WASTE PLASTICS CHEMICAL RECYCLING IN THE CONTEXT OF REFINING AND PETROCHEMICAL INDUSTRIES

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Rising demand for plastic materials results in increasing volumes of plastic waste generated globally. This poses a question of waste collection and handling of the growing waste volumes. With quality limitations of reuse and mechanical recycling, especially end-of-life mixed plastic waste is mostly landfilled, incinerated or lost to environment. Thermochemical recycling, especially pyrolysis, has been historically explored as an attractive alternative waste processing method with a potential to valorise the plastic waste into energy, fuels and more recently also chemicals and virgin polymers. Thermochemical plastic waste processing and treatment of the intermediates towards the final products have been found to be studied mostly in isolation. Therefore, this study provides a combined view. Updated state of pilot and demonstration projects is reviewed. Typical characteristics of plastic waste pyrolysis products are introduced and the areas of potential impacts on existing plants are highlighted. In order to address the circularity and economic aspect, a summary of recent relevant LCA and business studies is provided, showing common sensitivity factors and main assumptions used therein. Overall, this review summarizes the background behind the recycling of waste plastics and presents it in context of challenges and opportunities of integration with existing refining and petrochemical infrastructure.

Keywords: Thermochemical recycling, Plastic Waste, Pyrolysis, Steam Cracking, Refining, Process Integration

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1. Introduction

Since the start of production of plastic materials in 1930s and 1940s, the industry has been rapidly expanding after the World War II, annual production of plastics reached 390 Mt in 2021 (see Figure 1) and is poised to double by 2035 and quadruple by 2050 [1,2]. The plastic materials find utilization in a broad spectrum of industries and are hardly going to be replaced at scale by any superior substitute materials in the foreseeable future. The main raw materials used for production of plastics are natural gas/natural gas liquids and crude oil. In 2021 the global crude oil demand was 97.5 million barrels per day (Mb/day) and is forecasted to grow by 8.4 % to 105.7 Mb/day in 2028 [3]. In perspective, the plastics production volume accounts for ca 8 % of crude oil demand in 2021. Over the past 30 years the demand for plastics has been steadily increasing, whereas the demand for transportation fuels has peaked and recently started to decrease, putting more stress on the refiners to intensify petrochemical feedstock production [3,4].

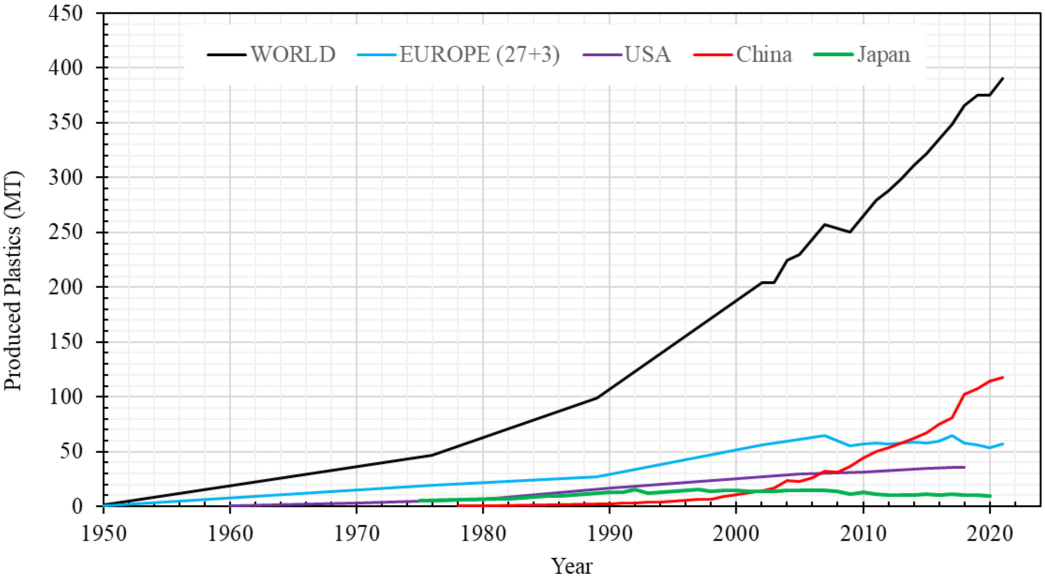

Figure 1: Plastics production worldwide and in selected regions [4-7]

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Primary polymer building blocks, ethylene and propylene, are predominantly produced by steam cracking of ethane, propane and C_{3+} hydrocarbons coming mainly from natural gas condensates (NGLs), shale gas, naphtha, hydrogenated vacuum gasoil (HVGO). Total world installed ethylene capacity of steam crackers in 2015 was 143.7 Mt [8] and continues to be expanded and documented by recently awarded construction projects i.e., RLPP [9], Amiral [10], GCC [11].

Total world propylene installed capacity is 150 Mt and poised to grow to 209 Mt by 2027 [12]. Steam cracking and fluid catalytic cracking (FCC) account together for almost 80% of the global propylene capacity, with each sharing almost equally 40% [13].

Besides FCC and steam cracking, the third largest (11 % share as of 2021) and quickly growing technology to produce propylene is propane dehydrogenation (PDH) with total world installed capacity of 17.2 Mt as of 2021 [13]. Rapid development has been registered in China with more than 30 plants under construction or planned since 2021 [14], and recent construction awards outside of China such as Sonatrach, Algeria [15]. The abovementioned installations are large capital projects with major operating cost spent on feedstock conversion step (cracking in furnaces, conversion in the reactor) and separation/purification of reaction products (low temperature separation).

On the other side of the value chain, there is plastic waste which has been historically landfilled and with increasing waste quantities, coming mainly from polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET) used for packaging, started to be collected and either reused, mechanically recycled or incinerated, refer to Table 1. Despite an increase in recycling and incineration, the global landfilling volume was still increasing in 2019, as shown in Table 1.

Mechanical recycling is limited by purity of the presorted and cleaned material and also by number of recycling cycles. Each mechanical recycling loop reduces the output material quality (downcycling). Incineration is a subject to strict environmental regulations for flue gas composition. Attempts have been made over the years to chemically convert the plastics back to their original monomers. Solvolysis is applied for condensation polymers. Since monomers are highly yielded in this process, it is also referred to as “Monomer recycling”. For addition polymer resins, thermal and/or catalytic cracking can be applied.

Table 1: Plastic waste collection and treatment (Mt) globally and in selected major regions (source: [23])

Waste route						Year					
	2000	2002	2004	2006	2008	2010	2012	2014	2016	2018	2019
						World					
Total Plastic Waste	156	174	195	215	231	255	276	296	320	342	353
Recycled	6	7	9	12	14	17	20	23	27	31	33
Incinerated	17	21	25	29	34	39	45	51	58	65	67
Landfilled	93	101	110	119	124	134	142	150	159	168	174
Mismanaged, Littered	41	45	51	56	59	64	69	72	76	78	79
						OECD EU					
Total Plastic Waste	33	35	38	40	41	43	45	46	47	50	51
Recycled	2	2	3	3	4	4	5	5	6	7	7
Incinerated	5	7	8	10	11	13	15	17	19	22	22
Landfilled	22	22	23	23	22	22	21	20	19	18	19
Mismanaged, Littered	4	4	4	4	4	4	3	3	3	2	2
						USA					
Total Plastic Waste	47	50	54	57	59	63	65	67	69	72	73
Recycled	1	1	2	2	2	2	2	3	3	3	3
Incinerated	7	8	9	9	10	11	12	12	13	14	14
Landfilled	35	37	40	42	44	46	48	49	51	52	53
Mismanaged, Littered	4	4	4	4	4	4	3	3	3	3	3
						China					
Total Plastic Waste	17	21	25	30	34	41	47	53	58	62	65
Recycled	1	1	2	2	3	4	5	6	7	8	8
Incinerated	2	2	3	4	5	7	9	11	13	15	16
Landfilled	4	6	7	9	10	13	15	18	20	22	24
Mismanaged, Littered	10	12	14	15	16	17	18	19	18	17	18
						Other Asia					
Total Plastic Waste	11	13	15	17	20	22	25	28	32	36	38
Recycled	1	1	1	1	1	2	2	2	3	4	4
Incinerated	2	2	3	4	4	5	6	7	8	10	10
Landfilled	5	6	6	7	7	8	9	10	11	12	12
Mismanaged, Littered	4	4	5	6	7	8	8	9	10	11	12

Alternatively, direct co-processing of waste plastics with conventional fossil feedstocks has been explored for various conversion processes e.g. FCC, delayed coking, hydrocracking/hydrotreating [16-21]. Since the products primarily resemble crude oil and its fractions, this approach is referred to as “Feedstock recycling”.

Feedstock recycling is suitable primarily for processing of end-of-life plastic waste, which would be too costly, or impossible to sufficiently pre-treat for mechanical recycling. Main products of the waste plastics conversion processes are generally char/coke, oil and gas. The oil and gas can be used for energy recovery in the process, however, lately became of interest as feedstock for fuels and petrochemical production.

Past experiences around the world have shown that the economics of the waste plastic chemical recycling plants was not favourable [21,22]. With the evolution in polymer production and environmental regulations, is there an opportunity in the current and future market to sustainably integrate refining and petrochemical infrastructure with end-of-life waste plastics recycling? What would be an optimal configuration? What technical challenges have to be addressed? Technical and economic aspects of the integration are subject of this review in order to explore the above stated-stated questions.

2. Plastic Waste Recycling as Part of Petrochemical and Refining Industry

Handling of plastic waste is to a large extent still part of an open-loop process not only in terms of material flow but also industrial structure. Petrochemical industry produces the raw materials, manufacturers buy them to produce end products and waste management industry takes care of the disposed product collection, sorting, reuse/mechanical recycling/incineration. Therefore, there is very little end-to-end accountability and integration in the fate of the produced materials. Under the circular economy efforts, this is about to change as understanding and mutual synergies between the refining/petrochemical industry and waste management industry need to be found, in order to close the material flow loop. This can be documented by formation of alliances and partnerships between traditional petrochemical producers and waste management companies structured around waste plastics recycling e.g.

- LyondellBasell and Suez formed a joint venture called QCP in 2020, where later LyondellBasell became a full owner after buying the 50% share of Veolia (merged with Suez in 2021/2022) [24]
- BASF with Quantafuel and Remondis signed a memorandum of understanding (MoU) to evaluate and cooperate in chemical recycling including a joint investment in a pyrolysis plant [25];
- Idemitsu Kosan created a joint venture with Environmental Energy Co. Ltd in 2023 to produce oil from used plastics in Japan [26];
- FCC, Cyclyx, Exxon Mobil and LyondellBasell signed a collaboration agreement with the city of Houston, USA in 2022 to expand collection of plastic waste, which will be subsequently directed to mechanical and chemical recycling [27]
- OMV and ALBA Recycling entered an exclusive agreement in 2022 to build a mixed plastic waste collection and sorting plant (200 000 tonnes/year) in Germany, that is planned to feed a planned large-scale OMV pyrolysis plant in Schwechat, Austria [28]

As of 2019 49 % of the plastic waste was landfilled and 19 % was incinerated. With the historical increase in plastic waste quantities, the separate collection and closed-loop approach has been adopted around the world on different scales in various regions (see Table 1).

The process was accelerated by local regulations, i.e ban of export of plastic waste to China in 2018 followed by extension to third world countries in 2019 by Basel convention [29,30]. Lately the regulation on CO_2 emissions are further forcing plastic waste recycling for use in refining/petrochemical industries, in order to reduce the carbon footprint of the produced fuels and plastics – e.g. REDII [1]. The carbon footprint of the products may soon become one of the conditions to retain the license to operate the facilities.

The European Union has set a target of only 10% of plastic waste to landfill by 2030, compared to around 20% at present. Taxes on incineration are also being increasingly used to limit this form of waste processing [31]. OECD have reported the status of the policies and incentives for waste recycling around the world, which shows that most of the world’s population lives in systems that lack operational incentives, see Figure 2. Furthermore, European Union comes up as a front-runner in initiatives on closed-loop waste management. This can be also documented by national systems for sorted waste collection summarized in Table 2.

The closed-loop pathways follow the general waste management hierarchy of reduce-reuse-recycle. Figure 3 shows an example of the plastic material lifecycle. The technical and economical resource cost increases from reuse to feedstock recycling and hence sets general priorities in handling the plastic waste.

Therefore, generally, the waste that cannot be technically or economically recycled via the less demanding pathways should be considered for the more demanding ones. This approach would render end-of-life mixed plastic waste a candidate fit for feedstock recycling under closed-loop waste management. This links the waste plastics recycling back to the (petro)chemical and refining industry. The conceptual link back to the refinery and petrochemical production can be in form of a direct co-processing with intermediate mechanical cleaning/sorting steps, or chemical pre-pre-treatment by conversion to liquid/gaseous products that can be further processed or blended with the conventional refinery/petrochemical feedstocks.

In 1960s plastics pyrolysis processes started to be developed and in 1970s – 1980s the first initiatives started to appear on the industrial scale, namely in Japan [21] and Germany [32].

Table 2: Local collection schemes in Europe (source: [21])

Country	Waste Collection system
Europe	Pro Europe sprl
Austria	ARA Alstoff Recycling Austria AG
Belgium	asbl Fost Plus vzw
Bulgaria	EcoPack Bulgaria
Cyprus	Green Dot Cyprus Public Company Ltd.
Czech Republic	EKO-KOM, a.s.
Finland	PYR Ltd
France	Aco Emballages SA;Adelphe
Germany	Duales System Deutschland
Greece	HE.R.R.CO Hellenic Recovery and Recycling Co.
Great Britain	Valpack Ltd; BIFFPACK; WASTE-PACK
Hungary	OKO-Pannon p.b.c.
Ireland	Repak Ltd.
Italy	CONAI (Consorzio Nationale Imballagi)
Latvia	Latvijas Zalais Punkts, NPO, Ltd
Lithuania	Zaliasis Taskas, UAB
Luxemburg	Valorlux asbl
Malta	GreenPak Malta
Norway	Materialretur A/S; RESIRK
Poland	RekoPol-Organizacja Odzysku S.A.
Portugal	Sociedade Ponto Verde, S.A.
Slovak Republic	Envi-pak, a.s.
Slovenia	Slopak d.d.o.
Spain	Ecoembalajes Espana, S.A.
Sweden	REPA-Reparagistret AB; RETURPACK PET
The Netherlands	SVM-PACT
Turkey	CEVKO

Since this study is focused on industrial integration of the pyrolysis processes and refining/petrochemical infrastructure, advances in the development of the pyrolysis processes themselves are not discussed in detail. However, as their understanding is an important pre-requisite to assess the integration scenarios, detailed reviews by [1,2,18,33-37] are referenced here providing detailed studies on state of the art, characteristics and challenges of various plastics pyrolysis methods.

The early commercial technology development is summarized by Scheirs [21] and Tukker [22] by regions in detail. Recently, many start-up companies and institutions have attempted to establish, operate and/or sell the plastics pyrolysis processes, which has created a quickly changing environment in the market of pilot, demonstration and scale-up attempts, as the technologies are not yet mature. A list of relevant active players, therefore, changes dynamically. A list of active technologies has been adapted from [38], and enhanced with recent information as of July 2023, see Table 3.

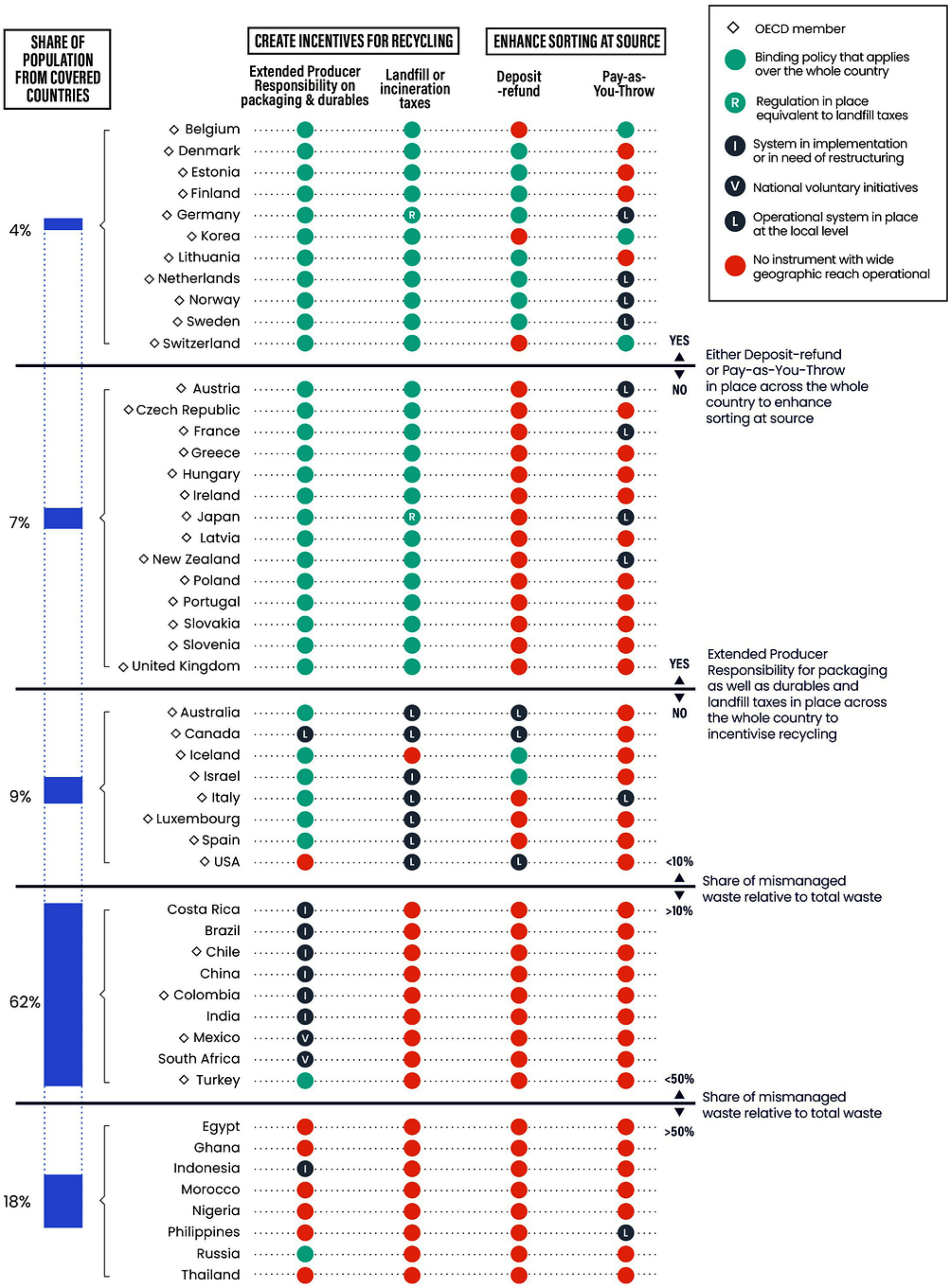
The portfolio of companies has in the meantime been expanded from standalone start-up companies and major petrochemical producers, also to established chemical technology licensors (e.g. Haldor-Topsoe, Lummus Technology, UOP) and EPC companies signalling stronger opportunities to implement the plastics chemical recycling at large scale.

Solis [39] evaluated the plastic waste chemical recycling technologies from the perspective of the technological readiness level (TRL). TRL matrix was developed based commercial scale of operation, process temperature, sensitivity to feedstock quality and polymer breakdown depth. TRL ranged from 1 to 9, where 9 is the highest. Eight plastics chemical recycling technologies were distinguished and it was concluded that there are three technologies with TRL 9: thermal cracking (pyrolysis), catalytic cracking and conventional gasification. Other technologies are still under development and are not at commercial stage yet, namely plasma pyrolysis, microwave-assisted pyrolysis, hydrocracking, plasma gasification and pyrolysis with in-line reforming.

The initial chemical recycling plant designs were intended to convert plastic waste into fuels utilized either by the process itself or for incineration to produce heat or electricity – waste-to-energy. With increasing scale and complexity, the next stage of efforts was directed to use the pyrolysis conversion products to produce transportation fuels – waste-to-fuels. Recently the conversion products are intended to be more and more directed to petrochemical plants in order to produce plastics and petrochemical intermediates (BTXSEb [40]), waste-to-chemicals.

Practical applications towards utilization of plastics and their pyrolysis products in refinery units were studied by Palos [18,41], potential synergies were highlighted for hydroprocessing and FCC applications. Co-feeding of PE/PP or derived waxes increases reactivity under the process conditions and improves yields. More recently detailed reviews towards utilization in modern steam crackers were published by Kusenberg [42,43] and Thunman [44] focusing on importance of detailed plastics pyrolysis product analysis, in order to properly pre-treat the streams by reducing aromatic and olefinic content as well as contaminants, that may be fatal for the cracking heater radiant coils (by promoting rapid coking and corrosion), deactivate catalysts, cause corrosion etc.

In order to identify the right configuration of waste-to-fuels and waste-to-chemicals technologies, compatibility of the converted recycled streams with the existing conventional refining and petrochemical technologies require to be assessed.



SHARE OF POPULATION FROM COVERED COUNTRIES		CREATE INCENTIVES FOR RECYCLING		ENHANCE SORTING AT SOURCE	
		Extended Producer Responsibility on packaging & durables	Landfill or incineration taxes	Deposit -refund	Pay-as-You-Throw
4%	◇ Belgium	🟢	🟢	🔴	🟢
	◇ Denmark	🟢	🟢	🟢	🔴
	◇ Estonia	🟢	🟢	🟢	🔴
	◇ Finland	🟢	🟢	🟢	🔴
	◇ Germany	🟢	R	🟢	L
	◇ Korea	🟢	🟢	🔴	🟢
	◇ Lithuania	🟢	🟢	🟢	🔴
	◇ Netherlands	🟢	🟢	🟢	L
	◇ Norway	🟢	🟢	🟢	L
	◇ Sweden	🟢	🟢	🟢	L
	◇ Switzerland	🟢	🟢	🔴	🟢
7%	◇ Austria	🟢	🟢	🔴	L
	◇ Czech Republic	🟢	🟢	🔴	🔴
	◇ France	🟢	🟢	🔴	L
	◇ Greece	🟢	🟢	🔴	🔴
	◇ Hungary	🟢	🟢	🔴	🔴
	◇ Ireland	🟢	🟢	🔴	🔴
	◇ Japan	🟢	R	🔴	L
	◇ Latvia	🟢	🟢	🔴	🔴
	◇ New Zealand	🟢	🟢	🔴	L
	◇ Poland	🟢	🟢	🔴	🔴
	◇ Portugal	🟢	🟢	🔴	🔴
	◇ Slovakia	🟢	🟢	🔴	🔴
	◇ Slovenia	🟢	🟢	🔴	🔴
	◇ United Kingdom	🟢	🟢	🔴	🔴
9%	◇ Australia	🟢	L	L	🔴
	◇ Canada	L	L	L	🔴
	◇ Iceland	🟢	🔴	🟢	🔴
	◇ Israel	🟢	I	🟢	🔴
	◇ Italy	🟢	L	🔴	L
	◇ Luxembourg	🟢	L	🔴	🔴
	◇ Spain	🟢	L	🔴	🔴
	◇ USA	🔴	L	L	🔴
62%	Costa Rica	I	🔴	🔴	🔴
	Brazil	I	🔴	🔴	🔴
	◇ Chile	I	🔴	🔴	🔴
	China	I	🔴	🔴	🔴
	◇ Colombia	I	🔴	🔴	🔴
	India	I	🔴	🔴	🔴
	◇ Mexico	V	🔴	🔴	🔴
	South Africa	V	🔴	🔴	🔴
	◇ Turkey	🟢	🔴	🔴	🔴
18%	Egypt	🔴	🔴	🔴	🔴
	Ghana	🔴	🔴	🔴	🔴
	Indonesia	I	🔴	🔴	🔴
	Morocco	🔴	🔴	🔴	🔴
	Nigeria	🔴	🔴	🔴	🔴
	Philippines	🔴	🔴	🔴	L
	Russia	🟢	🔴	🔴	🔴
	Thailand	🔴	🔴	🔴	🔴

◇ OECD member
🟢 Binding policy that applies over the whole country
R Regulation in place equivalent to landfill taxes
I System in implementation or in need of restructuring
V National voluntary initiatives
L Operational system in place at the local level
🔴 No instrument with wide geographic reach operational

YES ▲ ▼ NO Either Deposit-refund or Pay-as-You-Throw in place across the whole country to enhance sorting at source

YES ▲ ▼ NO Extended Producer Responsibility for packaging as well as durables and landfill taxes in place across the whole country to incentivise recycling

<10% ▲ ▼ >10% Share of mismanaged waste relative to total waste

<50% ▲ ▼ >50% Share of mismanaged waste relative to total waste

Figure 2: Policy instruments status to promote plastic waste recycling worldwide (source: [23])

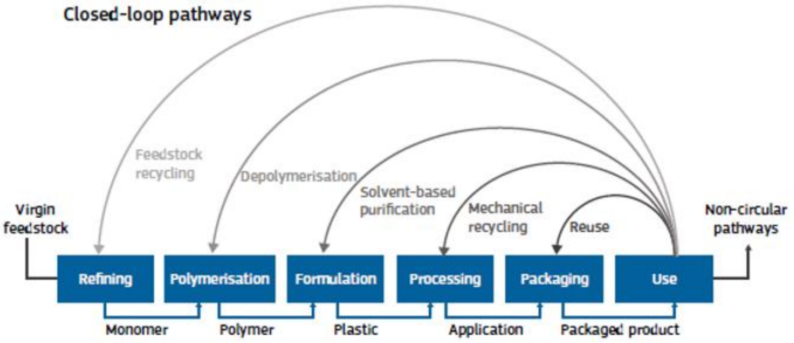


Figure 3: Closed-loop pathways of handling plastic waste (source: [30])

Table 3: Active plastics pyrolysis technologies operating at demonstration/pilot or commercial scale (adapted from [38] and updated)

	Company	Country	Process	Raw material	Process temperature	Products	Capacity (tonnes/year)	Partner	Status/summary
1	Sulapac	FIN	Catalytic pyrolysis	Biocomposite	400–600 °C	Liquid HCs		VTT	The producer of biodegradable products is developing a pyrolysis plant in cooperation with VTT.
2	Indaver	B	Pyrolysis	Unsorted plastic waste, PE, PP		Liquid HCs, waxes, paraffins	7 000	Univ. Ghent, Univ. Antwerp, INEOS	The waste disposal company operates a pilot plant with a capacity of 7 000 tonnes/year; an industrial plant with 65 000 tonnes/year is under construction. Planned start-up is 2024 with initial capacity of 26 000 tonnes/year to be scaled-up to full capacity by 2027.
3	PowerHouse Energy	UK	Gasification	Unsorted plastic waste	1000–1200 °C	CO, H_2	9 000		A demonstration plant was built based on the DMG® technology (distributed modular generation) from Pyromex. An additional plant with a capacity of 12 000 tonnes/year is planned.
4	Recycling Technologies	UK	Pyrolysis	Plastic waste	400–600 °C	Liquid HCs	7 000	Total, Nestle, Mars	The company's own technology for the production of smaller or mobile plants (suitable for container). Ceased operation in 2022
5	Plastic Energy	UK	Pyrolysis	PE, PP, PS	400 °C	Liquid HCs	7 000	SABIC	Modular technology is applied in Spain at sites in Seville and Almeria.
6	Itero (formerly CGC)	UK	Pyrolysis	Plastic waste	350–500 °C	Liquid and gaseous HCs	27 000		Itero operates a pilot plant with a capacity of 5 500 tonnes/year. An industrial pyrolysis plant in the Netherlands is planned to start up in 2023.
7	Susteen Technologies	DE	Thermo-catalytic reforming (TCR®)	Plastic waste, organic waste	400–500 °C	Liquid and gaseous HCs, coke	4 000	Fraunhofer UMSICHT	Demonstration plant using a technology developed by Fraunhofer UMSICHT (Germany). Pyrolysis oil is catalytically reformed in a separate step. Shutdown in 2020
8	Pyrum	DE	Pyrolysis	Plastic waste, tyres	300–1200 °C	Liquid and gaseous HCs	7 000	BASF	The developer of the technology operates a demonstration plant and a pyrolysis plant for waste tyres with a capacity of 10 000 tonnes/year. BASF has announced a 16 Mn EUR investment for two additional pyrolysis plants from Pyrum. BASF uses the pyrolysis oil in the framework of the ChemCycle™ project.
9	Clariter	PL/LUX/UK	Pyrolysis	Plastic waste (PE, PP, PS)	400 °C	Liquid HCs, waxes, paraffins	1 000	TotalEnergies Fluids	Pyrolysis products are used as high-value raw materials to produce solvents, oils and waxes. Demonstration plant in east London. Additional 3 plants under construction in Poland, Israel and Netherlands with combined capacity of 180 000 tonnes/year (3 x 60 kta)
10	Pohjanmaan Hyötyjätekuljetus (PHJK)	FIN	Pyrolysis	Unsorted plastic waste		Liquid HCs	4 000		The waste disposal company operates smaller plants.

Table 3 (cont.): Active plastics pyrolysis technologies operating at demonstration/pilot or commercial scale (adapted from [38] and updated)

	Company	Country	Process	Raw material	Process temperature	Products	Capacity (tonnes/year)	Partner	Status/summary
11	ReOil / OMV	A	Pyrolysis	Plastic waste, PE	450 °C	Liquid HCs	900	Borealis	Developed by ReOil (belongs to the refinery operator OMV), which operates a small demonstration plant for the pyrolysis of LDPE and heavy oil residues. A scale-up to a 16 000 tonnes/year demo plant was planned to start operation in 2023. Furthemore, full large scale plant (200 000 tonnes/year) is planned to be built by 2027.
12	Splainex	NL	Pyrolysis	Plastic waste, wood, WEEE	500 °C	Liquid and gaseous HCs	35 000		The plant engineering company develops the pyrolysis process and plant concept. The plants are sold globally.
13	Smuda/Agrob Eko	PL	Catalytic pyrolysis	Organic waste, plastic waste	300–450 °C	Liquid HCs	10 000		The technology was developed by Henryk Smuda; the plant is located in Zabrze, Poland.
14	Leitner Technologies	SLO	Pyrolysis	Plastic waste	400 °C	Liquid HCs	360		Plant engineering company for smaller plants.
15	Quantafuel	N/DK	Catalytic pyrolysis	Plastic waste	420 °C	Liquid and gaseous HCs, coke	20 000	BASF	The developer of the technology started operating its own plant in Aarhus in 2019. A cooperation with Remondis and BASF was announced in 2021. Quantafuel will deliver the technology for a 250 000 tonnes/year plant at BASF location Ludwigshafen and will operate the plant starting in 2025. Remondis will deliver the plastic waste; the pyrolysis oil will partly cover the demand of BASF.
16	Fuenix Ecogy	NL	Pyrolysis and plasma treatment	Plastic waste, PE, PP	500–800 °C	Liquid and gaseous HCs		DOW	Ecogy® plasma treatment delivers the main item of the pyrolysis technology, implemented in the plant located in Weert. In 2019, a cooperation with DOW was concluded with the objective to deliver 100 000 tonnes/year of secondary raw materials, starting in 2025.
17	Neste	FIN	Pyrolysis	Organic waste, plastic waste	400–600 °C	Liquid and gaseous HCs		Alterra	The refinery operator and producer of raw materials for the chemical industry is developing a modular pyrolysis technology for plastic waste and renewable raw materials. A demonstration plant was built with the objective to recycle 100 000 tonnes/year of plastic waste starting in 2030.
18	Cassandra Oil	SWE	Catalytic pyrolysis, mechanically activated	Plastic waste, tyres (no PVC)	600 °C	Liquid HCs	15 000	Sacyr	Technology developer for waste disposal and recycling companies with the largest pyrolysis plant in operation (Jerez, Spain, capacity 15 000 tonnes/year). According to Cassandra Oil, the break-even oil price is 25 USD/bbl.
19	New Energy	HU	Pyrolysis	Tyres	800–1000 °C	Liquid HCs	10 000	BASF	New Energy signed a contract with BASF for the delivery of 4 000 tonnes/year after the successful pilot phase in Ludwigshafen.

Table 3 (cont.): Active plastics pyrolysis technologies operating at demonstration/pilot or commercial scale (adapted from [38] and updated)

	Company	Country	Process	Raw material	Process temperature	Products	Capacity (tonnes/year)	Partner	Status/summary
20	MOL	HU	Pyrolysis, cracking	Plastic waste, organic waste	300–360 °C	Liquid HCs			The refinery operator developed its own pyrolysis process on a pilot scale. Current combined capacity is 40 000 tonnes/year with a planned expansion to 100 000 tonnes/year. In 2023 MOL announced a partnership with Lummus Technology to cooperate in integration of plastics chemical recycling technologies with MOL's existing assets.
21	LyondellBasell	IT	Pyrolysis	Unsorted plastic waste	< 550 °C	Liquid and gaseous HCs, coke	80	KIT	Operation of the pilot plant MoReTec started in 2020 in Ferrara, Italy. The technology was developed at KIT in Germany. Engineering for another MoReTec plant to be located in Wesseling, Germany started in 2022.
22	Paterson Energy	IND	Catalytic pyrolysis	Plastic waste	500 °C	Diesel	2 000		Paterson Energy operates several plants in India. The process yield is 50 %, which is too low for the current state of development.
23	Agile Process Chemicals LLP (APChemi)	IND	Pyrolysis	Plastic waste, tyres		Liquid HCs, waxes, paraffins	10 000	Shell	The plant engineering company developed a pyrolysis process and plant concept. The plants are sold globally.
24	Rudra Environmental Solutions	IND	Catalytic pyrolysis	Plastic waste	380–430 °C	Liquid and gaseous HCs, coke	1 800		Technology developer for waste disposal and recycling companies
25	Polycycl Private Limited	IND	Pyrolysis	Plastic waste		Liquid HCs		Ramky	The technology company developed a continuous process for waste disposal and recycling companies and operates a demonstration plant.
26	Toshiba Plant System	JPN	Pyrolysis	PS	700 °C	Styrene	1000		Process and plant for waste prevention in the company's own factory.
27	Toyo Styrene	JPN	Pyrolysis	PS	450–550 °C	Styrene	3000	Agilyx	Technology licenced by Agilyx (USA). Construction started in 2022 and commissioning planned for Q1 2024
28	JSW	JPN	Pyrolysis	PMMA	400 °C	MMA	n.a.	Arkema	Technology supplier in the research project MMAtwo initiated by Arkema (Horizon 2020, budget 6.6 Mn. EUR). Pilot experiments were carried out in June 2020.
29	Sapporo Plastics / Klean Industries	JPN/ USA	Pyrolysis	PE, PP, PS (+PET, PVC < 20 wt%)	400 °C	Liquid HCs	15 000	Toshiba	The technology developed by Toshiba was transferred in 2011 to Klean Industries, which is proceeding to market the technology.
30	Hitachi Zosen Corporation	JPN	Pyrolysis	PE, PP, PS, ABS, PVC	250–350 °C	Liquid HCs	n.a.		The plant engineering company developed a pyrolysis process and plant concept.
31	Chiyoda Corporation	JPN	Pyrolysis	PE, PP, PS, ABS, PVC	2-step pyrolysis with distillation columns, 340–390 °C	Liquid HCs	6000	Rexol, Fuji	The plant engineering company developed its own pyrolysis process, which was realized in a plant. Rexol is responsible for marketing the pyrolysis products.

Table 3 (cont.): Active plastics pyrolysis technologies operating at demonstration/pilot or commercial scale (adapted from [38] and updated)

	Company	Country	Process	Raw material	Process temperature	Products	Capacity (tonnes/year)	Partner	Status/summary
32	Nissan / Mitsui Chemicals	JPN	Pyrolysis	PP, PE, PET	315 °C	Liquid HCs	Pilot phase		Cooperation for the use and prevention of waste in the automotive industry.
33	Mitsui / Microwave Chemicals	JPN	Microwave-induced pyrolysis	ASR, SMC PUR		Carbon fibers Liquid HCs	Bench scale demo		PUR recycling process based on Microwave's PlaWaveTM technology for microwave decomposition of plastics. Benc scale demonstration project planned for Q2 2023 with objective to achieve demonstration tests in Q1 2024 and commercialize by Q1 2026.
34	Showa Denko (Resonac Group)	JPN	Pyrolysis/ gasification	PE, PP, PS	2-step process, 600–700 °C, 1300–1500 °C	CO, H_2	64 000	Ebara Corporation, Ube Industries	Ebara Ube Process (EUP) delivers H_2 for NH_3 production. Showa Denko now uses plastic waste from McDonald's in Kawasaki for the proof of concept.
35	Nippon Steel	JPN	Pyrolysis in a blast furnace	PE, PP, PS	1200 °C	Liquid and gaseous HCs, coke	200 000		Known technology from the steel industry is applied in Japan for recycling and resource recovery.
36	Jinan Niutech Environment Technology Corporation	CN	Pyrolysis	Plastic waste	500 °C	Liquid HCs	10 000		The plant engineering company developed a continuous pyrolysis process and plant concepts for different raw materials (waste plastic, tyres, biomass). The plants are sold globally.
37	Xinxiang Huayin Renewable Energy Equipment Co., Ltd.	CN	Pyrolysis	Tyres, Plastic waste	400–700 °C	Liquid and gaseous HCs, coke	3500		The plant engineering company developed a pyrolysis process and plant concept; the plants are sold globally.
38	Bioland	CYP	Pyrolysis	Tyres		Liquid HCs			The waste disposal company developed its own pyrolysis process for plastic waste.
39	Agilyx	USA	Pyrolysis	PS, PMMA	450–550 °C	Styrene, MMA	7000	AmSty, Lucite	In their joint venture, Regenyx, Agylix, and AmSty demonstrated an example of an industrial cycle. Waste polystyrene is depolymerized to styrene and used to manufacture new products. In cooperation with Lucite, research is conducted for a process for a PMMA cycle.
40	GEN2WTE	USA	Pyrolysis	Unsorted plastic waste (no PVC)		Liquid HCs	5800		Technology was licenced by Gen Tech.
41	Braven	USA	Pyrolysis	Unsorted plastic waste		Liquid HCs	65 000		Braven announced its plans to build a large plant in the USA in 2021. Furthermore, in 2021, Braven announced an agreement with Chevron Phillips Chemical to supply the pyrolysis derived feedstock to CPChem for plastics production.
42	Green Enviro-Tech	USA	Pyrolysis	Tyres, unsorted plastic waste		Liquid HCs	35 000		

Table 3 (cont.): Active plastics pyrolysis technologies operating at demonstration/pilot or commercial scale (adapted from [38] and updated)

	Company	Country	Process	Raw material	Process temperature	Products	Capacity (tonnes/year)	Partner	Status/summary
43	Nexus Fuels	USA	Pyrolysis	HDPE, LDPE, PP, PS		Liquid HCs, waxes, paraffins	18 000	Shell	Nexus operates its own recycling plants.
44	Plastic Advanced Recycling Corporation (P.A.R.C)	USA / CN	Pyrolysis	Plastic waste, tyres, waste oil	500 °C	Liquid and gaseous HCs, coke	10 000		The plant engineering company developed a pyrolysis process and plant concept in China.
45	Plastic2Oil	USA	Catalytic pyrolysis	Unsorted plastic waste	350–450 °C	Liquid HCs	15 000		Conversion of plastic waste to fuel.
46	QCI (ReMining Corporation)	USA	Pyrolysis	Unsorted plastic waste		Liquid and gaseous HCs, coke	17 000		QCI processes plastic waste and waste tyres to fuel, solvents, and carbon black. An extension of the plant capacity to 100 000 tonnes/year was announced for 2021.
47	Resynergi	USA	Microwave-induced pyrolysis	PE, PP, PS	650–700 °C	Liquid and gaseous HCs, coke	3500	University of Minnesota	This start-up company implements microwave-induced pyrolysis plants in 20-foot containers. According to the producer, the cost of a 20-foot container plant is 350 000 USD; a 40-foot container plant costs 2 Mn USD.
48	RES Polyflow (BrightMark)	USA	Pyrolysis	Unsorted plastic waste	420 - 815 °C	Liquid HCs, waxes, Paraffins	100 000	BP	A large plant will be built after operation of the first pilot plant. In this project, BP acts as a customer.
49	Renewology	USA	Pyrolysis	Unsorted plastic waste	400–550 °C	Liquid HCs	3500		The capacity refers to a demonstration plant in Salt Lake City which shut down in 2020/2021; a larger plant will be built in Phoenix.
50	Vadxx/Alterra Energy	USA	Pyrolysis	Unsorted plastic waste	300–600 °C	Diesel, naphtha, syngas	25 000	Neste	A continuous pyrolysis process was developed by Vadxx, which is now part of von Alterra Energy.
51	Green Mantra	CAN	Thermocatalytic depolymerization	PE, PP, PS	300–600 °C	Waxes, polymers, additives	1100	Sun Chemical, INEOS	Pyrolysis products are used as high-value additives. Additional polystyrene from waste is completely recycled.
52	New Hope Energy	USA	Pyrolysis	PE, PP, PS		Liquid HCs	50 000	Lummus Technology	New Hope Energy operates its own pyrolysis plant in Trinity Oaks Tyler. In 2021 agreement was signed with Chevron Phillips Chemical to provide pyrolysis oil. The plant will be expanded to accommodate partnership for pyrolysis oil supply to Dow. In 2022 New Hope Energy entered a commercial agreement with Total Energies to build a new plant with a capacity of 310 000 tonnes/year by 2025. Total Energies will use 100 000 tonnes/year for polymer production.

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Table 3: Active plastics pyrolysis technologies operating at demonstration/pilot or commercial scale (adapted from [38] and updated)

	Company	Country	Process	Raw material	Process temperature	Products	Capacity (tonnes/year)	Partner	Status/summary
53	Adherent Technologies	USA	Vacuum pyrolysis Pyrolysis, solvolysis	PE, PP, PS, epoxy	300–600 °C	Liquid and gaseous HCs			A pilot plant was built based on the technology developed by Adherent. The focus was placed on recycling polymer fibers by Adherent Technology.
54	Pyrowave	CAN	Microwave-induced catalytic pyrolysis	PS	300–400 °C	Styrene		INEOS Styrsolution America LLC	The technology developer delivers microwave reactors for pyrolysis plants. Pilot plant has been built in Beauharnois-Salaberry CRM, Canada.
55	Encina Technologies	USA	Catalytic Pyrolysis	Mixed plastic waste	300–400 °C	Liquid HCs	160 000	Braskem	The technology developer plans to build a pyrolysis plant in 2023 to produce recycled PP from Braskem. Initial capacity to be 175 000 tonnes/year with possible future expansion to 450 000 tonnes/year
56	BP	DE	Pyrolysis	Unsorted plastic waste		Liquid HCs		SABIC	BP and Sabic signed an agreement with the objective to cooperate in the field of the circular economy. BP will deliver ethylene produced from pyrolysis oil to SABIC as raw material for products from the TRUCIRCLE™ portfolio.

3. Plastic Waste Pyrolysis Products and Their Processing

As was introduced in the section 2, the products of the plastics pyrolysis require to be characterized, in order to determine compatibility with the existing refining/petrochemical processes.

For such purposes, four basic characterization categories can be distinguished.

a) Physico-chemical properties
b) Chemical composition (main hydrocarbon components and groups)
c) Chemical composition – heteroatoms
d) Chemical composition – trace contaminants

Physico-chemical properties translate into material transportation, blending and separation characteristics to be accommodated by the hydraulic design of the plant. Moreover, storage and safety characteristics are also included in this group.

Main hydrocarbon and group composition provides information for heat and mass balancing and yield modelling for selection of downstream processing path. Further treatment needs of specific hydrocarbon groups (typically aromatics, olefins) can be also identified based on this data.

Heteroatom and trace contaminant content mainly determines a need for further upgrading, in order to avoid fouling, excessive corrosion of equipment and poisoning of catalysts in downstream units. Additionally, removal of contaminants is important to comply with the end-product specifications.

An example of compositions and properties of mixed plastic waste pyrolysis gas and oil are summarized in Table 4 and Table 5 adapted from [21,45]. Parameter range is driven by plastic waste composition, selected pyrolysis method and process conditions, which can be tuned towards a desired product composition. Comprehensive summaries of various compositions and experimental conditions are provided by [2,33].

Hydrocarbon group yields in liquid products of various plastic waste type pyrolysis in fixed bed batch reactor at 700 °C have been summarized by Kusenberg [42], refer to Figure 4. Similarly, in order to address variability in the mixed-waste plastic feedstock composition and its impact on the intermediate product composition, a further sensitivity study of the composition data is required.

Pyrolysis gas contains high content of light C_2 – C_4 olefins, which are desirable for separation and directing towards polymer production. Treatment of CO and CO_2 is required, in order to achieve C_2, C_3 polymer grade purity. The light olefin content is the highest for PE/PP waste and reduces with aromatic polymer addition such as PET or PS.

Depending on the pyrolysis temperature, the gas yields can reach > 70 wt. % [21]. Nonetheless, the author has observed that most of the attention is given to the liquid products in the research literature in the context of downstream processing.

Table 4: An example of mixed plastic waste (PE/PP 57%, PS 19%, PVC 13.7%, Inorganic 5.5 %) pyrolysis gas composition at reaction temperatures from 680 °C to 790 °C (adapted from [45])

Product Gas Components (wt%)	Temperature (°C)		
	680	735	790
Hydrogen	0.7	0.7	1.9
Carbon monoxide	8.4	14.2	6.3
Carbon dioxide	20.4	20.8	3.4
Methane	16.7	22.7	46.5
Ethene	18.4	20.7	26.0
Ethane	10.1	7.2	7.8
Propene	13.8	7.8	3.3
Propane	1.7	0.5	0.2
Butenes	4.6	1.5	0.4
Buta-1,3-diene	1.9	1.6	1.2
Penta-1,3-diene	0.1	0.0	0.0
Pent-1-ene	0.6	0.1	0.0
Cyclopentadiene	0.6	0.5	0.3
Isoprene	0.3	0.2	0.0
Hex-1-ene	0.1	0.0	0.0

Table 5: An example of mixed plastic waste (HD/LDPE 40%, EPC 10%, PP 38%, PS 10%, PA 6.6%, PVC 1%) pyrolysis liquid product composition and properties at reaction temperatures from 500 °C to 550 °C (adapted from [21])

Product	Naphtha	Diesel	Light Paraffinic Oil
Aliphatic olefins (wt%)	37.1-37.9	44.2-45.3	40.6-41.9
Paraffins (wt%)	42.5-44.3	54.7-54.9	58.1-59.4
Aromatics (wt%)	17.8-20.4	0-1	NR
Benzene	0.8-0.9	0-0.1	
Toluene	0.3-0.9	0.1	
Ethylbenzene	2.1-2.7	0.2-0.3	
Styrene	12.2-14.5	0.1-0.3	
Xylenes	0.5-0.8	0-0.2	
Other	1-1.5	0.1-0.2	
M (g/mol)	118-121	242-248	NR
Density (g/cm^3)	0.753-0.759	0.781-0.793	0.818-828
Viscosity (mm^2/s, at 40 °C)	NR	4.3-4.4	NR
C/H	6	6.1-6.2	6.1-6.2
Flash point (°C)	NR	94-98	216-219
Pour point (°C)	(-49)-(-47)	(-13)-(−9)	61-68

NR - not reported

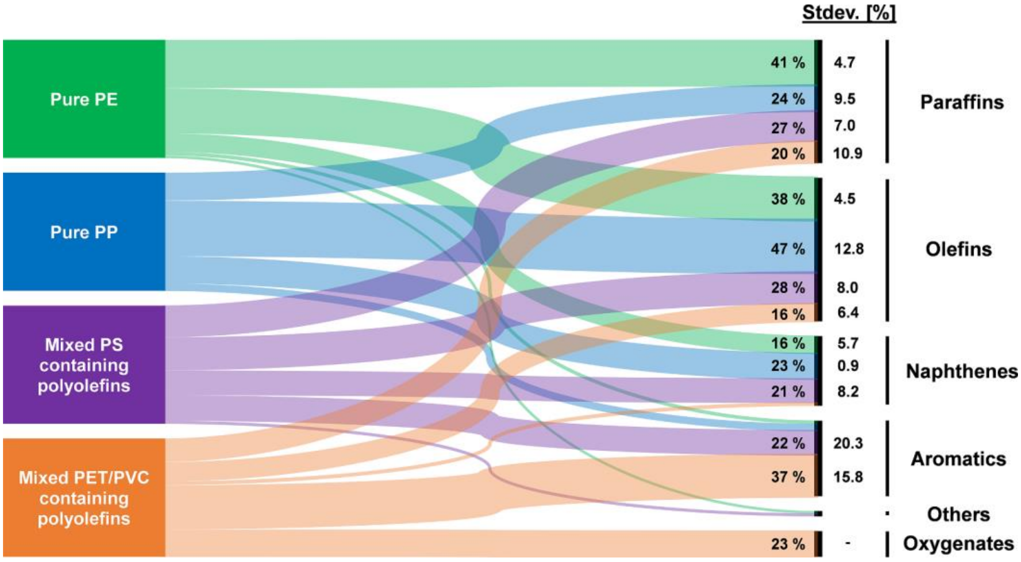

Figure 4: Hydrocarbon group distribution in liquid products of pyrolysis of various plastic feedstocks in fixed bed batch reactor at 700 °C (source [42])

The author puts emphasis on the fact that the high olefin content in the pyrolysis gas is an attractive source of C_2 – C_4 olefins, that (unlike the pyrolysis oil) do not need to be cracked again in the refinery/petrochemical plant, reducing the associated monomer production cost. Therefore, a closer analysis on scenarios for pyrolysis gas valorisation schemes is required, in order to describe the potential benefits more specifically.

Pyrolysis oil contains C_{5+} aliphatic hydrocarbons, olefins and aromatics. The groups are represented based on source plastic waste composition and pyrolysis conditions [40,46-48]. Pyrolysis oils are thermodynamically unstable and tend to polymerize and oxidize to form gums, sediments and agglomerations of asphaltenes [47].

The main advantage of products of plastics pyrolysis is generally low or no sulphur content. On the other hand, high content of other heteroatoms (O, N, Cl) and metals presents a main challenge for refining and petrochemical unit compatibility, because these components are present is much higher concentrations compared to the conventional refinery/petrochemical unit feedstocks, as shown in Table 6. Detailed inorganic contaminant review was presented in literature [42,47,49].

Table 6: Comparison of composition and contaminants in Plastic Pyrolysis Oil and in conventional refinery and steam cracker feedstocks (adapted from [47])

Elements	Plastic Pyrolysis Oil (PPO) [15]	Vacuum Gas Oil (VGO) [31]	Light Cycle Oil (LCO) [32]	Steam Cracker Feedstock (Naphtha)
		Hydrocarbons(wt%)		
Paraffins	19.8	8.49	22.3	41.7
Olefins	59.5	-	-	-
Naphthenes	7.1	29.16	15.9	46.2
Aromatics	13.6	62.34	61.8	12.1
		Contaminants (wt%)		
S	0.0046	1.17	0.1771	0.5
N	0.1143	0.23	0.1375	Light feedstock: 0.01 Heavy feedstock: 0.2
O	<0.1	NR	NR	0.1
		Other Contaminants (ppm)		
Cl	474	NR	NR	3
Si	28	NR	NR	1
Na	82	NR	NR	0.025

NR - Not reported

The major source of the inorganic contaminants are additives included in the formulation of various plastics grades. The contribution of the contaminants comes from the original formulation of the plastics as well as from the cross contamination during their lifecycle and waste handling. Hahladakis [49] reviewed the additives used in plastics formulation and their faith through the lifetime of the material. By examining recycled postconsumer LDPE, HDPE waste over 1000 chemicals were identified. Further insight into the characteristics and lifecycle of the additives in the plastic waste will help set more appropriate analytical schedules and methods for pyrolysis product contamination testing. Subsequently, such analytical results of pyrolysis products can be used to appropriately address the contamination in treatment path design of the pyrolysis products [50].

Fuels production applications of the pyrolysis oils were extensively studied by [21,32,33,35]. Possibilities to process the pyrolysis oils by hydroprocessing, FCC and delayed coking were discussed. Due to the low oxidation stability and high contamination, the pyrolysis oil require pre-treatment prior to further processing. High heteroatom and metal content may contribute to quick deactivation of the FCC and hydroprocessing catalysts. Furthermore, high olefin and aromatic content accelerates coking in FCC and heat balance between the reactor and regenerator needs to be revisited before pyrolysis oil is processed. Several authors have reported that co-processing of the pyrolysis oils in the mentioned refinery units didn't show any impact up to 5 wt % of pyrolysis oil in a conventional feedstock [21]. Petrochemical application for steam cracking has been recently reviewed by [42,43,47]. Unlike refinery unit, steam crackers are more sensitive to trace contaminants and dilution ratios of pyrolysis oil and conventional feedstock during co-processing were reported to theoretically reach 1/12-17 as minimum.

Kaminsky studied suitable process conditions for production of aromatic hydrocarbons (BTXSEb) [40]. The pyrolysis solid carbon residue – char – concentrates most of the inorganic contaminants and heteroatoms from the feed mixed plastic waste. In case of virgin low-contaminated polymers, char can be used for production of e.g. adsorbents, carbon tubes, etc. [47]. In case of mixed-plastic waste, the char can be used in a cement blast furnace. Alternatively, the chars can be treated by organic solvent extraction and acid demineralization to remove the inorganic metal contaminants and recover trapped pyrolysis oil. High efficiency in the oil extraction (up to 81%) and high efficiency of demineralization by HCl (86%) was reported by Belbessai [47].

4. Chemical Recycling of Plastics – published data on economics and LCA

4.1. Business Studies

In order to process and valorise waste plastics pyrolysis products in the refinery and petrochemical units, several technical challenges related to their composition and contamination need to be addressed, as discussed in Section 2. As an extension of the technological scenarios, an appropriate assessment is required for economics and environmental aspects, such that investors and industrial operators are able to select the most sensible and feasible pathways.

An integrated economic model was published by McKinsey [51] for mechanical recycling recovery and reuse of plastic waste that gets otherwise landfilled or incinerated. The study identified over 1000 combinations of plastic type, application, global geographies and recovery/reuse routes. The model identified 20% of cases with potential return on invested capital > 15% assuming oil price of 60$ per barrel. The model utilized an assumption of a single owner value-chain and didn't consider any feedstock recycling yet, since it considered state-of-play as of 2018. To address both of these assumptions, technological data about feedstock recycling need to be made available and specific regional owner structures to be defined as the market develops.

In another associated study, McKinsey [52] mapped a global plastics waste generation and developed projections of recovery rates by 2030 and 2050. As a conclusion the study showed that mechanical recycling has an expansion potential by 2030 at oil prices of 75$ per barrel, whereas below 65$ per barrel the economics becomes challenging. On the other hand, under a high adoption scenario, pyrolysis of waste plastics integrated with a steam cracker was reported as more resilient to oil prices as low as 50$ per barrel.

BCG [53] have conducted a comprehensive analysis of the global waste markets and business environment of plastics recycling with aim to assess business cases for mechanical recycling and viability of plastic waste pyrolysis. Despite regional differences, the overall reported conclusion was that plastic waste pyrolysis is viable globally. Nonetheless, economic feasibility is some regions relies on regulations to make landfilling less financially attractive.

4.2. Life-cycle assessment studies

The plastic waste feedstock recycling is often positioned as replacement for landfilling and incineration, and complementary method to mechanical recycling. The role of life cycle assessment (LCA) in this domain is to account the environmental impacts of the chemical recycling scenarios, and verify the benefits compared to landfilling and/or incineration waste management methods [54].

Costa [55] has performed a critical review of 18 LCA studies on the subject of the plastics chemical recycling. It was highlighted, that despite having commercial units in operation (refer also to Table 1), most scientific studies are conducted based on laboratory scale reactors with simplified models excluding detailed engineering parameters of the technology (heat/mass transfer limitations, feed contamination treatment, auxiliary material streams, etc.). Furthermore, the modelling results in most of the reviewed studies compare plastic waste chemical recycling only to landfilling and incineration. It is suggested, that mechanical recycling and alternative scenarios of chemical recycling are included in the comparison to provide granular and relevant comparison. The aim of the observations is to (rightfully) avoid biased conclusions in either direction.

With reference to Figure 2, EU is identified as a region with highly developed incentives and waste collection infrastructure. Despite LCA studies for other global regions are also published [56,57], the author focuses below on specific selected studies published for EU region.

Oasmaa [58] presented a study based on a bench-scale testing of plastic waste pyrolysis. The conclusions confirmed positive environmental impact compared to business-as-usual in Finland. Further benefits could be obtained by coupling the pyrolysis with mechanical recycling of plastic waste, where only the reject for plastics waste recycling would be sent for pyrolysis. Business feasibility, however, wasn’t presented in the study.

Volk [59] studied recycling of lightweight packaging in Germany. Mechanical recycling, chemical recycling (pyrolysis) and their combinations were assessed. Products of the pyrolysis were considered for steam cracking to produce virgin plastics. Pre-treatment of pyrolysis products was considered, but details of the steam cracking plant integration were not discussed. The combined mechanical-chemical recycling scenario was confirmed to have the highest saving in global warming potential (GWP) indicator.

Somoza-Tornos [60] conducted an LCA study based on process simulation of a theoretical waste PE pyrolysis process. The results were compared to business-as-usual scenario of naphtha steam cracking. Despite showing lower production cost and environmental impact of the ethylene produced from PE compared to naphtha cracking, it was acknowledged that PE feed and product treatment as well as more detailed pyrolysis modelling are required.

Ambrieres [31] has reviewed the global status of plastics recycling and confirmed that at the state-of-the-art plastics recycling is always the most environmentally friendly. However, in case waste incinerators become more efficient in energy recovery, in the short-term horizon, incineration may be environmentally the most suitable option in regions with coal-based energy mix (e.g. China and parts of Europe) based on GHG analysis presented in the study.

Gutierrez [29] under European Commission Joint Research Center published an environmental and economic assessment for plastic waste recycling. Mechanical, chemical recycling and incineration were compared based on feedback received through a survey among European industrial stakeholders. In the conclusions it was highlighted that economic feasibility of the recycling generally depends on oil price, that translates into virgin polymer price. Mixed polyolefin waste pyrolysis was identified as not viable without further public support. A hypothetical viability scenario is identified when sum of CAPEX and OPEX is below 350 EUR/t and feedstock prices are at ca 100 EUR/t. Future scale-up, higher adoption and technology maturity are expected to improve the economic viability of the technology.

5. Conclusions

Thermochemical recycling of plastic waste has been reviewed from the historical perspective as technology under development since 1970s aiming to convert mixed post-consumer plastic waste back to virgin polymers. The conversion can be achieved either by direct co-processing of the mechanically pre-treated plastic waste with conventional refinery/petrochemical feedstocks, or by thermally pre-processing the plastic waste into gas/oil and solid residue.

Pyrolysis gas is attractive for high C_2 – C_4 olefins content, which can be sent to a refinery or steam cracker separation section to recover the monomers without a need for additional cracking. Pyrolysis oils are suitable for a number of applications. Depending on their ratio of aliphatic/aromatic/olefinic compounds, aromatic components (BTXSEb) can be separated. Alternatively, fractions with high aliphatic content may be routed towards FCC or steam cracking. Treatment of olefinic and aromatic content, and removal of contaminants is the first step to be designed with respect to process and mechanical demands of the downstream refinery or petrochemical plant. With advances in analytical technology, pyrolysis products can be comprehensively characterized. This is pointed out as a key factor to correctly identify appropriate steps in the processing pathway.

A number of sites at various scales are operational mostly in EU, USA, Japan and China with a momentum for further development driven by circular economy and GHG regulation. In order to facilitate logistics across the plastics value chains, several new joint ventures and partnerships between waste management companies and traditional refinery/petrochemical operators have emerged. With exception of EU, other regions many times don’t have plastic waste collection and sorting systems at scale. Therefore, setting-up the collection and sorting logistics presents an additional step for implementation of the plastics pyrolysis in such regions. This demonstrates, that waste management and petrochemical/refining businesses need to closely integrate, in order to support economic feasibility of waste plastics chemical recycling.

Reviewed business and life cycle assessment studies suggest, that despite showing potential for GHG saving, waste plastic pyrolysis processes are not yet economically self-sustainable, and require external funding e.g. in form of public support, gating fees, or extended producer responsibility schemes (EPR). It has been found from the literature review, that further improvements of the economic feasibility may be expected with increased scale of the operations. Moreover, local energy mix, oil price and landfilling cost are important sensitivity factors.

Currently, the recycled quantities of plastic waste account for < 0.8 % of the global oil demand. Therefore, thermochemical recycling of plastic waste still contributes more towards waste management rather than as major feedstock resource. Due to the low produced volumes, the pyrolysis products are mostly aimed to be co-processed with conventional feedstocks in existing refineries/petrochemical plants. However, a gap still exists in form of landfilled volumes, that present an opportunity of growth for the chemical recycling together with globally increasing plastics demand and corresponding waste generation. It has been noticed, that researchers mostly use only simple technological flow schemes for the economic studies without considering more detailed energy and material integration of the plastic pyrolysis stream. Therefore, the author of this paper identifies an opportunity for further research in developing a more detailed processing model under a number of defined scenarios. Subsequent heat and mass balance with a detailed model would then yield economic assessment and GHG evaluation results as more realistic. Performing a regionally specific techno-economic analysis of plastic waste thermochemical recycling will enable to define solutions reflecting specific market conditions, energy mix, oil price and waste collection schemes.

Nomenclature

ABS	Acrylonitrile-butadiene-styrene
ASR	Automotive shredder residue
BTXSEb	Benzene, toluene, xylenes, styrene, ethylbenzene
CAPEX	Capital expenses
EPC	Ethylene-propylene copolymer, in Table 4
EPC	Engineering, procurement, construction, in Section 2
EPR	Extended producer's responsibility
FCC	Fluid catalytic cracking
FCC	FCC Environmental Services, in Section 2
GHG	Greenhouse gases
GWP	Global warming potential
HDPE	High density polyethylene
HVGO	Hydrogenated vacuum gasoil
LCA	Life cycle assessment
LCO	Light cycle oil
LDPE	Low density polyethylene
NGL	Natural gas liquids
OPEX	Operating expenses
PA	Polyacrylate
PE	Polyethylene
PET	Polyethylene terephthalate
PMMA	Polymethyl methacrylate
PPO	Plastic pyrolysis oil
PS	Polystyrene
PVC	Polyvinylchloride
VGO	Vacuum gasoil
WEEE	Waste from electrical and electronic equipment

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