subset of the PET market, at **$8.6 billion**, and is expected to grow at a significant **CAGR of 6.7%** until 2028 (12). Meanwhile, the global **DMT market** was valued at **$790 million** with a CAGR of 5.7% (13) and the global **EG market** was valued at **$26.1 billion** with a CAGR of 3.3% (14).

Taken together, the **total addressable market** for DMT and EG amounts to **$26.9 billion**. Assuming a similar market penetration of recycled products as PET, the **serviceable addressable market** amounts to **$8.6 billion**. On a basis of 100,000 tons of PET per year, the **share of market** occupied by TereCycle is **$126 million** per year.

Macro Trends

Absolute demand for PET has been rising, accounting for some growth of the rPET market. However, recent trends in sustainability have also greatly driven the uptake of rPET. Several current events have presented the immediacy of the climate crisis, such as the occurrence of COP26, the release of the apocalyptic 2021 IPCC Report, bans on the use of single-use items such as straws, styrofoam takeout containers, and plastic bags, and the 2017 Chinese prohibition of waste imports.

In turn, this has shifted public attitudes. For example, 83% of consumers under 44 have stated that they would be willing to pay a premium for sustainable products (15). In response, several major players in the food & beverage and textile spaces, such as Nestle and Danone, have pledged to earmark billions of dollars for eco-friendly packaging and sustainable or recycled materials. Such a major shift has only happened in recent years; as a result, rPET has only recently become economically sustainable to produce. This change is apparent in the rapid increase in the price of rPET over the past 6 years, with an approximate CAGR of 14.7%.

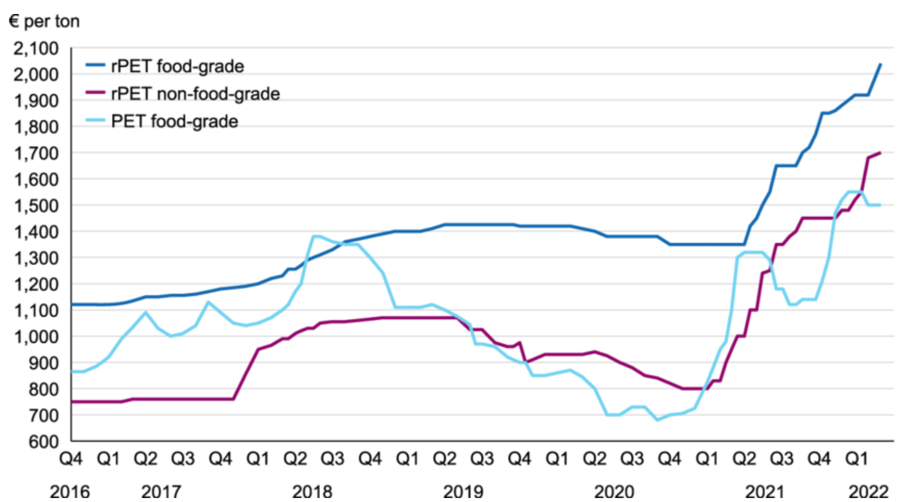


Figure 2: Changes in price of rPET and PET materials since 2016.
Source: https://polymerist.substack.com/p/recycled-plastics-making-strong-gains?s=w

Customer Segment

TereCycle will target two major pain points at either end of the PET lifecycle for packaging and textile producers.

1. rPET supply is stretched to capacity, and with demand increasing in both the packaging and textile industries, it is likely that there will be shortages and skyrocketing commodity prices. Companies have realized that they can do well by doing good, and TereCycle will help its customers reach their ESG goals.
2. Manufacturers of PET goods spend significant amounts of money for waste disposal. Furthermore, it seems likely that in the future, governments will impose fees for negative externalities incurred by the disposal of plastic product (as they have already done with carbon credits). TereCycle will reduce the logistical and financial issues associated with waste disposal through enforcing plastic circularity.

Competition

There are 3 commercially-used reaction pathways to recycle PET: methanolysis, glycolysis, and hydrolysis. Each of these alternative pathways present unique challenges. Glycolysis, though currently widely used, produces a wide array of undesirable side products and creates BHET dimers which may revert to PET polymers. Hydrolysis requires high temperatures and pressures, a long reaction time, and uses corrosive solvents that are counterproductive to PET recycling's environmental goals.

Thus, methanolysis is the current prime candidate for PET depolymerization. Though the final purification stages for methanolysis plants are relatively expensive, it is also much easier to rapidly recycle MeOH and EG within the process. In the future, given the advent of in-house PET recycling, methanolysis plants can be placed directly within PET production lines as well.

Our key competitor in methanolysis PET recycling is Loop Industries:

- Loop Industries
  - Facilities:
    - $100 million small scale plant in Quebec
    - $250 million planned plants in USA and France
  - Strengths and Weaknesses:
    - Loop claims to have developed a proprietary catalyst enabling methanolysis at low temperatures and atmospheric pressure. Such a catalyst would give Loop an enormous competitive advantage, given the significant energy costs of heating and pressurizing PET during the depolymerization reaction. However, Hindenburg Research was unable to replicate this catalyst in independent testing.(16) They have alleged that Loop has no viable technology, as Loop has claimed a 100% yield on PET in the past, which is impossible for any chemical processing context. Furthermore, the company founders have no prior post-graduate experience or technical background in chemistry or chemical engineering. An anonymous employee has also stated that they were pressured to fudge positive results.
    - Loop has partnered with Suez (a major French environmental group) and Indorama (a PET manufacturer) for plant construction. However, Loop has already fallen behind on key milestones, such as the construction of its South Carolina plant.
    - Loop has already signed agreements to supply Pepsico, Danone, and L'Oréal with branded rPET packaging.(17,18) However, it was unable to meet supplier milestones with Coca-Cola Cross Enterprise Procurement Group, who terminated their contract as a result. It is likely that these supply chain failures will continue, if no drastic changes are made.
    - Loop is targeting a very high EBITDA margin of 50-55% on its investor presentation. However, it is likely that these financials are inaccurate, given that the CEO hired a convict guilty of stock manipulation to raise startup capital.(19)

Due to our partnership with Company X (F500 with a >$10 billion market cap), our team will be able to obtain the necessary funding for a larger facility than Loop's, meaning we will recycle PET more rapidly. We will also be able to use Company X's proprietary catalyst which will be cheaper than the Loop catalyst; our depolymerization will also be able to proceed at low temperatures and pressures. Given Company X's brand recognition and our innovation in the pre-sorting and purification blocks (and potential future patentability), we can produce an rEG and rDMT product that will be priced at a premium due to its high quality.

Capital Investment

This plant will require a total bare module cost of $105 million. Of this sum, $87 million will be allocated to fabricated equipment, $11 million will be allocated to preprocessing equipment, and $6.5 million will be allocated to storage equipment. There will also be spare equipment worth $961,000 that will be necessary to maintain production rates, should key equipment components break down.

Equipment Category	Bare Module Cost (USD)
Fabricated Equipment	$87,000,000
Preprocessing Equipment	$11,000,000
Storage Equipment	$6,500,000
Spare Equipment	$961,000
Total	$105,461,000

Once additional considerations have been factored in, the total capital investment of the project will be $176 million. Structuring TereCycle as a joint venture will allow us to obtain the necessary funds and we anticipate that our team will hold minority ownership in the TereCycle facility.

Investment Summary	
Total Bare Module Costs	$107,000,000
Direct Permanent Investment	$118,000,000
Total Depreciable Capital	$139,000,000
Total Permanent Investment	$171,000,000
Working Capital	$5,000,000
Total Capital Investment	$176,000,000

Revenue and Cost Model

PET, EG, DMT, and DEG are commodities; as such, our revenue model will be dictated by commodity pricing. However, an increased corporate focus on sustainability has driven rPET prices to a 16% premium above virgin materials as of 2022. Given current sustainability trends and past data, this premium is projected to grow 15% per year (20). Thus, our focus will be on providing rDMT and rEG to produce rPET and TereCycle products will be priced at a similar premium.

Price of TereCycle EG	Price of TereCycle DMT	Price of TereCycle DEG

$0.89/kg	$1.59/kg	$3.28/kg

Once translated to a yearly basis, with 330 days of operation per year and 24 hours of operation per day, the products will generate annual revenue of $183 million. With given raw material commodity prices, the annual cost of raw materials is $121 million.

Product	Price (USD/kg)	Annual Revenue (USD)
DMT	$1.59	$153,386,597.22
EG	$0.89	$26,874,510.95
DEG	$3.28	$2,538,970.95
Total*		$183,000,000

Raw Material	Cost (USD/kg)	Cost (USD/kg DMT)	Annual Cost (USD)
PET	$0.87	$0.90	$87,100,000
MeOH	$0.41	$0.12	$11,833,908
Sodium Carbonate	$0.40	$0.01	$564,871
MPT	$31.84	$0.10	$21,048,729
Total*		$1.13	$120,548,000

The process will also require significant utility input in the form of steam, cooling water, refrigerant, electricity, and the like. This will cost $25 million.

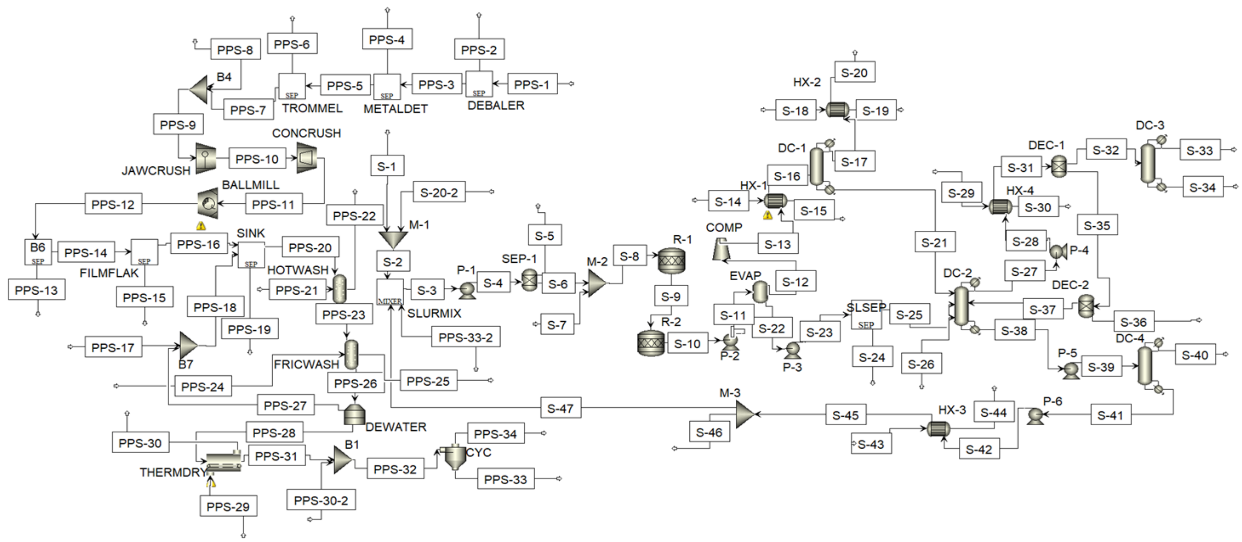
Cost Factor	Typical Factor in American Engineering Units	Cost (USD/hr)	Annual Cost (USD)
Electricity	$0.07/kWh	$728.45	$5,769,324
Steam (150 psig)	$7.00/1,000 lb	$552.01	$4,371,890
Steam (450 psig)	$8.00/1,000 lb	$1,445.41	$11,447,682
Refrigeration (10°F)	$2.00/ton-day	$45.20	$357,997
Cooling Water	$0.10/1,000 gal	$87.30	$691,445
Process Water	$0.80/1,000 gal	$7.56	$59,875
Landfill	$0.08/dry lb	$216.26	$1,712,779
Wastewater	$0.15/lb organic removed	$125.40	$993,168
Total*		$3,207.60	$25,000,000

Economic Analysis

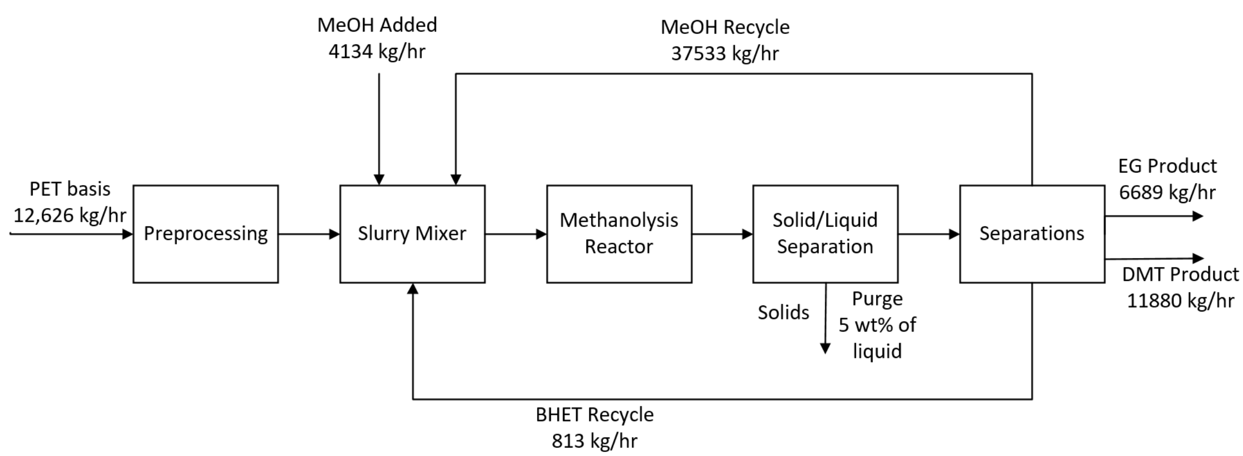
At this current revenue and cost model, with the given capital investments, the net present value of the depolymerization plant will be -$198 million, with an ROI of -12.18% in the 3rd year and a negative IRR. However, a breakeven NPV (at a 15% discount rate) would occur if DMT is priced at $2.32/kg or if variable costs are decreased to $110 million. Furthermore, if a 15% growth rate is used (as per the above CAGR of recycled PET), one can expect a plant NPV of $677 million.

Process Flow Diagrams

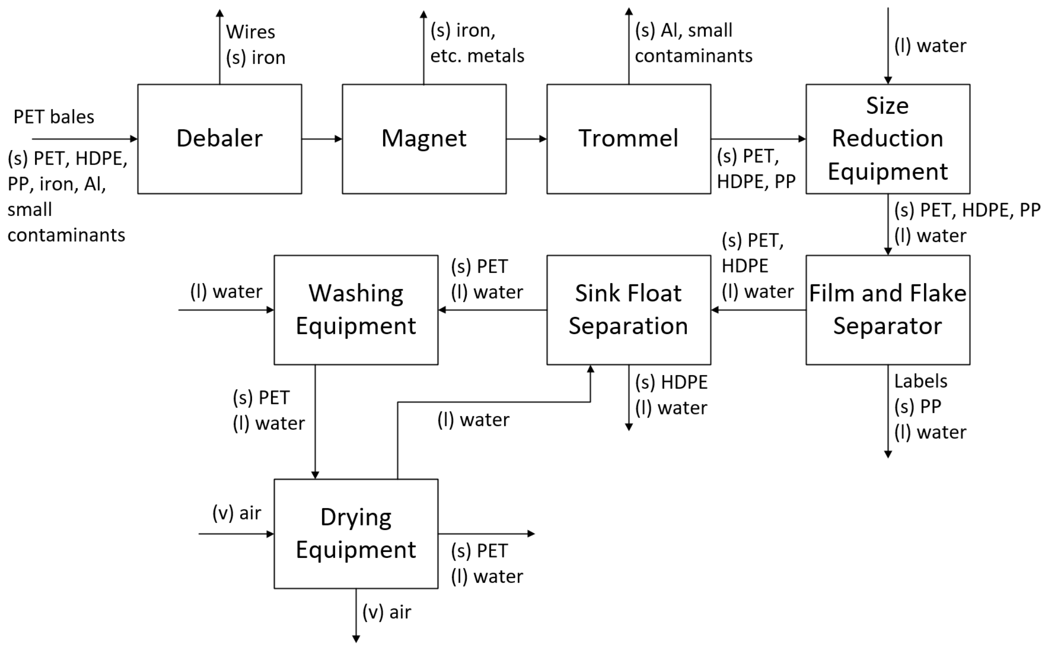
Complete Aspen Flowsheet



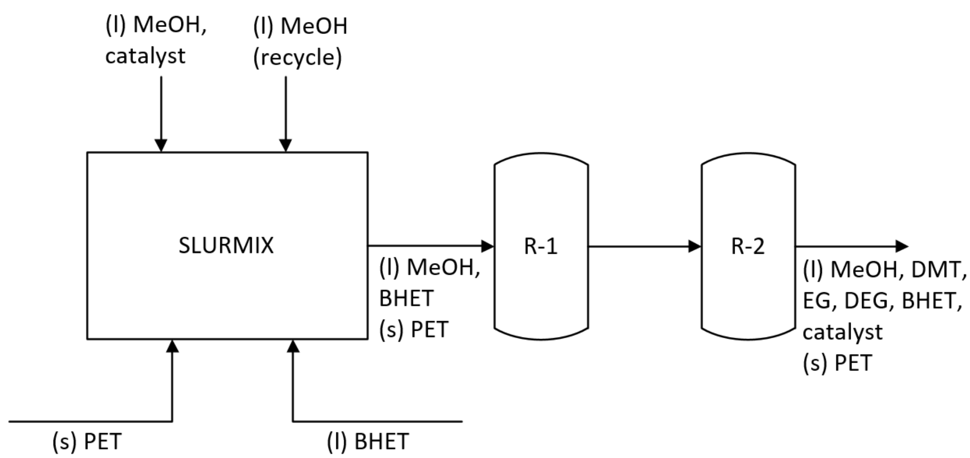
Generic Block Flow Diagram



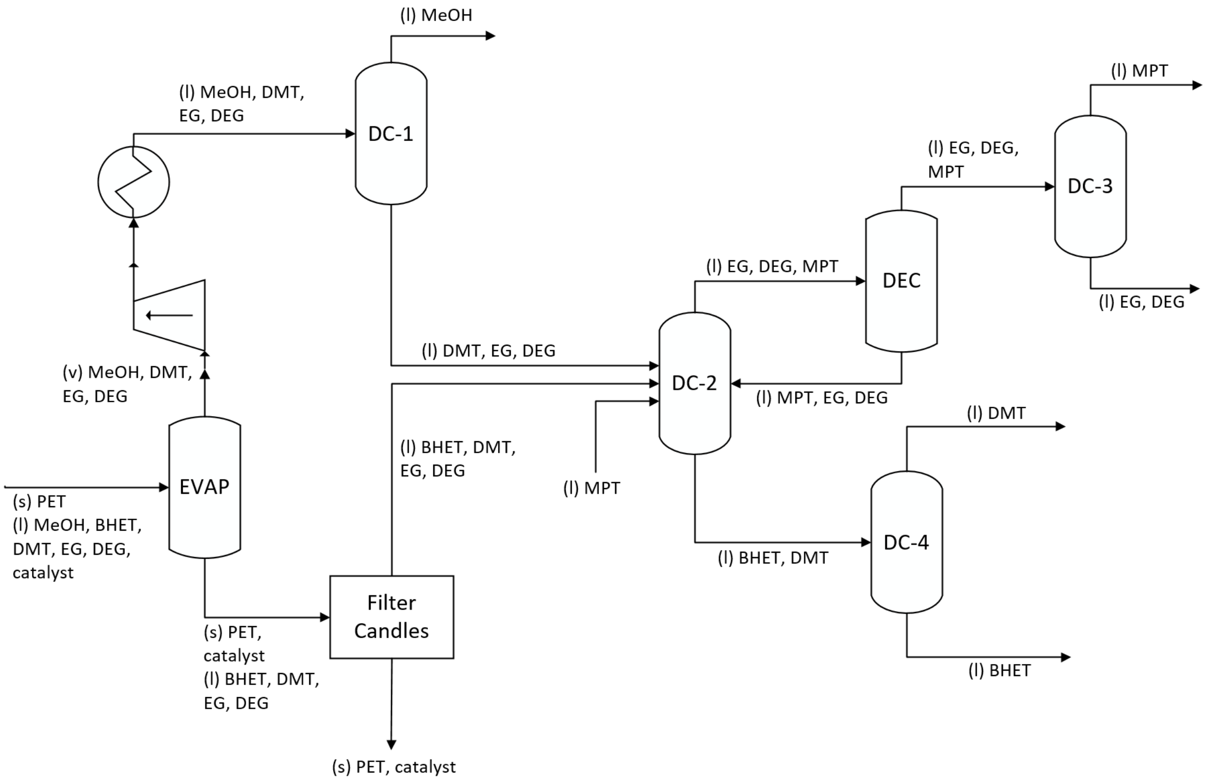
Preprocessing Block



Reaction Block



Separation Block



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