3.1.2 Chemical Recycling

Chemical recycling is used for *cross-linked polymers* or for thermoplastic polymers if no sufficient quality can be achieved using mechanical recycling. Chemical processes are used to convert the polymer chains to *low molecular weight* compounds or, in some cases, the original plastic monomer (feedstock). The monomers can be used for polymerization to generate the original polymer again, whereas the low molecular weight compounds are used as feedstock for the petrochemical industry. Common processes for this recycling method are hydrolysis, hydrocracking, pyrolysis, and depolymerization. Because of the large amounts of energy and chemicals consumed by the currently available processes, chemical recycling is only economically and ecologically reasonable for a very limited number of polymers such as polymethyl methacrylate (PMMA) and polyether ether ketone (PEEK). Chemical recycling of polyethylene terephthalate (PET) has been successfully developed. However, it is hindered by the processing cost. Furthermore, the chemical processing has been proven to be technically possible for polyolefins but is still in the laboratory stage of development. This is a fast growing research area, where significant breakthroughs can be expected in the next decade. [3, 4, 6, 7, 8]

■ 3.2 Recycling Different Types of Plastic Waste

As mentioned before, plastic waste can be divided into *preconsumer waste* (manufacturing scrap) and *postconsumer waste* (recovered waste). These different plastic waste types are recycled differently.

3.2.1 Preconsumer Waste

3.2.1.1 Manufacturing Scrap

Preconsumer waste, such as runners, gates, sprues, and trimming, is normally recycled using primary mechanical recycling. It is ground and remelted in-house.

3.2.1.2 Dilution Effect

Manufacturing scrap is often mixed into virgin material to reduce material cost while at the same time minimizing the effects of degradation on part performance. Depending on the mixing ratio, either the virgin material is diluted with regrind or the regrind is refreshed with virgin material. By using a constant mixing ratio during continuous processing, the regrind waste itself is diluted by material that has been reprocessed once, twice, three times, etc. The composition of a material with a proportion of recyclate q after n processing cycles can be calculated using Equation 3.1.

$$\sum_{i=1}^{n} q^{n-i}(1-q)=1 \qquad 3.1$$

For small proportions of recyclate, the regrind material contains only minimal amounts of material that has passed through a large number of processing cycles and therefore is highly degraded.

Figure 3.1 shows the composition of material with different mixing ratios of recycled and virgin material. The first column shows 30% recycled and 70% virgin material. Under these conditions, the regrind material contains less than 0.8% of material that has been reprocessed five times or more. Seventy percent of the material is virgin material, 21% has been processed once, 6.3% twice, and 1.9% three times. As proportions of material smaller than 1% do not have a significant influence on the material properties and can be neglected [9], the properties will be dominated by fractions that have been processed four times or less. Thus, it can be concluded that the properties of a material with small amounts of recyclate will not fall below a certain level. [10]

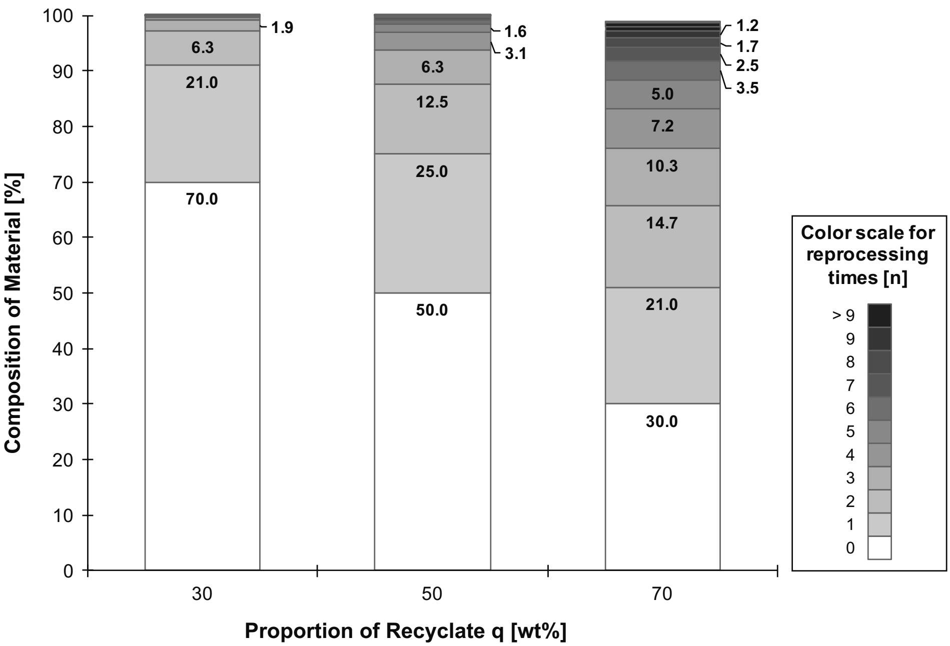

Figure 3.1 Composition of recycled plastic material after **n** reprocessing steps for 30%, 50%, and 70% recycled material

However, regrind material with high proportions of recyclate contains significant amounts of highly degraded material, as can be seen in the right column in Figure 3.1, in which 70% of the regrind is recycled and 30% is virgin material. This regrind material contains 5.0% material that has been reprocessed five times, as well as 30% that is virgin material, 21% that has been processed once, 14.7% twice, 10.3% three times, and 7.2% four times. After nine processing cycles, the material still contains 1.2% of the initial material. Although this mix contains significant portions of highly degraded material, after 10 reprocessing cycles the material reaches a steady state in which performance properties are not affected anymore by further processing. Therefore, this mixing ratio is used quite frequently for packaging products, e. g., PET containers.

3.2.2 Postconsumer Waste

Consumer plastics are largely made from six different polymer resins, which are indicated by a number, or *resin code*, from 1 to 7 molded or embossed onto the surface of the plastic product. The number 7 indicates any polymer other than those numbered 1 to 6. Table 3.1 lists the polymer resins, their resin codes, and the general applications for virgin and recycled plastics made from these resins. The percentages of the different types of postconsumer plastic waste in municipal solid waste (MSW) in the United States in 2017 are given in Table 2.1. [11]

Table 3.1 Plastic Types and Products from Virgin and Recycled Materials

Resin Symbol and Plastic Type	Products Created from Virgin Plastics	Products Created from Recycled Plastics
01 PET Polyethylene terephthalate	Bottles for water, soft drinks, salad dressing, peanut butter, and vegetable oil	Egg cartons, carpet, and fibers and fabric for T-shirts, fleeces, tote bags, shoes, etc.
02 HDPE High-density polyethylene	Milk and juice cartons, detergent containers, shower gel bottles, and shipping containers	Toys, pails, drums, traffic barrier cones, fencing, and trash cans
03 PVC Polyvinyl chloride	Packaging materials, plastic pipes, decking, wire and cable products, blood bags, and medical tubing	Shoe soles, construction material, and boating and docking bumpers

4.4.2 Plastic Reprocessing Costs

After PET is baled in the MRF, the bales are transported to a *plastic reprocessing facility*, where they are further treated, as schematically presented in Figure 4.3.

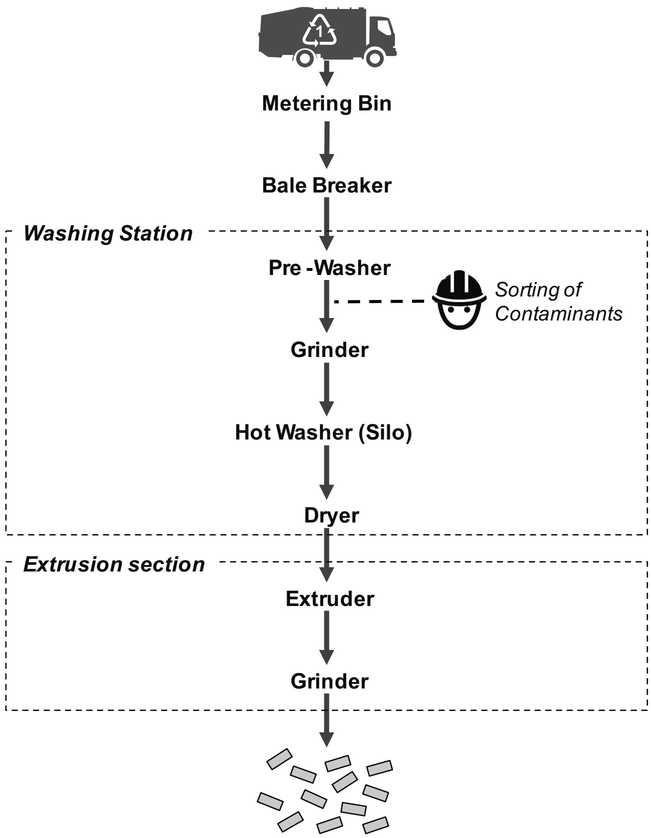

Figure 4.3 Schematic of plastic reprocessing facility

From the tipping floor, PET bales are grabbed by a loader and laid into a metering bin, which constantly meters the plastic waste into a bale breaker. The bale breaker dismembers the PET bales into individual free flowing items (e.g., food containers and bottles). [49, 50]

The individual items are conveyed to a washing station. After a short prewashing to remove labels and dirt from the outside of the items and a manual hand sorting of contaminants, PET items are ground into flakes by a wet granulator. These ground flakes are transported to a silo for hot washing, which removes the last dirt and glue. In a final step at the washing station, these clean flakes are dried. [49, 50]

6 Optimization of Plastics Recycling

Chapter 5 concluded that recycling is the best option for handling plastic waste from an environmental point of view and can significantly contribute to minimizing air, soil, and marine pollution.

But, as presented in Chapters 2, 3, and 4, there are two central issues with recycling: on the one hand, only 9% of plastic waste in the United States is recycled at the moment due to technical limitations (see Chapter 3) and, on the other hand, recycling is currently unprofitable from an economic point of view due to low oil prices (see Chapter 4). Recycling and selling 1 t of recycled plastic results in a loss of more than $10.

To improve both profitability and recycling rate, two process optimization possibilities are presented in this chapter.

■ 6.1 Optimization I: Reduction of Sorting Processes

The first process optimization proposed is reducing the number of sorting processes. Therefore, the so-called *dual-stream recycling* would need to be implemented. Dual-stream recycling means that the plastic waste is directly separated by consumers in their households, which is similar to systems established in Europe (see Section 7.1). Consequently, the sorting process in the materials recovery facility (MRF) is not required anymore. The optimized process is shown in Figure 6.1. [1]

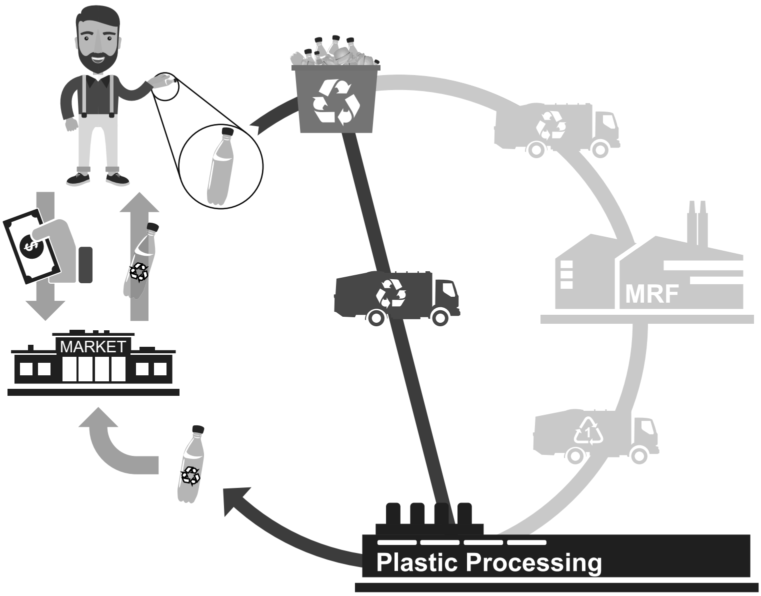

Figure 6.1 Optimization I: Dual-stream recycling

To calculate the profitability of the optimized process, the original profitability calculation of the plastic recycling process is used as a basis. The costs of polyethylene terephthalate (PET) processing as well as the revenues realized by selling recycled PET remain unchanged. Processing 1 t of plastic waste costs **$72.37** and the revenues for sale of 1 t of recycled plastic are **$146.94**. But to handle plastic in the same facility, additional machines and processes need to be installed. The additional costs are split up in two main categories: investment costs (1) and operation and maintenance costs (2). The assumptions for this optimization are shown in Table 6.1 and in more detail in Table 8.21 in the Appendix.

Table 6.1 Optimization I: Assumptions

Lifetime [years]	10
Yearly working hours [h]	6,240
Yearly plastic waste handling [t]	100,000
Total plastic waste capacity (10 years) [t]	1,000,000
Yearly PET capacity [t]	15,000
Total PET waste capacity (10 years) [t]	150,000
Separation efficiency [%]	91

Additional investment costs are split up in building and site, machine, and equipment costs. To handle plastic waste in only one facility, additional land, site work, and buildings as well as a scale house are required. These building and site costs amount to $1,775,000. Furthermore, three new machines need to be installed: a metering bin, an optical PET sorting machine, and a baler. The investment costs of all machines add up to $925,000. For additional conveyors, rolling stock, and waste collection cars, total costs are $1,250,000. As presented in Table 6.2, total additional investment costs are **$3,950,000** (see also Table 8.22 in the Appendix). [2, 3, 4]

Table 6.2 Optimization I: Additional Investment Costs

Additional building and site investment costs [$]	1,775,000
Additional machine investment costs [$]	925,000
Additional equipment investment costs [$]	1,250,000
Total additional investment costs [$]	**3,950,000**

Additional operating and maintenance costs are salaries of the additional personnel, operating and maintenance costs of the machines and the rolling stock, and especially transportation and collection costs. Yearly operating and maintenance costs are **$5,713,797**, so overall **$57,137,976**, as presented in Table 6.3 and in more detail in Table 8.23 in the Appendix. [3, 5, 6, 7, 8]

Table 6.3 Optimization I: Additional Operating and Maintenance (O&M) Costs

Personnel salaries per year [$]	963,000
Facility costs per year [$]	250,000
Machine O&M costs per year [$]	68,417
Rolling stock O&M costs per year [$]	748,380
Transportation and collection costs [$]	3,684,000
Yearly O&M costs [$]	**5,713,797**
Overall O&M costs (10 years) [$]	**57,137,976**

Summarizing both additional investment and operating and maintenance costs, total additional costs are **$61,087,976**. Since 100,000 t of plastic waste must be handled per year in this new facility area (to gain 15,000 t of PET waste, around 100,000 t of plastic waste has to be sorted), the additional costs of 1 t of plastic waste are **$61.09**.

Knowing that the revenues of recycling 1 t of plastic waste are **$146.94** and the costs for further processing the plastic waste are **$72.37**, the profitability of this optimization is calculated in Table 6.4.

Table 6.4 Total Profit per Ton of Plastics Recycled

Revenues per ton of plastics recycled [$/t]	146.94
Sorting [$]	61.09
PET processing [$]	72.37
Profit per ton of plastics recycled [$/t]	**13.48**

Table 8.12 Economic Analysis of Waste-to-Energy Plant: Average Lower Heating Value (LHV) of Municipal Solid Waste

Type of Waste	LHV [MJ/kg]	% in Waste [%]	Total [MJ/kg]
Paper	19.12	25.00	4.78
Glass	0.00	4.20	0.00
Metals	0.00	9.40	0.00
Plastics	36.16	13.20	4.77
Rubber and Leather	31.28	3.40	1.06
Textiles	16.05	6.30	1.01
Wood	11.63	6.70	0.78
Food	6.05	15.20	0.92
Yard Trimmings	6.98	13.10	0.91
Other	21.05	3.50	0.74
Total [MJ/kg]			**14.98**

Table 8.13 Economic Analysis of Waste-to-Energy (WTE) Plant: Tipping Fee

State	Number of WTE Plants	Average WTE Tipping Fee [$/t]	Total
Alabama	1	25.00	25.00
Connecticut	7	64.00	448.00
Florida	12	52.92	635.04
Iowa	1	64.00	64.00
Massachusetts	7	69.00	483.00
Minnesota	9	55.00	495.00
New Hampshire	2	69.00	138.00
New Jersey	5	85.00	425.00
New York	10	72.34	723.40
Washington	3	98.00	294.00
Wisconsin	2	51.00	102.00
Total	59		3,832.44
Overall Average Tipping Fee			**64.96**

■ 8.3 Economic Analysis of Recycling

Table 8.14 Economic Analysis of Plastics Recycling: Overall Assumptions

Percentage of PET in Plastic Waste [%]	14.16
Average Price of Recycled PET Pellets [$/lb]	0.58
Price of Recycled PET Pellets [$/kg]	1.26
Electricity Price [$/kWh]	0.1027
Diesel Price [$/gallon]	2.198
Diesel Price [$/l]	0.5807
Water Price [$/gallon]	0.015
Water Price [$/l]	0.0040

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