2015 PLASTICS-TO-FUEL PROJECT DEVELOPER'S GUIDE

Prepared For: The American Chemistry Council

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About OCEAN RECOVERY ALLIANCE: OCEAN RECOVERY ALLIANCE (ORA) and the American Chemistry Council are working together to reduce plastic in the ocean environment. ORA is a 501c3 registered non-profit in California and a registered charitable organization in Hong Kong that seeks to introduce innovative projects and initiatives that will help improve our ocean environment by bringing together new ways of thinking, technologies, creativity and collaborations. ORA strives to lead a variety of stakeholders, leveraging each of their qualities and institutional capacities when needed, while combining forces with the business and technology sectors in ways that have not been done before. The group has two projects at the Clinton Global Initiative related to plastic waste reduction on a global scale, and is one of the first NGOs in the world to be working with both the United Nations Environment Programme (UNEP) and the World Bank on their respective ocean programs related to waste reduction.

At ORA, we also believe that the marine litter issue will not be solved through bans, taxes and legislation alone. Instead, we believe that market-based solutions, and especially those which create conditions where plastic waste can be used as a resource, play a significant role in reducing marine litter, plastic pollution and waste management burdens on communities. In particular, plastics-to-fuel is one such technology with enormous potential for certain plastics that are not recycled because the technologies and/or infrastructure for proper recycling or value-added processing do not exist.

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TERMINOLOGY

Term	Definition	Source
ASTM D975	ASTM International Standard specification for diesel fuel oils that covers seven grades suitable for various types of diesel engines including: Grade No. 1-D S15; Grade No. 1-D S500; Grade No. 1-D S5000; Grade No. 2-D S15; Grade No. 2-D S500; Grade No. 2-D S5000; and Grade No. 4-D.	ASTM International
ASTM D396	ASTM International Standard specification for fuel oils including: Grades No. 1 S5000, No. 1 S500, No. 2 S5000, and No. 2 S500 for use in domestic and small industrial burners; grades No. 1 S5000 and No. 1 S500 adapted to vaporizing type burners or where storage conditions require low pour point fuel; Grades No. 4 (Light) and No. 4 (Heavy) for use in commercial/industrial burners; and Grades No. 5 (Light), No. 5 (Heavy), and No. 6 for use in industrial burners.	ASTM International
Blendstock	Any hydrocarbon fuel that is blended to produce a petroleum product such as gasoline or diesel.	
Catalyst	A substance that increases the rate of a chemical reaction.	
Crude Oil	A mixture of hydrocarbons that exists in liquid phase in natural underground reservoirs and remains liquid at atmospheric pressure after passing through surface separating facilities. Depending upon the characteristics of the crude stream, it may also include 1. Small amounts of hydrocarbons that exist in gaseous phase in natural underground reservoirs but are liquid at atmospheric pressure after being recovered from oil well (casing head) gas in lease separators and are subsequently comingled with the crude stream without being separately measured. Lease condensate recovered as a liquid from natural gas wells in lease or field separation facilities and later mixed into the crude stream is also included; 2. Small amounts of non-hydrocarbons produced with the oil, such as sulfur and various metals; 3. Drip gases, and liquid hydrocarbons produced from tar sands, oil sands, gilsonite, and oil shale.	US Energy Information Association
Synthetic Crude Oil	A hydrocarbon rich unrefined petroleum product with properties similar to crude oils derived from fossil fuels, produced from alternative processes such as pyrolysis.	
Light Sweet Crude Oil	A naturally occurring, hydro-carbon rich unrefined petroleum product that can be refined to produce usable products such as gasoline, diesel and various forms of petrochemicals. Light sweet crude oil contains smaller amounts of hydrogen sulfide and carbon dioxide than other crude oils.	
Feedstock	Any waste polymer processed by a PTF system.	
Feedstock Supplier	Any entity that provides feedstock to a PTF system for processing. Can include but is not limited to: industry, municipality, waste hauler, or recycler.	
Fractional Distillation	The separation of different fractions of crude oil by heating liquid to different boiling points.	
Distillate Fuel Oils	A general classification for one of the petroleum fractions produced in conventional distillation operations. It includes diesel fuels and fuel oils. Products known as No. 1, No. 2, and No. 4 diesel fuel are used in on-highway diesel engines, such as those in	Rick Wallace, Dept. of Energy

	trucks and automobiles, as well as off-highway engines, such as those in railroad locomotives and agricultural machinery. Products known as No. 1, No. 2, and No. 4 fuel oils are used primarily for space heating and electric power generation.	
Gasoline	A refined petroleum product from lighter distillates, which has highly flammable and evaporative properties. Gasoline is used primarily for combustion in internal combustion engines.	
No. 2 Distillate Fuel	A petroleum distillate that can be used as either a diesel fuel (see No. 2 Diesel Fuel) or a fuel oil (see No. 2 Fuel Oil).	US Energy Information Association
No. 2 Diesel Fuel	A fuel that has distillation temperatures of 500 degrees Fahrenheit at the 10-percent recovery point and 640 degrees Fahrenheit at the 90-percent recovery point and meets the specifications defined in ASTM Specification D 975. It is used in high-speed diesel engines that are generally operated under uniform speed and load conditions, such as those in railroad locomotives, trucks, and automobiles.	Rick Wallace, Dept. of Energy
No. 2 Diesel Fuel, High Sulfur	No. 2 diesel fuel that has a sulfur level above 500 ppm.	Rick Wallace, Dept. of Energy
No. 2 Diesel Fuel, Low Sulfur	No. 2 diesel fuel that has a sulfur level between 15 ppm and 500 ppm (inclusive). It is used primarily in motor vehicle diesel engines for on-highway use.	Rick Wallace, Dept. of Energy
No. 2 Diesel Fuel, Ultra Low Sulfur Diesel (ULSD)	No. 2 diesel fuel that has a sulfur level below 15 ppm. Used primarily in motor vehicle diesel engines for on-highway use.	Rick Wallace, Dept. of Energy
No. 2 Fuel Oil (Heating Oil)	A distillate fuel oil for use in atomizing type burners for domestic heating or for use medium capacity commercial-industrial burner units, with distillation temperatures between 540-640 degrees Fahrenheit at the 90-percent recovery point; and the kinematic viscosities between 1.9-3.4 centistokes at 100 degrees Fahrenheit as defined in ASTM Specification D396-92.	US Energy Information Association
Residual Fuel Oils (No 5 Fuel Oil and No 6 Fuel Oil)	A general classification for the heavier oils, known as No. 5 and No. 6 fuel oils, that remain after the distillate fuel oils and lighter hydrocarbons are distilled away in refinery operations. It conforms to ASTM Specifications D396 and D975 and Federal Specification VV-F-815C. No. 5, a residual fuel oil of medium viscosity, is also known as Navy Special and is defined in Military Specification MIL-F-859E, including Amendment 2 (NATO Symbol F-770). It is used in steam-powered vessels in government service and inshore power plants. No. 6 fuel oil includes Bunker C fuel oil and is used for the production of electric power, space heating, vessel bunkering, and various industrial purposes.	US Energy Information Association
Kerosene	A light petroleum distillate that is used in space heaters, cook stoves, and water heaters and is suitable for use as a light source when burned in wick-fed lamps. Kerosene has a maximum distillation temperature of 400 degrees Fahrenheit at the 10-percent recovery point, a final boiling point of 572 degrees Fahrenheit, and a minimum flash point of 100 degrees Fahrenheit. Included are No. 1-K and No. 2-K, the two grades recognized by ASTM Specification D 3699 as well as all other grades of kerosene called range or stove oil, which have properties similar to those of No. 1 fuel oil.	US Energy Information Association
Materials Recovery Facility (MRF)	A solid waste management facility that provides for the extraction from solid waste of recyclable materials, materials suitable for use	Solid Waste Association of North

	as a fuel or soil amendment, or any combination of such materials.	America
Marine Litter	Any persistent solid material that is manufactured or processed and directly or indirectly, intentionally or unintentionally, disposed of or abandoned into the marine environment	National Oceanic and Atmospheric Administration
Plastic Film	Plastic items with a thickness of less than 10 mils (i.e., 0.010" or 0.25 mm). Plastic films can be comprised of HDPE, LDPE, PP, PVC, LLDPE and Nylon.	Headley Pratt Consulting for the American Chemistry Council
Middle Distillates	A general classification of refined petroleum products that includes distillate fuel oil and kerosene.	US Energy Information Association
Naphtha	Refined or partly refined light distillates with an approximate boiling point range between 122 and 400 degrees Fahrenheit. Blended further or mixed with other materials, they make high-grade motor gasoline or jet fuel. Also, used as solvents, petrochemical feedstocks, or as raw materials for the production of town gas.	US Energy Information Association
Non-Bottle Rigid Plastics	Non-bottle rigid plastics include non-bottle containers (such as thermoform packaging, cups, trays, clamshells, food tubs), and all bulky rigid plastic (such as carts, crates, buckets, baskets, toys, lawn furniture).	2012 National Post-consumer Non-Bottle Rigid Plastic Recycling Report
Offtake Partner	An entity that enters into a binding agreement to purchase petroleum or other secondary end products produced from a PTF system.	
PET	PET (Polyethylene terephthalate) is typically labeled plastic code #1 on the bottom of the container. PET is often used for soft drink and disposable water bottles, but can also include other containers or packaging.	Franklin Associates, American Chemistry Council
HDPE	HDPE (High-density polyethylene) is usually labeled plastic code #2 on the bottom of the container, and refers to a plastic often used to make bottles for milk, juice, water and laundry products. It is also used to make plastic grocery bags.	Franklin Associates, American Chemistry Council
LDPE	LDPE (Low-density polyethylene), usually labeled plastic code #4, is often used to manufacture plastic dry cleaning bags. LDPE is also used to manufacture some flexible lids and bottles.	Franklin Associates, American Chemistry Council
LLDPE	LLDPE (Linear low-density polyethylene) is used in high-strength film applications. Compared to LDPE, LLDPE's chemical structure contains branches that are much straighter and closely aligned, providing it with a higher tensile strength and making it more resistant to puncturing or shearing.	Franklin Associates, American Chemistry Council
PP	PP (Polypropylene) is used in packaging, automotive parts, or made into synthetic fibers. It can be extruded for use in pipe, conduit, wire, and cable applications. PP's advantages are a high impact strength, high softening point, low density, and resistance to scratching and stress cracking. A drawback is its brittleness at low temperatures	Franklin Associates, American Chemistry Council
PS	PS (Polystyrene) has applications in a range of products, primarily domestic appliances, construction, electronics, toys, and food packaging such as containers, produce baskets, and fast food containers.	Franklin Associates, American Chemistry Council
PVC	PVC (Polyvinyl Chloride) is produced as both rigid and flexible	Franklin Associates,

	resins. Rigid PVC is used for pipe, conduit, and roofing tiles, whereas flexible PVC has applications in wire and cable coating, flooring, coated fabrics, and shower curtains.	American Chemistry Council
Post-consumer Plastics	A material or finished product that has served its intended use and has been diverted or recovered from waste destined for disposal, having completed its life as a consumer item by an individual or business.	US EPA via, Moore Recycling Associates.
Post Industrial Plastics	Materials generated in manufacturing and converting processes, such as manufacturing scrap and trimmings/cuttings.	US EPA via Moore Recycling Associates
Rigid Plastics	Plastic that is formed or molded and maintains its shape when empty and unsupported.	
Wax	A byproduct of the petroleum refining process usually consisting of a variety of light and intermediate hydrocarbons (paraffins, aromatics, naphthenics).	
Syngas	A byproduct of the pyrolysis process comprising a fuel gas mixture consisting primarily of hydrogen, carbon monoxide, and sometimes trace amounts of carbon dioxide.	
Char	A byproduct of the pyrolysis process comprising of a solid residue of matter that is cannot be converted to syngas.	

A. INTRODUCTION

Plastics are an essential material for modern existence. Plastics make up many of the everyday products we use, as well as the packaging that encloses a vast variety of products. As economies continue to expand, the production and consumption of plastics has increased to meet the needs of growing markets. Global plastics production is an estimated 300 million metric tons each year and is growing at a rate of 4% annually.[1] With plastic production increasing, plastic waste generation is also on the rise. The World Bank projects that 1.3 billion metric tons of MSW is generated each year, a number that is expected to grow to 2.2 billion metric tons per year (MTPY) by 2025. 10% of the total MSW produced, or 130 Million MTPY, is plastic.[2]

Waste management is one of the world's greatest environmental challenges. An estimated 4.8 to 12.7 metric tons of plastic litter enter the ocean every year[3] and despite global initiatives to reduce it, volumes of marine litter continue to increase as the world's consuming population grows.[4] Largely rooted in inadequate waste management practices on land, an estimated 80% of marine litter originates from land-based sources. Experts believe that the largest generators are urban, industrial and recreational activities adjacent to coastal and riparian zones[5] in middle-income countries that have transitioned to a disposable economy but have not yet developed the waste collection and treatment infrastructure for proper management.[6] These weak systems can reduce to a number of environmental impacts, one of which is water pollution.

Managing plastic marine litter is challenging. Once plastics enter the ocean, its sources and impacts are trans-boundary by nature, making it difficult to assign jurisdictional responsibility for mitigation and clean up. Existing global regulatory frameworks focus almost exclusively on maritime issues after plastics have already become marine litter, rather than on litter prevention and upstream interventions. Complicating matters, marine litter is seldom recognized in solid waste management policy and regulations, leading to debates over whether it falls under the realm of national solid waste, water, storm water, wastewater or marine authorities. Municipal and national solid waste management strategies that improve waste collection and management systems offer the best opportunity for reducing marine litter loading rates.

Over the past few years, plastics-to-fuel (PTF) technologies have emerged as one potential solution to reducing plastic marine litter and the landfilling of end-of-life plastics.[7] PTF is an advanced waste conversion technology that is considered complementary to existing recycling efforts as it typically does

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[1] Global plastics production was estimated at 288 million metric tons in 2012. Source: http://www.plasticseurope.org/documents/document/20131014095824-final_plastics_the_facts_2013_published_october2013.pdf

[2] The World Bank, "What a Waste: A Global Review of Solid Waste Management," March 2012, http://documents.worldbank.org/curated/en/2012/03/16537275/waste-global-review-solid-waste-management

[3] Jambeck, Jenna et al., "Plastic Waste Inputs from Land into the Ocean," Science 13 February 2015: Vol. 347 no. 6223 pp. 768-771, http://www.sciencemag.org/content/347/6223/768, Accessed February 20, 2015.

[4] United Nations Environment Programme

[5] Greenpeace. "Plastic Debris in the World's Oceans." 2002, http://www.greenpeace.org/austria/Global/austria/dokumente/Studien/meere_Plastic_Debris_Study_2006.pdf

[6] Armitage, N. (2007) 'The reduction of urban litter in the storm water drains of South Africa', Urban Water Journal, 4:3, 151 — 172

[7] End-of-life plastics are defined as plastics that would otherwise be disposed of in a landfill. They can originate from post-consumer or post-industrial sources and be made up of both rigid and film plastics

not target plastic resins that are highly valued by commodity recycling markets. Furthermore, since plastics have an energy value higher than coal,[8] the landfilling of end-of-life plastic waste constitutes a loss of an important energy resource.[9,10,] Not intended as a replacement to traditional recycling practices, but given the large percentage of plastic waste that bypass recycling programs for reasons such as lack of infrastructure, capacity, and technology, PTF is becoming a viable addition to a jurisdictions mix of MSW management strategies. By creating demand for end-of-life plastics, PTF technologies can not only help address this global challenge and mitigate the flow of plastic to the ocean, but can also create jobs and generate an alternative local fuel source that can serve as a substitute to fossil fuel derived crude oil. Through different configurations of pyrolysis technologies, the principal output of PTF technologies is a liquid petroleum product -- either a synthetic crude oil or refined fuels which can be used as home heating oil (fuel oil No. 2), a blendstock in the production of No. 2 diesel fuel, gasoline and kerosene, fuel for combined heat and power generation equipment and industrial purposes, and residual fuel oils for sale to heavy oil users. In many parts of the world, liquid petroleum products derived from plastics represent a lower-sulfur content product, yielding air quality benefits as well.

B. STUDY METHODOLOGY AND OBJECTIVES

Waste collectors, recyclers, investors and governments are becoming increasingly interested in the potential for integrating PTF technology into waste management strategies. While a body of marketing materials exists, there are a limited number of independent evaluations of available technologies and their proven ability to perform as stated.

OCEAN RECOVERY ALLIANCE conducted an 11-month study spanning from January – November 2014 (Study Period), during which time it:

- Identified PTF technology suppliers (Suppliers) as well as existing and planned PTF systems,
- Engaged in preliminary communications with Suppliers in order to pre-qualify them for additional evaluation on the basis that:
    - The technology offering include the pyrolysis of plastics to produce liquid petroleum products, and
    - The Supplier is making advancements towards commercialization. Suppliers in research and development (R&D) were excluded from further review.
- Conducted interviews with pre-qualified Suppliers, financing entities and Project Developers to:
    - Assess proven technological performance and system economics,
    - Identify industry challenges, opportunities and lessons learned, and
    - Identify financing opportunities and requirements for obtaining investment.

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[8] Themelis, NJ et al. "Energy And Economic Value Of Non-recycled Plastics (NRP) and Municipal Solid Wastes (MSW) That Are Currently Landfilled In the Fifty States," Columbia University, August 16, 2011. http://www.seas.columbia.edu/earth/wtert/sofos/ACC_Final_Report_August23_2011.pdf Accessed January 2015.
[9] "Toward the Circular Economy: Opportunities for the Consumer Goods Sector," Ellen MacArthur Foundation, 2013.
[10] Plastic film is a flexible material made from different types of resins: LLDPE, LDPE, HDPE, PP, PVC, and Nylon.[10] Examples of plastic film products include trash bags, plastic bags, sacks & wraps and lined paper bags and sacks. According to the Flexible Packaging Association (FPA), the estimated amount of flexible packaging waste (FPW) generated in the US is 5.8 million tons per year. Flexible packaging waste represents 2.4% or 1.5 % of the total Municipal Solid Waste generated in the US, according to the EPA.

- Conducted site visits to operating PTF systems that met the following criteria:
  - System must be operational,
  - Operating status must first be verified (by phone or in writing) by system owner/operator,
  - Technology in operation must represent the company's current commercial offering,
  - System has a design capacity greater than or equal to 1 short ton per day (TPD)[11],
  - System must be processing a minimum of 75% plastic feedstock. Suppliers and systems that exclusively or predominantly process tire or other waste were excluded from further review, and
  - System must be producing a liquid petroleum end product – synthetic crude oil or refined fuel/s. Suppliers and systems that exclusively produce wax or syngas were excluded from further review.

Supplemental Resources

ORA developed a supplemental PTF Cost Estimator in conjunction with this report to assist stakeholders in estimating the fully loaded cost per unit of liquid petroleum product produced. The tool is flexible, allowing users to input and vary project specific factors to increase their understanding of system economics and the impacts of cost drivers such as: capital costs, feedstock acquisition costs, liquid petroleum product yields and market pricing. The tool can be downloaded at http://www.oceanrecov.org/about/plastic-to-fuel-report.html or http://plastics.americanchemistry.com/Plastics-to-Fuel-Cost-Estimating-Tool.

This report and PTF Cost Estimator are intended as discussion tools for a variety of local and international stakeholders including: municipal and national governments, corporations, community leaders, business associations, NGOs, project developers, and others interested in the management of end-of-life plastic waste. They aim to inform stakeholders of the current state of the PTF marketplace and serve as instruments to help guide decision-makers in developing PTF systems. By highlighting the opportunities available for creating value from end-of-life plastics, in concert with the regulatory, technical and logistical barriers that need to be overcome on the path towards the widespread commercial adoption of PTF technology, this report can be used to promote knowledge- sharing and regulatory convergence to expedite project deployment.

C. ORGANIZATION

This report is comprised of data collected from a third-party review of existing operating systems, site visits to select facilities, interviews with PTF stakeholders and a comprehensive review of secondary data sources. Using information collected from operating systems and stakeholder interviews, the report summarizes criteria for decision-makers and Project Developers on developing PTF projects.

The report is structured in two parts –

[11] ORA prioritized PTF systems processing >=1 TPD due to their potential for greater scale and overall impact on the plastic waste stream.

Part One of this report characterizes developments in the PTF market to date. This includes:

- A summary of PTF technologies available,
- A comprehensive summary and assessment of Suppliers and existing PTF systems, and
- Successes and challenges of the PTF market to date.

Part Two of this report provides guidance for Project Developers interested in deploying a PTF system. This section outlines key components of developing a PTF system including:

- Determining Project Development Structure,
- Assessing Technical Viability,
- Assessing Financial Viability,
- Partnership Development,
- Mobilizing Project Finance,
- Siting and Permitting, and
- Risk Mitigation Strategies.

D. LIMITATIONS

Due to the nascence of the PTF market, primary sources, including, but not limited to independent engineering analyses and fuel assays, were deemed confidential and not shared with ORA although Suppliers indicated a willingness to share this information with prospective and/or active partners. As such, the existence of PTF systems was verified through personal communications with system owner/operators and/or Suppliers and the status of operating systems that met criteria outlined in Section B was verified by way of site visit, when feasible. Where ORA observed the processing of plastic feedstocks and the production of synthetic crude oil or refined fuels, it is noted. ORA did not conduct an independent analysis of feedstock composition, quality of synthetic crude oil or refined fuel products or whether planned or operating facilities are processing end-of-life plastics. This report is not intended to offer a comparative assessment of deploying PTF technology versus expanding plastics recycling infrastructure.

PART ONE: HISTORY AND CURRENT STATUS OF THE PLASTICS-TO-FUEL INDUSTRY

PTF technologies have the potential to address a unique set of environment and energy challenges. In the United States, plastics represented approximately 12.7% of the total MSW stream, or approximately 32 million tons in 2012.[12] Of the amount generated, only 8.8% was recovered – either through waste-to-energy or recycling -- leaving a significant missed opportunity to recoup value from end-of-life plastics. Growing foreign and domestic markets for high-density polyethylene (HDPE) and polyethylene terephthalate (PET) yield high recycling rates of 28.2% and 30.8%, respectively.[13] However, recycling rates for other non-bottle rigid plastics such as low-density polyethylene (LDPE), polypropylene (PP) and polystyrene (PS) are significantly lower due to sorting and separating challenges, while an estimated 12% of plastic films, including plastic bags, sacks and wraps were recycled in 2012.[14]

PTF technologies can address a critical fraction of the plastic waste stream that has been historically difficult to reutilize, such as LDPE, PP and PS, preventing littering and the landfill disposal of end-of-life plastics. When PTF technologies target end-of-life plastics that are not easily or economically absorbed in recycling markets, they are considered complementary to recycling and existing waste hierarchies. The development of PTF infrastructure can also:

- **Create green indirect and direct jobs,**
- **Divert end-of-life plastics from landfill disposal**, extending the lifespan of existing disposal sites and prolonging the siting and construction of new ones,
- **Create local demand for low-value plastics** that can find their way into streets, streams and the ocean,
- **Produce a local source of synthetic crude oil and/or refined fuels** to displace fossil fuel derived imports, and
- **Reduce air pollution in many parts of the world** by substituting low or ultra-low sulfur content fuels for high-sulfur content fuels.

1.1 HISTORY

[12] US short tons. United States Environmental Protection Agency, "Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2012", http://www.epa.gov/solidwaste/nonhaz/municipal/pubs/2012_msw_fs.pdf Accessed: December 2014.
[13] United States Environmental Protection Agency, "Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2012", http://www.epa.gov/solidwaste/nonhaz/municipal/pubs/2012_msw_fs.pdf Accessed: December 2014. Data is specific to: PET bottles and jars and HDPE Natural (White Translucent) Bottles.
[14] Ibid.

While pyrolysis technology has been used to generate energy from wood waste and coal for more than 30 years, the application of pyrolysis technology to plastics for oil generation is an innovation of the past decade. In the last industry assessment for the American Chemistry Council in 2011, there were 23 PTF companies identified and 11 associated systems.

According to the 2011 report, historical drivers to develop PTF systems included 1) constraints on land availability for future landfill development, 2) policy drivers for increased landfill diversion and materials recovery, and 3) a movement to increase value capture from waste stream materials. The 2011 report highlighted several key challenges, which were indicative of an emerging market. Namely, the challenges over the past few years have involved demonstrating the technical feasibility of PTF technologies and the marketability of end products as well as the creation of a policy environment that is conducive to the development of PTF systems. While these operational and policy challenges still remain to some extent, the past few years have witnessed marked progress in the development of the PTF industry.

ORA established contact with 13 of the 23 companies identified in 2011 and identified 25 new or previously unidentified players in the global marketplace. As with any emerging industry, several companies have succumbed to challenges and have ceased operations. In total, ORA contacted 38 Suppliers for pre-qualification – of the companies that were pre-qualified, 13 participated in the research for this report.

This assessment identified 35 PTF systems constructed at a pilot, demonstration or commercial scale. 3 systems met the ORA site visit criteria and were verified as being operational by way of site visit during the Study Period (See Section 1.5). One additional system owned and operated by MK Aromatics Limited in Tamil Nadu, India met the site visit criteria. However, ORA learned of its presence at the end of the Study Period and therefore was not able to accommodate an in-person visit. Requests for a virtual tour were not granted.

Alternative technologies for managing end-of-life plastics exist. Some produce second-generation biofuels and renewable chemicals through MSW gasification, while others utilize pyrolysis to convert plastics to wax. This report focuses exclusively on pyrolysis technologies that convert plastics into liquid petroleum products – synthetic crude oil or refined fuel products.

1.2 PTF TECHNOLOGY OVERVIEW

Pyrolysis refers to the thermal decomposition of a material in an oxygen-free or limited oxygen environment. The process of thermal decomposition is modeled after natural geological processes that produce fossil fuels. Thermal decomposition breaks down complex polymer molecules into shorter hydrocarbon chains through a process known as depolymerization. Pyrolysis used for PTF conversion involves introducing a polymer feedstock material into a high temperature chamber ranging between 430-550 °C to produce a vapor. Vapors are then condensed into condensable (synthetic crude oil) and non-condensable (synthetic gas) fractions. Depending on the technology offering, synthetic crude oil may then be fractionated onsite, usually by way of fractional distillation, into a range of light, middle and heavy distillate fuel oils. If fractionation does not occur onsite, the liquid petroleum product, typically classified as a light sweet synthetic crude oil, is sold to a refinery for further processing. Secondary byproducts can include char, syngas and wax (Figure 1). Output quality and quantity from the pyrolysis processes depends on feedstock (quantity and composition) and the technology.

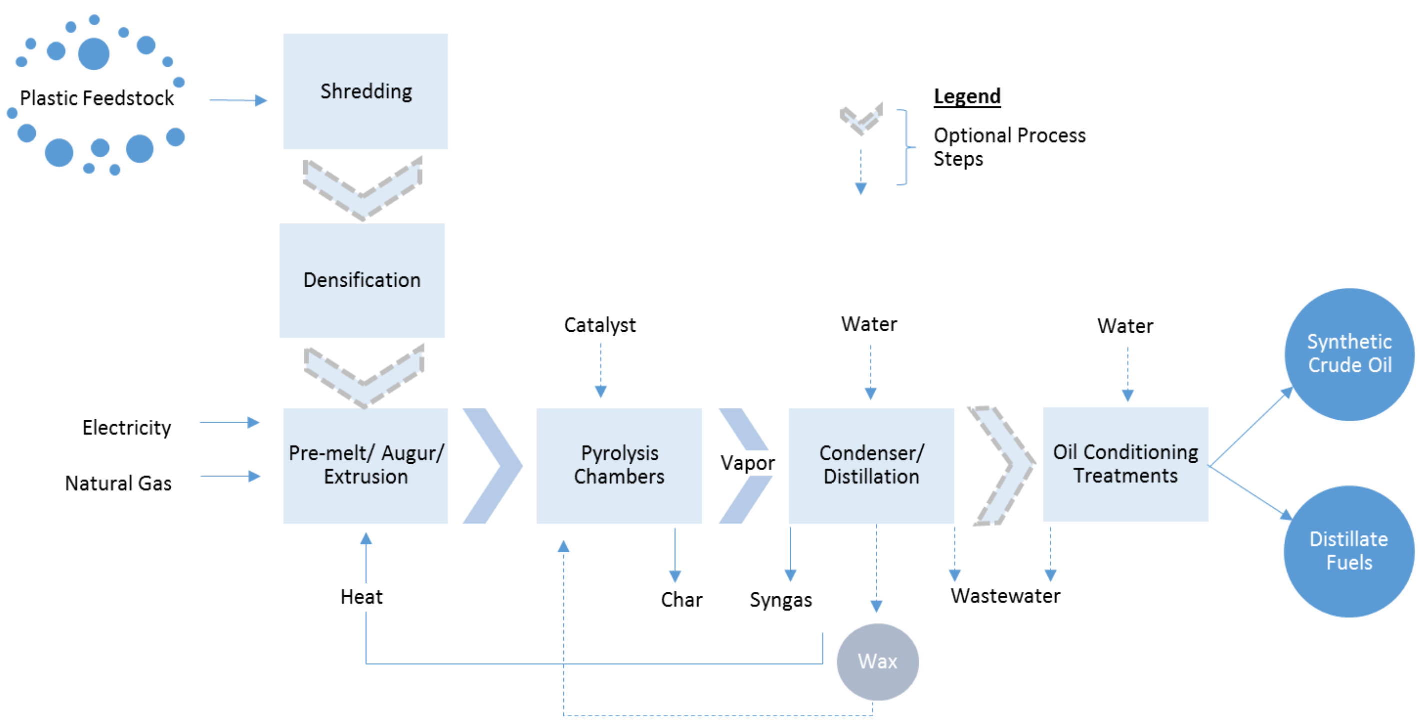

Figure 1 - Generic PTF Process

1.3 PTF TECHNOLOGY SUPPLIERS

System Classifications

On the path to developing a commercial PTF system, Suppliers undergo several stages of development (Figure 2). As such, PTF systems can be classified by scale and by operating status. For the purposes of this analysis, the scale of evaluated systems are classified as:

- Bench Scale – Laboratory scale, basic infrastructure to test proof of concept.
- Pilot Scale – Small-scale model of commercial offering with the goal of demonstrating proof of concept, testing different feedstocks and evaluating oil yields and product quality. Pilot scale

systems can be used to test design modifications for other pre-processing and back-end processing configurations.

- **Demonstration Scale –** Full commercial scale system with the goal of demonstrating proof of concept, testing different feedstocks, evaluating oil yields and product quality at commercial scale. Demonstration scale PTF systems can be converted into commercial systems following a period of testing and optimization.
- **Commercial Scale –** Full-scale infrastructure built at the design capacity of company's commercial offering. The goal of a commercial scale system is to produce a liquid petroleum product to be marketed to offtakers for the purposes of achieving profitability.

Figure 2 – Commercial Development Stages

Built systems can also have varied operating statuses. For the purposes of this assessment, the operating status of evaluated systems is classified as:

- **Continuous Operations** - System is processing feedstock for a minimum of four days per week on an ongoing basis. Continuous operations can occur at or below a system's design capacity.
- **Discontinuous Operations** - System is processing feedstock on an intermittent basis, less than four days per week. Discontinuous operations can occur at or below a system's daily design capacity but are always below a system's annual design capacity.

It is not uncommon for pilot and demonstration scale systems to operate in a discontinuous manner given their purpose to test inputs and outputs and that per unit operating costs can be higher compared to commercial scale systems. Only systems operating on a continuous basis are defined as operating at or below design capacity through the course of this study.

Once a commercial scale system has been designed, permitted, constructed and financed, and feedstock supply and offtake agreements have been secured, it may undertake a period of discontinuous operations in order to test feedstocks and make process improvements prior to achieving full continuous operations. This is referred to as the commissioning stage.

Finally, systems can also have varied economic statuses. Bench, pilot and demonstration scale systems are typically funded by the Supplier, and in some instances, also supported by revenues from the sale of end products. Commercial scale systems may rely on start-up funds during commissioning, but must be economically self-sustaining in order to be considered a fully commercialized system. For the purposes of this report, economic status is only provided for systems that are constructed at a commercial scale and were verified through communications directly with the system owner/operator to be operating at design capacity, on a continuous basis. Therefore, commercialization is defined as being constructed at commercial scale, operating at design capacity on a continuous basis and being economically self-sustaining from the sale of end products.

Participating and Contributing Suppliers
The 38 Suppliers identified were in various stages of development ranging from research and development, to having commercial scale systems in the commissioning stage, to reportedly having sold and installed equipment for multiple commercial scale systems[15]. Several Suppliers either declined to participate in the report or were not reachable for comment. For a complete list of PTF Suppliers identified, see Appendix A.

In order to better understand the progress towards commercialization among Suppliers, ORA's research focused on companies that either have an operating pilot, demonstration or commercial scale system and/or have made measurable progress towards commercialization including: having secured feedstock supply, offtake agreements, permits or financing for the development of a commercial scale system.

Of the Suppliers identified, 13 were prequalified based on the criteria outlined in Section B for future evaluation. 10 actively participated in providing information for this report (Participating Suppliers) while 3 Suppliers either provided marketing materials or incomplete data (Contributing Suppliers).

Participating Suppliers
Agilyx
Cynar Plc
Golden Renewables
JBI
Nexus Fuels, LLC
Plastics Advanced Recycling Corporation (PARC)
PK Clean
Pyrocrat Systems LLP
RES Polyflow
Vadxx

Contributing Suppliers
Blest
Klean Industries (Toshiba Technology)
MK Aromatics Limited (Polymer Energy Technology)

1.3.1 TECHNOLOGY OFFERING OVERVIEW

Of the Suppliers pre-qualified for this report, ORA identified two differentiating configurations for processing plastic feedstock: feed process and method of depolymerization.

Feed Process – Batch or Continuous: This configuration describes the process through which input plastic materials are inserted into the front-end reactor. A batch feed process entails inserting discrete quantities of plastic feedstock into cartridges at selected intervals. Each batch of plastic feedstock is processed before a new batch is inserted, which may require starting and stopping the machinery. Batch feed systems typically require that cartridges be cleaned before processing new batches. A continuous feed process entails insertion of plastic feedstock into the front-end reactor at a constant rate. Suppliers offering continuous feed systems advertise reduced downtime and increased efficiency. Although the majority of Suppliers presented in this report have continuous feed processes, historically Suppliers have used batch feed systems and are now developing newer generations to continuously process material.

Method of Deploymerization – Catalytic or Thermal: Depolymerization can be initiated by heat or catalyst. A catalyst is a chemical additive used to reduce chamber residence time and temperature requirements,

[15] ORA was not able to verify these details, as the names and contact information for system owner/operators were not disclosed.

thereby increasing process energy efficiency. Companies surveyed did not report the composition of the catalyst, as this is proprietary information. There are unverified reports of catalysts comprising synthesized materials from fly ash, HY zeolite, Mordenite and silica-alumina(S-A).[16]

Available Design Capacities

All pre-qualified Suppliers furnish modular PTF systems. All Suppliers noted an ability to install PTF units in parallel to increase throughput capacity, but cited the requirement for additional R&D to scale down design capacity to accommodate smaller quantities of waste. The majority of Suppliers offer smaller design capacities relative to other MSW conversion systems like mass burn waste-to-energy and gasification that commonly process more than 200 TPD. Typical PTF systems range from 10 – 60 TPD although Blest offers solutions that process <1TPD, Pyrocrat Systems LLP markets design capacities of 3 and 6 MTPD and Klean Industries stated offerings up to 150 MTPD.

[16] Chung, Soo Hyun et al., "Pyrolysis of Waste Plastics Using Synthesized Catalysts from Fly Ash," Korea Institute of Energy Research, http://www.netl.doe.gov/publications/proceedings/99/99korea/shchung.pdf, Accessed December 2014.

Table 3: Pre-Qualified Supplier Technology Offering

Technology Supplier	Participating or Contributing Supplier	PTF Systems Developed to Date (Location/ Scale/ Status)[17]	Regions Currently Served (Interests for Future Expansion)	Method of Depolymerization/ Feed Process	Available Design Capacities (Plant Availability)	Pre-Sorting /Pre-Processing
Agilyx	Participating Supplier	1. **Tigard, OR, USA** Pilot (10 TPD)-Gen6; Continuous Operations, At Capacity **2. Plymouth, MN, USA*** Commercial-Gen5; Operating Status Unknown **3. Lithia Springs, GA, USA** Commercial-Gen5; Did Not Disclose **4. North Portland, OR, USA*** Commercial-Gen5; Operating Status Unknown	North America (International)	Thermal Depolymerization Generation 5 technology- Batch Feed Generation 6 technology- Continuous Feed	50 TPD (92%)	No/No
Cynar	Participating Supplier	**1. Portaloise, Ireland** Pilot (10 MTPD); Discontinuous Operations **2. Almeria, Spain*** Commercial (20 MTPD); In Commissioning 3. **Bristol, UK** Commercial (20 MTPD); In Commissioning **4. Seville, Spain*** Commercial (20 MTPD); In Construction	Europe, Latin America (Europe, Latin America, Asia, North America, Australia)	Thermal Depolymerization Continuous Feed	20 MTPD (82%)	No/No
Blest	Contributing Supplier	**1. Whitehorse, Yukon Canada** Pilot (528 lbs/day); Discontinuous Operations[18]	Blest- International	Thermal Depolymerization Continuous Feed	528, 1320, 2640, 5280 lbs/day; 5, 16,	

[17] PTF systems developed to date that are known to process a minimum of 75% plastic feedstock. Systems processing exclusively tire or other wastes are excluded.

[18] Blest reports more than 60 installations in Japan, Africa and Nepal. ORA was not able to independently verify the location or operating status of systems aside from that in Whitehorse, Yukon.

					21 TPD (100%)[19]	
Golden Renewables	Participating Supplier	1. **Yonkers, NY, USA** Demonstration (24 TPD); Discontinuous Operations	US (Caribbean)	Thermal Depolymerization Continuous Feed	24 TPD (90%)	No/Yes
JBI	Participating Supplier	1. **Niagara Falls, NY, USA** Demonstration (25 TPD); Not Operational	US	Catalytic Depolymerization Continuous Feed	20-30 TPD (75%)	No/No
Klean Industries[20]	Contributing Supplier	1. **Sapporo, Japan** (Toshiba is Technology Supplier and Sapporo Plastics Recycling, Co. is system owner/operator) Commercial (40 MTPD); Not Operational	International	Thermal Depolymerization Continuous Feed	3, 5, 10, 15, 20, 25, 30, 50, 100, 150 MTPD (Unknown)	Unknown
MK Aromatics Limited / Polymer Energy (Technology Supplier)	Contributing Supplier	**1.Alathur, Tamil Nadu, India** Commercial (10 MTPD); Continuous Operations, At Capacity Economic status unknown	India	Catalytic Depolymerization Continuous Feed[21]	10 MTPD (82%)	Yes/Yes
Nexus Fuels	Participating Supplier	1. **Atlanta, GA, USA** Pilot (1.5-2 TPD) Discontinuous Operations	US (International)	Thermal Depolymerization Continuous Feed	50 TPD (96%+)	No/Yes
PARC	Participating Supplier	1. **Xinghua, Jiangsu Province, China***[22] Demonstration (~15 MTPD); Continuous Operations; Operating Capacity Unknown 2. **Nantong, Jiangsu Province, China***[23]	China (US)	Catalytic Depolymerization Continuous Feed	15, 25, 60 MTPD (Unknown)	No/No

[19] Plant availability data based on marketing materials. Data not verified by Supplier or facility operator.
[20] ORA was not able to verify the nature of Klean Industries business relationship with Toshiba Corporation.
[21] Mk Aromatics utilized technology from Polymer Energy LLC. Polymer Energy was not reachable for comment as their website is no longer functioning.
[22] System does not represent company's current offering.
[23] System does not represent company's current offering.

		Demonstration (20 MTPD); Discontinuous Operations 3. **Huaian, China** Commercial (60 MTPD); Not Operational (Currently Relocating Equipment)				
PK Clean	Participating Supplier	1. **Salt Lake City, UT, USA** Pilot (5 TPD); Continuous Operations, At Capacity	US (International)	Catalytic Depolymerization Continuous Feed	10, 20 TPD (90%)	No/ Option to include
Pyrocrat Systems LLP	Participating Supplier	**15 systems located across: Maharashtra, Rajasthan, Karnataka, Tamil Nadu, Gujarat, and Andhra Pradesh, India and 1 system in an undisclosed location in Europe*** Commercial (2-10 MTPD); Continuous Operations, At Capacity, Economic status unknown	India (International)	Catalytic Depolymerization Continuous Feed	3,6,12 MTPD (82%)	No/ Option to include
RES Polyflow	Participating Supplier	1. **Perry, OH, USA** Demonstration (60 TPD); Not Operational	US (International)	Thermal Depolymerization Continuous Feed	60 TPD (100%)	No/Yes
Vadxx	Participating Supplier	1. **Danville, PA, USA** Pilot (1 TPD); Discontinuous Operations[24] 2. **Akron, OH** Commercial (60 TPD); In Construction	US (International)	Thermal Depolymerization Continuous Feed	60 TPD[25] (90%)	No/No

* Supplier reported data and/or information not verified by system owner/operator

[24] Not operational during Study Period.
[25] Assumes 8% moisture level with 55 TPD entering the extruder.

1.3.2 BUSINESS MODEL OVERVIEW

Several business model options are available for interested Project Developers. Models vary by the level of involvement the technology Supplier chooses to have. In general, ORA observed that companies are tending towards high levels of involvement at earlier stages of development in order to ensure commercial viability. Available business models include:

- Design, Build, Own, Operate (DBOO)
- Joint Venture (JV)
- Sales and Service (S&S)
- Licensing
- Licensing and Trailing Royalty
- Public Private Partnership (PPP)

Additional details on business models are included in Part 2.

Given the emerging nature of PTF technology, project development is currently dominated by the private sector. While municipalities and/or their service providers are committing feedstock in many cases, ORA only identified one system in India that was developed under a PPP model.

Willingness to Self-Finance

PK Clean, Vadxx, Nexus Fuels, and Agilyx all expressed the willingness to self-finance the DBOO or JV of future PTF projects through existing partnerships with private equity, venture capital and/or private investors. Cynar indicated a willingness to enter into a special purpose vehicle to facilitate financing. MK Aromatics Limited develops projects through a PPP structure with municipal government and is willing to commit 20% of the total capital costs for all future systems. Additional details on project financing are included in Part 2 of this report.

Table 4: Pre-Qualified Supplier Business Model

Technology Supplier	Business Model	Lead Time for System Deployment	Willingness to Self-Finance
Agilyx	DBOO, JV, S&S, License	12-15 months (including permitting)	Yes for DBOO and JV
Cynar	Licensing Agreement + Trailing Royalty	18 months on equipment and construction	SPV possibilities
Blest	Equipment Sales	4 – 6 months on equipment delivery[26]	No, Leasing options available
Golden Renewables	Licensing, Sales and Service	4 months on equipment	Yes
JBI	Licensing Agreement + trailing royalty, Sales and Service	Unknown	Unknown
Klean Industries	Unknown	Unknown	Unknown
MK Aromatics Limited	PPP	Unknown	Willing to commit 20% of capital cost

[26] 4 months on 528 lb/day unit, 6 months on all other units.

Nexus Fuels	DBOO, Licensing Agreement	9-12 months[27]	Yes. Partnership in place with undisclosed financial investor to jointly own/operate systems in the US.
PARC	Did not disclose	10 months	Did not disclose
PK Clean	JV, Equipment Sales	6 months on equipment	Yes
Pyrocrat Systems LLP	Equipment Sales	3-4 months	No
RES Polyflow	DBOO, Licensing Agreement, Other [28]	12 month on equipment and construction	Not currently. Equity raise underway for first system.
Vadxx	DBOO, Licensing Agreement + Trailing Royalty	9-12 months on equipment and construction	Agreement in place with Liberation Capital to jointly develop multiple systems in the US. Willingness to self-finance in the future will be opportunity dependent.

1.3.3 SYSTEM INPUTS

1.3.2A Definition and Sources of Plastic Feedstock

This report assesses PTF as a management option for end-of-life plastic waste. End-of-life plastics are defined as plastics that would otherwise be disposed of in a landfill. End-of life plastics can originate from post-consumer or post-industrial sources and can be made up of both rigid and film plastics[29]. Plastics can also be broadly categorized into thermoplastics and thermosets. Thermosets differ from thermoplastics in that when molded, they take on an irreversible chemical bond, which cannot be broken again thermally or chemically. Thermosets are not a suitable feedstock for PTF systems. While Suppliers reported to process end-of-life plastics, ORA was not able to independently verify whether existing or planned facilities are processing plastics that were previously destined for landfill disposal.

Resin Classification Code

Plastics are made from a multitude of different polymers, with the most common polymer types being: PET, PP, PS, Polyvinyl Chloride (PVC), HDPE and LDPE. In countries where the plastic resin identification system is in use, plastics are imprinted with the code that corresponds with their resin type, signaling to consumers and recyclers which materials can be recovered for re-processing (Image 1).

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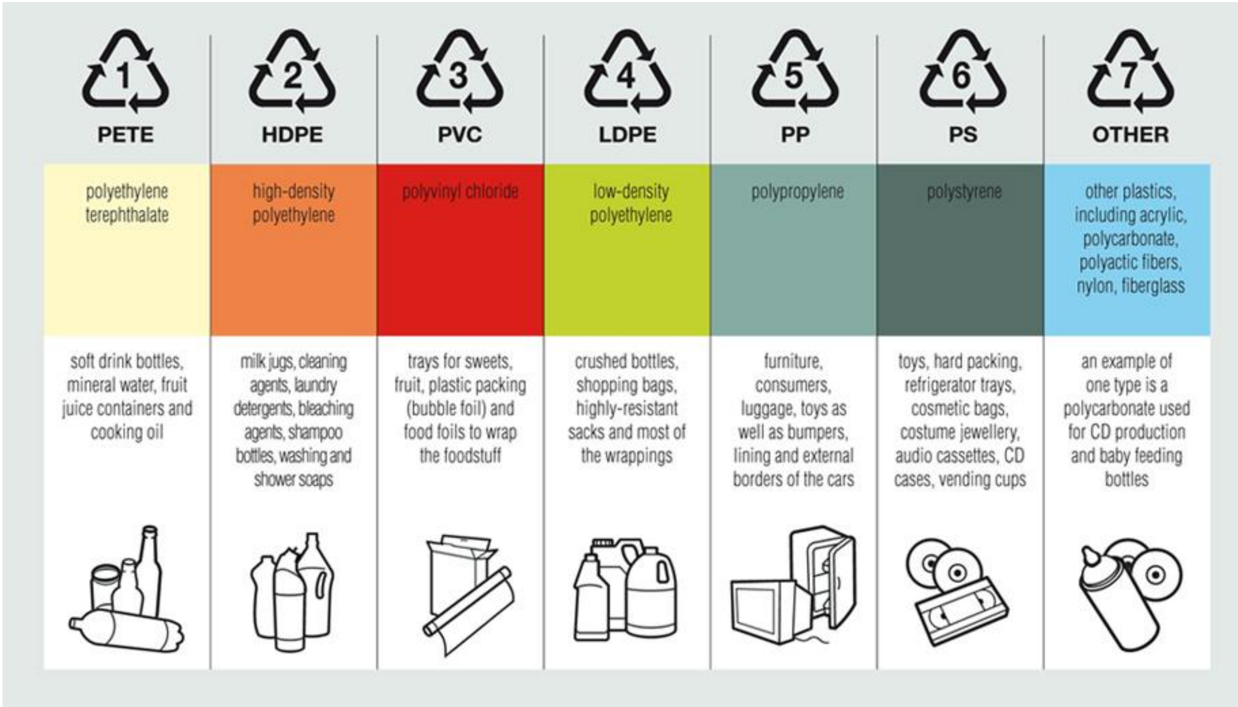
[27] 12 months on equipment and construction on first commercial installation; 9 months on projects thereafter

[28] Open to alternative future business models

[29] Plastic film is a flexible material made from different types of resins: LLDPE, LDPE, HDPE, PP, PVC, and Nylon.[29] Examples of plastic film products include trash bags, plastic bags, sacks & wraps and lined paper bags and sacks. According to the Flexible Packaging Association (FPA), the estimated amount of flexible packaging waste (FPW) generated in the US is 5.8 million tons per year. Flexible packaging waste represents 2.4% or 1.5 % of the total Municipal Solid Waste generated in the US, according to the EPA.

Image 1 - Plastic Resin Identification Codes



[30]

In countries where the system is not in use, plastics are commonly classified as either rigid or flexible. The most prevalent rigid plastics are HDPE, PP and PS. Flexible plastics consist of films such as plastic bags and packing materials and are regularly made of PP, PVE, PET and LDPE. This basic classification system does not classify waste by resin type.

Post-Consumer Plastics

Post-consumer plastics are produced by residential and commercial generators and are typically collected as part of a municipal recycling program. Plastics are sorted into bales at a Material Recovery Facility (MRF) and then sold into recycling markets. Bale composition and contamination rates vary depending on several factors including: market demand for plastics and consequently the types of plastics targeted by the recycling program, and technology configuration and efficiency. Municipal recycling programs typically exclude plastics for which markets are weak or do not exist, however some communities choose to target all rigid plastic to increase participation and improve overall materials capture rates. In these instances, low or non-value

Image 2 - Sample Bale Processed by PK Clean

[30] Source: www.gbpyrolysis.com Accessed February 2015

plastics are typically baled together and either sold or landfill disposed. Given that plastic bales vary from location to location and over time, not all bales are suitable feedstock for a PTF system.

Where formal collection programs do not exist, plastics are often collected and sorted by the informal recycling community. Similar market forces exist whereby informal recyclers target high value plastics, such as PET bottles and HDPE and pass over lower value materials.

Post-Industrial Plastics
Post-industrial plastics, also known as pre-consumer plastics, are a by-product of industrial or manufacturing processes. Post-industrial plastics bypass municipal recycling programs and are typically sold directly into recycling markets. Due to their homogenous nature and generally lower contamination rates, post-industrial plastics can be highly desired by recycling and PTF systems alike.

1.3.2B Feedstock Quality

Composition and Form
All PTF technologies favor HDPE, LDPE, PP and PS. The willingness to accept other plastic varies by Supplier. Suppliers typically place limits on PVC and other chlorinated resins such as chlorinated polyethylene (CPE), and PET although some assert to have developed proprietary technologies and pre-sorting systems to allow for the acceptance of higher incoming quantities of PVC and PET. PVC contains chlorides that produce hydrochloric acids and a range of dioxins, which companies indicated are corrosive to equipment and can be too costly to remove. PET has low oil yields and contains oxygen, which can push the pyrolysis reaction towards combustion. Fortunately, PET is the most readily recycled plastic resin and is typically extracted upstream of PTF systems. PVC is not commonly found in municipal mixed plastics, however chlorines can also be present in plastics in the form of applied flame retardants and fillers, which can only be detected by a burn test known as the Beilstein test.[31] System operators reported performing visual inspections of incoming loads, including the use of real time instrumentation, float tests and burn tests to ascertain feedstock composition and ensure compliance with contamination limits.

Feedstock form is also an important determinant of compatibility with PTF systems. Rigid and film plastics possess different product densities and therefore can require different management techniques. Participating Suppliers indicated the ability to process plastic films although some desire it in limited quantities while other prefer to avoid it due to material handling issues. Because film plastic occupies a greater amount of space, the liquid petroleum product yields on a per volume basis are less than for rigid plastics. Therefore, Suppliers recommend blending film with rigid plastics with a preference for higher quantities of rigid feedstocks. ORA did not identify a Supplier or system exclusively processing film plastics.

Additional challenges to feedstock quality are the presence of multilayer plastics in incoming feedstock and non-plastic contaminants. Multilayer plastics typically contain several plastic resins layered or bonded together in order to create plastic products with different attributes representative of each plastic type. In some cases, multilayer plastics may also contain other materials such as aluminum. For example, food packaging plastic film may contain several plastic resins: PP as a water vapor barrier, PE as a sealant, and LLDPE for optical and mechanical properties, etc. Stakeholders cited difficulty ascertaining the

[31] Williams, R. Scott et al., "Guide to the Identification of Common Clear Plastic Films," SPNHC Leaflets, Fall 1998, http://www.spnhc.org/media/assets/leaflet3.pdf, Accessed December 2014.

composition of multi-layer plastics, exacerbated by the fact that product manufacturers change composition frequently in a continual effort to reduce costs and increase packaging performance. Non-plastic contaminants include but are not limited to: dirt, metals, paper and wood. Contaminant levels are directly correlated with char production rates. High char production rates impact overall system economics due to reductions in liquid petroleum product yields and increases in char management costs, therefore system operators seek to reduce non-plastic contaminants by either A) placing strict contamination limits on incoming feedstock or B) undertaking additional on-site sorting steps.

Each resin has a different plastics-to-fuel conversion rate therefore, variations in feedstock composition can have a significant impact on yields, and consequently, economic performance (Table 5). Although data on the conversion rate of HDPE was not identified through the course of this study, HDPE was found to be a highly sought after feedstock for PTF systems.

Table 5: Plastics-to-Fuel Conversion Rate

Resin	Conversion Rate (%)[32]
PET	30%
HDPE	Data Not Available
PVC	30%
LDPE	70%
PP	50-60%
PS	80-85%

Examples of products reportedly sought by PTF system operators may include but are not limited to:

- Post-consumer plastics from MRFs, although threshold of contamination can vary by company and investors desired return on investment. This can include:
    - Rigid and film plastic packaging
    - Non-recycled caps, labels and rejects from MRFs
    - E-waste
- Post-industrial plastics from industrial or manufacturing processes. This can include:
    - Agricultural plastics such as silage bags and polytunnels
    - Auto shredder residue (ASR) plastics
- Scrap carpet
- Tires

Examples of products **NOT** sought by PTF system operators may include but are not limited to:

- Metals, papers, glass, brick, wood and other non-polymer wastes
- Thermoset plastics
- Nylon (Supplier/ operator dependent)
- Expanded PS (Supplier/ operator dependent)
- Films (Supplier/ operator dependent)

Pre-Processing Requirements

Suppliers varied in pre-processing requirements of plastic feedstock but indicated that quality of feedstock is a principal determinant for ensuring the financial feasibility of PTF systems. Unlike some waste conversion technologies that process mixed MSW, PTF systems require pre-sorting to isolate plastic from other waste streams. Suppliers may also require that feedstock be prepared to reduce moisture, which ultimately lowers the efficiency of production, and/or size which may entail shredding or

[32] Provided by Cynar.

chipping to ¼” to 2” particles. Several participating Suppliers reported de-dusting feedstock to reduce fiber contamination and corresponding char production rates. Whether a Supplier undertakes pre-sorting and pre-processing onsite is primarily a function of their business model. Suppliers that do not provide these services rely on feedstock providers to extract and prepare the target feedstock prior to delivery, which typically results in increased feedstock acquisition costs.

1.3.2C Feedstock Quantity

System economics are optimized when material throughput matches design capacity. Suppliers interviewed offer modular PTF packages ranging from 0.25 - 165 TPD. Design capacity refers to the total quantity of feedstock entering the pyrolysis reactor. This quantity of material can also be referred to as usable feedstock. Feedstocks with high contamination or moisture levels can demand that larger overall quantities of incoming feedstock be sourced for the system, potentially increasing material acquisition, pre-processing and residual waste management costs.

1.3.2D Additional Inputs

In addition to feedstock, some technologies also require other inputs – either at startup or through the entirety of the process. Actual inputs and quantities required vary by Supplier and system throughput. These inputs include:

- **Water** – Some technologies use a water quench to condense syngas vapors into the liquid petroleum product at the tail end of the pyrolysis process or for oil conditioning[33]. Some companies require a water supply connection, while others source water from condensation from the pyrolysis process. Of the Suppliers that provided water requirement data, demand ranged from 21-227[34] gallons/ton of feedstock processed.
- **Electricity** – All evaluated technologies require connection to an electric grid to support motors and control systems. Some Suppliers reported plans for utilizing excess syngas or a portion of the liquid petroleum product for the generation of onsite electricity. Of the Suppliers that provided system electricity requirement data, demand ranged from 455 - 1,300 kWh/ton of feedstock processed.
- **Natural gas –** Natural gas is used at the start-up of most processes. As many of the PTF technologies utilize or plan to utilize syngas produced through pyrolysis to satisfy the system’s parasitic load, natural gas supply is typically not needed once systems are operational.
- **Hydrogen –** One Supplier utilizes a hydro-treating technology to improve the quality and cleanliness of their refined fuel products, which requires access to a hydrogen source. Hydro treating can reduce sulfur, nitrogen and aromatics while enhancing cetane number, density and smoke point.[35] Hydrogen can be sourced in a number of ways, which include: 1) from a system that is producing a hydrogen byproduct (i.e. - a refinery), 2) obtaining it from mobile sources or 3)

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[33] Oil conditioning encompasses different processes to stabilize oil end products from volatile materials to be ready for market. Oil conditioning processes used in PTF systems include: fractionation, distillation, hydrogenation and water treatments.
[34] Supplier reported filtering and re-circulating water onsite.
[35] Shell Global, “Hydrotreating”, http://www.shell.com/global/products-services/solutions-for-businesses/globalsolutions/refinery-chemical-licensing/refining-technology/hydrotreating.html, Accessed: December 2014.

producing it onsite. Proximity to and market pricing for hydrogen will impact system economics. The Supplier did not report the quantity of hydrogen required.

- **Catalyst** – For Suppliers that employ the use of catalytic depolymerization, a catalyst is used to trigger the reaction. Catalysts are proprietary and typically provided by the Supplier. PK Clean reported the use of an optional catalyst, only recommended when processing difficult to crack polymers, such as HDPE. JBI reported catalyst requirements of 400 lbs/month for a 24 TPD system and Pyrocrat Systems LLP reported catalyst requirements of 0.1-0.5% of the weight of incoming feedstock.

  Fuel Additives - Fuel additives or antioxidants can be used to stop oxidation and prolong storage times.

Table 6: PTF System Inputs

Technology Supplier	Feedstock Requirements	Accepted Feedstocks	Contamination Limits	Additional Process Inputs	System Footprint of Commercial Offering	Number of Employees Required by Commercial Offering
Agilyx	Cleaned, mostly dried and chipped/ shredded to a dimension of ¼”-3/8”.	Rigid and Film Plastics #2,4,5,6	<5-10% PVC and PET (combined). [36]	Electricity, Water, Natural Gas	17,000 ft2 building; 0.4 acre[37]	31
Cynar	Separation from non-target plastics (PVC and PET) and contaminants; Size <300mm	Rigid and Film Plastics #2,4,5,6	PVC: 0% PET: 2%	Electricity, Water	4,920 ft2 system footprint[38]	10 Operators, 2 Admin
Golden Renewables	Feedstock must be clean; dried (no more than 5% moisture); Size: 0.5”[39]	Rigid Plastics #3-7	PET, PVC contamination thresholds not specified	Electricity, Start-up Gas	5,000 ft2 building[40]	20
JBI	Separation and cleaning; Size: 24” diameter	Rigid and Film Plastics #2,4,5,6	PVC and PET thresholds not specified	Electricity, Water, Catalyst, Start-up Gas	Did not disclose	Did not disclose
Klean Industries	Continuous – requires shredded materials <100mm No pre-treatment	Most suitable: Plastics #2,4,5,6; Semi Suitable: ABS, PA, PUR, EVA – [41]	PVC, PET, K-coated products. Thresholds not specified	Unknown	Unknown	Unknown
MK Aromatics Limited	Separation from non-target plastics (PET and PVC) and contaminants.	Rigid and Film Plastics #2,4,5,6	PET, PVC contamination thresholds not specified	Electricity, Water, Catalyst	Did not disclose	Did not disclose
Nexus Fuels	Separation from non-target plastics (PET and PVC) and contaminants.	Rigid and Film Plastics #2,4,5,6	PVC: <=1% Tolerated	Electricity, Water	Did not disclose	20

[36] Contamination thresholds driven by required financial return.
[37] Only include system equipment. Additional square footage may be required for front-end processing.
[38] PTF system only. Does not include material storage, buffers, etc.
[39] Particle size subject to change with hardware upgrades
[40] Includes pre-processing, processing, distillation and storage area
[41] Acrylonitrile butadiene styrene (ABS), Polyamide (PA), Polyurethane (PUR), Ethylene-vinyl acetate (EVA)

			PET: <=2% Preferred			
PARC	Separation from non-target plastics (PET and PVC) and contaminants.	Rigid and Film Plastics #1-7	PVC: <5% PET: Sorted out for financial reasons	Catalyst[42]	½ acre	Did not disclose
PK Clean	Separation from contaminants. Feedstock should be shred.	Rigid Plastics #1-7	<40% PVC and PET (combined)	Electricity, Natural Gas for start-up, Water, Catalyst[43]	3,000 ft2 Building	10 TPD = 2-3 people/shift 20 TPD = 4-5 people/shift
Pyrocrat Systems LLP	Separation from contaminants. <=5% dust, <=5% moisture; calorific value of raw material must be above 7000KCal/Kg; Particle size: Less than 25mm, density more than 0.2MT/KL	Rigid and Film Plastics #2,4,5,6, Rubber, Waste Oils	PVC: <1% PET: <5%	Electricity, Water, Catalyst	3 MTPD: Land- 6,458 ft2; Building – 2,690 ft2 6 MTPD: Land- 10,764 ft2; Building – 5,382 ft2 12 MTPD: Land – 19,375 ft2; Building- 8,073 ft2	3 MTPD: 10 6 MTPD: 12 12 MTPD: 12
RES Polyflow	Separation from contaminants.	Rigid and Film Plastics #1-7, Carpet, Tire Shreds	PET, PVC contamination thresholds not specified	Electricity, Water, Natural Gas/Propane for startup, Undisclosed consumable	75Kft2 building for front end processing, 20Kft2 for conversion, 1-2 acres for upgrading and ancillary systems/ materials handling.	32
Vadxx	Size: <=2” Metal/Wire contaminant: Max diameter: 1/8” Max length: 1”	Rigid and Film Plastics #2,4,5,6,7, Tires, EPDM[44], TPO[45], Butadiene Rubber, Styrene	PET, PVC contamination thresholds not specified [47]	Electricity, Natural Gas for startup	20,000ft2 Building, 2 acre site	16 operators, 1 plant engineer and 1 plant manager

[42] Water and electricity connections are infrastructure requirements.
[43] Catalyst is optional-depending on feedstock
[44] EPDM rubber (ethylene propylene diene monomer (M-class) rubber)
[45] Thermoplastic olefin.
[47] Maximum contamination levels are a function of investors required rate of return.

	Butadiene Rubber, ABS[46], Styrenics	

[46] Acrylonitrile butadiene styrene.

1.3.3 SYSTEM OUTPUTS

1.3.3A Definition of Petroleum Products

There is much variation in how Suppliers label the liquid petroleum products produced from PTF systems. For the purposes of this report, oil and refined fuel end products are collectively referred to as liquid petroleum products. Products that are characteristic of synthetic crude oil are referred to either as synthetic crude oil or oil and end products that undergo onsite fractionation into refined fuels are referred to as distillate fuel oils, refined fuels, or fuel blendstocks. ORA standardized terminology to the extent possible; however some Suppliers required that specific terminology be used to describe their liquid petroleum products. ORA recommends contacting Suppliers directly for additional information about end product characteristics.

1.3.3B Petroleum Outputs

Through different configurations of pyrolysis technologies, the principal output of PTF technologies is a liquid petroleum product -- either a synthetic crude oil or refined fuels. Product quantity and quality vary across Suppliers.

Given that crude oils are comprised of different fractions of hydrocarbon mixtures that condense at different boiling points, fractionation can produce a combination of light (gasoline and naphtha), middle (No. 2 fuel oil, No. 2 diesel fuel, kerosene) and/or heavy cut fuels (residual fuel oils) (Table 7). The term fractionation is used broadly in this report to describe fractional distillation and other techniques used to produce refined fuels. Refined fuels are considered finished products and can be sold directly to a fuel blender, distributor or other industrial end user. Suppliers that undertake fractionation onsite have the ability to tailor the distribution of distillate fuel oil outputs within a pre-determined range through onsite blending and process modifications to optimize system economics.

Suppliers that produce synthetic crude oil may undertake condensation, separation and conditioning steps to improve the quality of their end product. Generally, the light and middle or light and heavy cut fuels are then blended together and sold as light sweet synthetic crude. Synthetic crude oil from PTF systems is typically characterized as being light (API gravity >31.1°) and sweet (sulfur content <0.5%) (low viscosity and low sulfur). Suppliers that produce synthetic crude oil sell direct to refineries for offsite processing into other refined petroleum products.

For additional information on crude oil classification see Appendix B.

Table 7: Petroleum Outputs, End Users and Corresponding ASTM/EN Standards

Oil Output	End Users	US Standards
	Un-distilled	
Light Sweet Synthetic Crude	Refinery	SPR 2008
	Heavy Distillates	
Residual Fuel Oils (No. 5 and No. 6)	Shipping/Aviation Industries	ASTM D396
	Middle Distillates	
No. 2 Fuel Oil	Heating Oil Companies	ASTM D396
No. 2 Diesel Fuel	Oil Blender, Oil Broker, Oil Distributor, Direct to End User for use in Energy Generation Equipment	ASTM D975 (EN590)
Kerosene	Aviation (jet fuel)	ASTM D3699
	Light Distillates	
Gasoline	Retail Transportation Fuel, Chemical Industries, Refineries, Fuel Blenders/Brokers	ASTM D4814
Naphtha	Chemical Industries, Refineries, Fuel Blenders/Brokers	ASTM 3734

Distillate fuel oils can either be classified as fuel blendstocks, which are mixed in varying proportions with refined fuels from other conventional sources, or drop-in fuels. Fuel blendstocks can also be classified as either being on-spec, indicating that they comply with the American Society for Testing and Materials (ASTM) or European Standards (EN) but have not be formally registered, or off-spec. Distillate fuel oils that have been formally registered with their respective governing body are considered on spec, drop-in fuels. While several Suppliers noted the production of on-spec fuels, only one Supplier reported undertaking product registration. The specifications of liquid petroleum products will differ based on the product type and contractual agreements with offtakers. Suppliers that sell directly to refineries work directly with refineries to ensure their product meets select criteria including: pour point, flash point, and chloride levels (Table 8).

Table 8: Example of Refinery Requirements for Synthetic Crude Oil

Properties	Typical Values
Composition, volume % - LPG - Naphtha - Middle Distillate - Heavy distillate - Residue	3.6% 24.6% 35.8% 35.5% 0.5%
API Gravity, degrees	40-45
Sulfur, mg/kg	90 -1,200
Pour Point, °C	25-35
Water, weight %	0.05 – 0.25
Total Acid Number, mg KOH/g	0.1 – 1.0
Metals content, mg/kg - Nickel	0.5 – 3.3

- Vanadium	<detection

Of the Suppliers that reported successfully selling or executing offtake agreements with end user, all have reported sales at current oil market prices. ORA did not identify any cases where PTF liquid petroleum products are being used as a drop-in fuel in vehicle engines. Reasons cited include the need for refueling infrastructure and potential to void vehicle engine warranties. All Suppliers marketing transportation grade fuels are currently undertaking an intermediate blending step.

Liquid Petroleum Production Rates and Distillate Fuel Distribution

The conversion rate of plastic to liquid petroleum products is dictated by feedstock composition and technology. The liquid oil/fuel conversion rates across pre-qualified Suppliers averaged between 60-80% with a range of 156-280 gallons of liquid petroleum product produced per ton of usable feedstock processed.[48] For Suppliers that fractionate onsite, the distribution of light, middle and heavy distillate fuel oils vary by input feedstock, technology and operating conditions. A sample distribution of distillate fuel oil outputs is provided in Table 9.

Table 9: Sample Distribution of Distillate Fuel Oil Outputs

	Cynar		PK Clean
Diesel Blendstock	70%	Diesel Blendstock	66%
Light Oil/Naphtha	20%	Light Oil	33%
Kerosene	10%	Wax	Re-circulated

Quality Control

Quality is one of the most salient challenges associated with synthetic liquid petroleum production and marketability. Unlike fossil fuel derived crude oil that has fairly predictable characteristics and is a well-known commodity, synthetic oils and distillate fuel oils from plastic waste is new to the market. Oil quality can vary weekly due to fluctuations in feedstock composition. High levels of nitrogen, sulfur, chlorines and halogens in incoming feedstock result in lower yields and lower quality liquid petroleum products. Several Suppliers indicated an ability to produce middle distillate fuel oils that meet low or ultra-low sulfur diesel standards, depending on the quality of the feedstock.

1.3.3C Additional Outputs

In addition to liquid petroleum products, PTF technologies produce all or some of the following outputs. Output quality and quantity varies by Supplier and system throughput. These outputs include:

- **Syngas** - Syngas, or synthesis gas, is a byproduct of the condensation process. Non-condensable gases are comprised of carbon monoxide, hydrogen and carbon dioxide. Syngas has a heating value of approximately two-thirds natural gas, and thus has an energy value that can be recovered through the process.[49] Many companies either utilize or plan to utilize this gas as an

[48] Converting tons to barrels of petroleum product requires the density of the oil or distillate fuel product. Therefore, a 70% conversion rate for synthetic crude oil will not equal a 70% conversion rate for distillate fuel products. Product density can vary by Supplier and product.

[49] US EPA, Energy Recovery, http://www.epa.gov/waste/hazard/wastemin/minimize/energyrec/index.htm, Accessed: December 2014.

energy source to support parasitic load. In cases where the syngas is not utilized, companies flare or thermally destruct it to comply with air emissions standards. Several companies reported expectations for excess syngas production in commercial scale operations, which could be sold or used for onsite electricity generation. Suppliers cited syngas production rates of 6-20% by weight of incoming useable feedstock.

- Char - Feedstock impurities are separated out into an inert, non-hazardous char. Char contains the additives and contaminants, such as fibers and glass that enter the system as part of the incoming feedstock. In all cases, Suppliers indicated that char generated from PTF was classified as an inert material that could be disposed in a non-hazardous landfill. In a few cases, Suppliers are exploring alternative applications for the char including use in road, carpet and roofing material. Suppliers most often cited additional energy recovery as the preferred management option for char. Because there is a carbon component in the char, this material can be sent to an incinerator, or burned onsite for additional energy recovery. These alternative uses for the char make the conversion process potentially a zero-landfill management option. Of study participants, MK Aromatics Limited is the only Supplier that reported successfully selling treated char[50] as coke for filler product in the electrode market in India. Participating Suppliers cited char production rates of 5-20% by weight of incoming useable feedstock.
- Wastewater - Some PTF systems use water in the condensation process to cool and contract gases into a liquid state. Other companies mix water with oil in the oil conditioning process to achieve desired pH for end products. Water is either produced through condensation of the pyrolysis process or sourced from local supply. Some Suppliers indicated that wastewater produced through the process is re-circulated through the system. However, in cases where excess wastewater is produced, onsite treatment and/or discharge to a local sewage system may be required. Of the participating Suppliers that generate wastewater onsite, one reported generation rates of 34 gallons/ton.
- Wax - Wax production may occur at the back end of the PTF system. ORA is not aware of companies selling wax byproduct as a marketable end product. While Nexus Fuels is in the process of identifying potential end markets, PK Clean recirculates wax back into the pyrolysis reactor for further processing. Nexus Fuels and Pyrocrat Systems LLP both cited wax production rates less than or equal to 10% by weight of incoming useable feedstock.

Table 10: PTF System Outputs

Technology Supplier	Petroleum Product/s	ASTM Standards Product Meets	Projected Oil Production/ Ton of Useable Feedstock	Other End Products (% by weight of incoming feedstock)
Agilyx	Light Sweet Synthetic Crude	Not applicable	~211 – 221 gallons/ ton	**Char:** 7-10 % **Syngas:** 7-15% **Other:** Amount not

[50] Treatment includes metal removal and filtering.

				disclosed[51]
Cynar	Middle Distillate Diesel blendstock (CynDiesel™) Light Oil (CynLite™) Kerosene (CynKero™)	CynDiesel™ meets ASTM 975 and EN590- pending registration[52]	~250 gallons/ ton	**Char**: 5% **Syngas**: 6%[53]
Golden Renewables	Diesel blendstock Gasoline blendstock	Did not disclose	~190 gallons/ton	**Char**: 5% **Methane**: 15%
JBI	Naphtha Diesel Blendstock Fuel Oil #6	Fuel Oil #6 meets ASTM D396	~265 gallons/ ton[54]	**Char:** Unspecified **Syngas:** Unspecified
Klean Industries	Light, Middle, and Heavy Distillate Fuel Oils	Did not disclose	Unknown	Unknown
Nexus Fuels	Light Sweet Synthetic Crude and distillate fuel oils depending on configuration[55]	Not formally tested but preliminary 3rd party testing shows compliance.	~220-280 gallons/ ton	**Char**: 5-10% **Syngas**: 8-12% **Wax**: 3-10%
MK Aromatics Limited	Light Sweet Synthetic Crude[56]	Not applicable	~195 gallons/ ton[57]	**Char:** 10% **Syngas:** Quantity not provided[58]
PARC	Light Sweet Synthetic Crude	Not applicable	~160 gallons/ ton	**Char:** 18%
PK Clean	Light Sweet Synthetic Crude	Not applicable	~250 gallons/ ton	**Char**: 5-10% **Syngas**: Quantity Not provided[59]
Pyrocrat Systems LLP	Light Sweet Synthetic Crude	Not applicable	156-216 gallons/ ton[60]	**Char:** 10-15% **Syngas:** 15-20% **Wax:** Nil to 10%
RES Polyflow	Naphtha blendstock, distillate blendstock and heavy oil	Did not disclose	~202 gallons/ ton	**Non-target Residues**[61]: Est. 10% **Wastewater**: 5% by volume **Char**: 3-5% **Syngas**: 20%[62]
Vadxx	Light end/Naphtha, Middle distillate diesel fuel No 2	Middle distillate meets ASTM D975	~210 gallons/ ton	**Char**: 5-15% **Syngas**: 15-20%[64]

[51] Other products include trace amounts of undissolved solids (hazardous) and wastewater.
[52] CynFuels™ has successfully undergone Registered
[53] 100% utilized onsite.
[54] Assumes 86.7% liquid oil conversion rate.
[55] Fuel blendstocks produced include diesel, naphtha, kerosene.
[56] Product is currently processed offsite at a refinery owned by MK Aromatics.
[57] Assumes 1 ton = 279.2 gallons of crude oil. Supplier reported a liquid oil conversion of 70%.
[58] Future systems will recirculate syngas for onsite use.
[59] 100% utilized onsite.
[60] Supplier reported oil production rates of 6,500-9,000 liters / 10K kg of waste mixed plastic scrap.
[61] Includes metals, wood, glass.
[62] 100% utilized onsite.
[64] 100% utilized onsite.

	blendstock[63], heavy end lubricant

1.3.4 SYSTEM ECONOMICS

PTF system economics are driven by numerous factors. These factors can be broadly categorized into capital cost (capex) drivers, operating and maintenance (O&M) cost drivers, and revenue drivers.

Capex Drivers:

- Design capacity
- System footprint and requirement for full enclosure
- Infrastructure requirements
- On-site pre-processing
- Chosen business model
- Technology
- Financing costs

O&M Drivers:

- Demand for and cost of inputs (water, electricity, labor, catalyst, hydrogen)
- Feedstock purchase and transportation costs
- Char production and landfill disposal rates
- Wastewater production and management costs
- Fuel transportation costs
- Maintenance costs
- Trailing royalty
- Insurance
- Management Fees

Revenue Drivers:

- Liquid oil/fuel conversion rate
- Market price for liquid petroleum products
- Potential for per ton tipping fees

Capex varies significantly across participating Suppliers and system location. Unadjusted total Capex[65] was reported to range from $305,400 for pyrolysis equipment and installation[66] to $20 Million for a turnkey system or $163 to $1,606/TPY of installed capacity. Costs are largely influenced by whether pre-processing occurs onsite, system size, technology, business model and local site development costs. PK Clean cited variable capital cost structures depending on design capacity and whether a direct equipment sale or JV model was used.

System footprint can also impact cost with footprints ranging from 700 ft2 for a modular, low-capacity 0.25 TPD unit to 95,000 ft2 for a large scale 60 TPD system including front-end processing. Cynar was the only Supplier that noted a preference to operate their system outside of an enclosed building. Typical land requirements range from ½-2 acres.

Suppliers cited unadjusted per unit O&M costs ranging from $25-70/Barrel[67]. Fixed O&M costs including maintenance and expenses associated with acquiring inputs and managing non-revenue outputs constitute the majority of O&M costs however, variable O&M costs such as feedstock purchase and transportation and fuel transport costs can have a significant impact as well. Several Suppliers offer

[63] Lighter or heavier fuels can be produced depending on developer's desires.
[65] Cost estimates have not been adjusted to account for local cost variations outside of the Suppliers current country of operation.
[66] Cost is exclusive of site development
[67] Cost estimates have not been adjusted to account for local cost variations outside of the Suppliers current country of operation. Cost components included vary across suppliers.

licensing agreements that require trailing royalties tied to the sale of oil, with the percentage point set on a case-by-case basis.

Most Suppliers indicated a willingness to purchase feedstock at market value although many are strategically developing systems with MRF owners or at landfill sites to guarantee a long-term, no or low cost supply of feedstock. One Supplier indicated that a purchase price exceeding $62/ton of plastic would impede economic performance while another indicated that O&M costs are reduced by 50% when obtaining feedstock free of charge.

System revenues are driven by a system's plastic-to-fuel conversion rate and market price for the liquid petroleum product/s produced. Suppliers that accept plastics #1-7 reported additional revenue streams from the sale of non-target plastics and metals and others indicated the potential for selling wax and/or utilizing excess syngas onsite in the production of electricity. Unlike other solid waste management technologies, tipping fees do not appear to be a significant revenue stream at this time. One Supplier indicated the potential to receive a tipping fee for specific, highly contaminated non-recyclable post-industrial plastics while another noted receiving tipping fees for a portion of incoming feedstock. Some Suppliers offer discounts or incentives to attract project partners. MK Aromatics Limited offers discounts on liquid petroleum products to government and corporate partners. In the event that they are not interested in purchase, the company offers the partner the difference between the discounted and actual sale price in the form of a rebate.

The breakeven cost of producing one barrel of light sweet synthetic crude oil or distillate fuel oil varies considerably by Supplier. Suppliers that produce refined fuels command higher market prices per unit of fuel produced and can presumably support higher breakeven costs than those that produce synthetic crude oil. Breakeven costs listed in Table 11 include capital repayment, although Suppliers assumptions differ around the cost of capital.

Table 11: System Economics of Commercial Offering

Technology Supplier	Capex	Capex/TPY	O&M	Breakeven
		SYNTHETIC CRUDE OIL PRODUCERS		
Agilyx	$12-13 Million[68]	$714 - 770	Proprietary	Did not disclose
MK Aromatics Limited	$3.5 Million[69]	$1,058	$39-49/barrel[70]	Did not disclose
PARC	Proprietary	Proprietary	Proprietary	Did not disclose
PK Clean[71]	Pricing starts at $2 Million[72]	Starting at $606	~$25-35/barrel[73]	$40/Barrel
Pyrocrat Systems LLP	3 MTPD: $305,400 6 MTPD: $437,200	$163-308	3 MTPD: $70/barrel 6 MTPD: $41/barrel	Did not provide

[68] Exclusive of front-end processing, building, site development, soft costs. Inclusive of processing equipment only.
[69] Capital cost for 10MTPD module. Additional modules cost $1.5 Million each. Cost is inclusive of all soft costs, construction, site development, etc.
[70] Supplier quoted $0.20-0.25/kg with no feedstock acquisition costs.
[71] Company is capable of selling fractionated fuels, depending on local markets
[72] For 10 TPD for JV model. Price varies based on capacity, business model, deal terms and pre-processing requirements. Inclusive of all costs except building purchase/lease and soft costs.
[73] Assumes no residuals management or feedstock acquisition costs.

	12 MTPD: $648,200[74]		12 MTPD: $26/barrel[75]	
		DISTILLATE FUEL OIL PRODUCERS		
Cynar	Proprietary	Proprietary	Proprietary	EUR 0.43/liter
Golden Renewables	$5-6 million[76]	$950 - $1,140	~$30/Barrel[77]	Did not disclose
JBI	$5-8 Million	$912 – $1,460	Did not disclose	Did not disclose
Klean Industries	Did not disclose	Did not disclose	Did not disclose	$48/Barrel
Nexus Fuels	$9-12 Million[78]	$514-629	Did not disclose	Proprietary
RES Polyflow	Proprietary	Proprietary	Proprietary	Did not disclose
Vadxx	$17 – $18 million[79]	$851-909	Did not disclose	<$50/Barrel

1.5 PTF SYSTEMS

ORA conducted site visits to known operating PTF systems to verify status and performance. Based on the criteria outlined in Section B, ORA conducted visits to three systems during the Study Period. All systems were operating on a pilot scale basis with two systems operating on a continuous basis and one system operating on a discontinuous basis.

1.5.1 NEXUS FUELS, LLC—ATLANTA, GA, USA

In early 2013, Nexus Fuels, LCC began operations at a pilot scale PTF system in Atlanta, GA. The system is currently processing an average of 1.5-2 TPD of waste plastics on a discontinuous basis. The system was self-financed and developed in collaboration with the Georgia Institute of Technology. The pilot system is also currently operating an R&D fractionation system by which it is producing gasoline, naphtha, diesel, and kerosene blendstocks, heavy oil and wax. All oil products are currently being stored onsite. The system has run in idle or operating mode continuously for 18 months with the number of operating days per week dictated by a self-imposed limit on onsite fuel storage. An independent study has reportedly been performed on the Nexus Fuels reactor with a second study on the design of a commercial system currently underway. The study was not made available to ORA.

[74] Inclusive of equipment, equipment installation, preoperative expenses and contingency. Excludes site development, pre-treatment, building, land, soft costs. Costs reflect those for Indian systems and have not been localized.
[75] Assumes manager labor rate of $3000/month, engineer labor rate of $2000/month and unskilled employee labor rate of $1000/month. Excludes debt service, depreciation, material acquisition, char management, and lease cost. Assumes an oil production rate of 600 liters/metric ton.
[76] Does not include storage tanks, site development costs, permitting.
[77] Includes labor, electricity, natural gas, utilities, license fees, maintenance. Does not include material purchases, residue management or general administration.
[78] Inclusive of all equipment, soft and site development costs. Exclusive of land purchase/lease.
[79] Exclusive of: permitting, planning, site design/layout, site identification, and building purchase/lease. Inclusive of: integration fee (license model), management and construction of all in process piping, recovery equipment, storage, instrumentation and control, and commissioning by Rockwell, shredder, drying, and safeguard/separation technology, working capital and start up. If optimal waste materials are selected, then $1.5 Million of these costs may be avoided.

ORA observed pre-shred HDPE drums being fed into the reactor, a liquid petroleum product exiting the condenser, the wax byproduct and the rudimentary fractionation of oil into refined fuels during its site visit.

Table 12: Nexus Fuels, LLC System Summary

Owner/Operator	**Nexus Fuels, LLC**
Technology	Thermal Depolymerization, Continuous Feed
Technology Provider	Nexus Fuels, LLC
System Location	Atlanta, GA, USA
Commercialization Stage	Pilot
Design Capacity	Pilot Scale, 1.5-2 TPD
Operating Status	Discontinuous
Operating Throughput	Undisclosed. Operations are for testing purposes only.
Feedstocks Processed	Rigid #2 (Reported Rigid #4, 5, and 6 but not observed during site visit)
Feedstock Sources	Post-Consumer Plastics from a local single stream MRF and Post Industrial HDPE drums from the food service industry
Liquid Petroleum Product/s	Light sweet synthetic crude, naphtha, gasoline, diesel and kerosene blendstocks, Fuel oil #2 and wax.[80]
Liquid Petroleum Product Production Rate	5.2-6.7 Barrels/Ton reported
End User	Currently being stored onsite for future use, onsite heating demand and operating power equipment
Site Visit Date	March 2014

1.5.1A Process Overview

Target feedstock undergoes shredding onsite before it is degassed and fed into the reactor where it is exposed to temperatures ranging from 375-415°C for a period of approximately four hours. Vapors produced are then condensed into a light sweet synthetic crude oil and non-condensable gases. A portion of the synthetic crude oil currently undergoes fractionation on an R&D basis to produce distillate fuel oils, which are used for onsite heating and equipment operations, and stored for use as start-up fuel for a

[80] Fractionated fuels have not been formally tested to determine whether they are on-spec.

future commercial system. 100% of non-condensable gases are utilized onsite, with a reported potential for excess gas to be converted into electricity.

1.5.1B Feedstock Supply

The Nexus Fuels pilot system is processing 1.5-2 TPD of predominantly HDPE drums from the food service industry with lesser quantities being sourced from a local single stream MRF. The pilot system does not currently process plastic films however future commercial systems are expected to be equipped with an upfront densification process, allowing for the processing of film feedstocks. Target resins include HDPE, LDPE, PP and PS with contamination limits of <=1% PVC and <=2% PET preferred, although samples have reportedly been processed with high contamination rates for testing and demonstration purposes. The pilot system is currently processing feedstock that has been provided at no cost although Nexus Fuels indicated they may be willing to pay for feedstock in the future.

1.5.1C Additional Inputs

The Nexus Fuels technology requires electricity and water although the current configuration utilizes a closed loop-cooling system, which eliminates the need for water. Onsite water and electricity requirements for the pilot system were not disclosed.

1.5.1D Outputs

Liquid Petroleum Product

One ton of target waste plastics reportedly produce 5.2-6.7 US barrels or 220-280 gallons of light sweet synthetic crude for a 72-79% plastic to oil conversion rate. Reported yields assume feedstock is relatively clean HDPE, LDPE, PP and PS. Light sweet synthetic crude has undergone R&D grade fractionation onsite into distillate fuels including gasoline and diesel blendstocks, naphtha and kerosene. According to Nexus Fuels, preliminary third party lab testing has indicated fuel components could meet most quality standards however fuels will not undergo formal testing until a commercial fractionation system is installed.

Wastewater

The pilot system does not currently produce wastewater due to its closed loop cooling system design. Future commercial systems will employ water-based cooling towers; however wastewater quantities are expected to be low.

Char, Non-condensable Gases and Other Byproducts

Based on the composition of feedstocks tested at the Nexus Fuels PTF system, char production rates range from 5-10% of incoming feedstock. Char is currently landfill disposed as non-hazardous waste. Wax is a secondary byproduct of the Nexus Fuels technology, which could provide an additional revenue stream should end markets be identified. Wax production is estimated at 3-10% of incoming waste. Syngas production ranges from 8-12% of incoming waste, which is currently used to operate the system.

1.5.1E System Costs

Capital and operating costs of the pilot system were not provided, as they are not reflective of future commercial offerings.

1.5.1F Outlook

Nexus Fuels has an undisclosed strategic investor with whom they will design-build-own-operate PTF systems across the United States. Nexus is willing to entertain alternative business arrangements both domestically and internationally whereby they would partner with Project Developers or municipalities in feedstock-for-preferred-pricing offtake agreements. Nexus Fuels is in the process of developing its first commercial scale, 50 TPD system in the southeastern US with operations anticipated in late 2015.

1.5.2 PK CLEAN—SALT LAKE CITY, UT, USA

PK Clean began operating their pilot scale, 5 TPD PTF system in Salt Lake City, Utah in July 2013. The system was relocated from the University of Utah to a private site in March 2014 and achieved continuous, 4 day/week operations in July 2014. The system was self-financed and employs 4 full time workers. An independent engineering analysis has reportedly been performed although it was not made available to ORA.

ORA observed metal contaminants being pulled from incoming feedstocks, plastic feedstocks being shred and fed into the reactor and oil products and wax exiting the multi-stage condenser. The bales stored on site and those being processed during the visit appeared to have a material composition consistent with that coming from a single stream MRF.

Table 13: PK Clean System Summary

Owner/Operator	PK Clean
Technology	Catalytic Depolymerization, Continuous Flow
Technology Provider	PK Clean
System Location	Salt Lake City, UT, USA
Commercialization Stage	Pilot
Design Capacity	Pilot Scale, 5 TPD
Operating Status	Continuous, At Capacity
Operating Throughput	5 TPD
Feedstocks Processed	Rigid #1-7
Feedstock Sources	Predominantly Post Consumer Plastics from multiple, regional single stream MRFs
Liquid Petroleum Product/s	Light sweet synthetic crude oil[81]

[81] Company reported an ability to sell synthetic crude oil or distillate fuel oils, depending on local markets. The Salt Lake City system has successful sold synthetic crude oil to date and is currently producing and storing distillate fuel oils for sale once they reach an unspecified quantity.

Liquid Petroleum Product Production Rate	6 US Barrels/Ton reported
End User	Sold to Local Refineries
Site Visit Date	July 2014

1.5.2A Process Overview

A mixture of baled and pre-shredded plastics is processed at the PK Clean system. Baled plastics undergo hand or mechanical removal of visible contaminants followed by shredding to achieve uniformity with materials that have been shred offsite by the company's material suppliers. The feedstock passes through a pre-melting process before entering the reactor where it is vaporized. The vapor then enters a three-stage condensing system where it condenses into a diesel oil product, light oil and a wax. The diesel oil product and light oil are blended together before being sold as crude to a local refinery while the wax is re-circulated into the reactor for additional processing.

1.5.2B Feedstock Supply

Waste plastics #1-7 are currently sourced from regional MRFs that process recyclables from municipal and commercial waste streams. Plastics #2, 4, 5 and 6 are targeted by the reactor for depolymerization. The majority of incoming feedstock is shredded by the MRF operator prior to delivery, although PK Clean is able and willing to undertake shredding onsite. PK Clean is not currently paying for feedstock from suppliers but is willing to pay a few cents per pound or share revenues in order to guarantee long-term supply. The company has developed a proprietary process that allows their system to accept more heterogeneous feedstocks from a variety of sources, including streams with combined quantities of PVC and PET as high as 40%. Profitability was said to decrease at higher levels.

1.5.2C Inputs

The PK Clean technology requires electricity and water. Onsite electricity requirements for the pilot system are approximately 200,000 kWh/year and onsite water requirements are approximately 1.5 million gallons/year. The company offers an optional, proprietary catalyst, which is only recommended for feedstocks containing high quantities of difficult to crack materials such as HDPE. The PK Clean system does not require additional fuel.

1.5.2D Outputs

Liquid Petroleum Product

The PK Clean system reportedly produces 6 US barrels or 250 gallons per ton of feedstock fed into the reactor, with 2/3 of the oil product exiting a three-stage condenser as a diesel blendstock and 1/3 as light oil. The relative distribution of end products can reportedly be manipulated depending on local end markets by modifying operating parameters. 100% of the liquid petroleum products produced are currently blended and sold as light sweet synthetic crude oil to one of five local refineries although PK Clean reported to be upgrading fuels onsite for future sale as distillate fuel oils.

Wastewater

Water is filtered and re-circulated onsite therefore; the PK Clean system does not produce wastewater that requires offsite treatment.

Char, Non-condensable Gases and Other Byproducts

Char production rates range from 5-10% of the incoming feedstock. Char is currently being stored onsite at the Salt Lake City facility until a large enough quantity is amassed to sell. Non-condensable gases are utilized onsite. Wax produced by the condensing process is re-circulated into the reactor for additional processing.

1.5.2E System Costs

The PK Clean pilot system was self-financed. Capital costs are not reflective of future commercial offering and therefore were not provided. O&M costs were said to range from $25-$37/barrel, with low-end costs reflecting no materials acquisition or residuals management costs. O&M estimates are inclusive of insurance, testing, labor, utilities, end product testing and transportation of oil to the end user.

1.5.2F Outlook

As of January 2015, PK Clean was undertaking a capacity upgrade at their Salt Lake City facility. Commercial scale operations are expected for summer 2015. The company is also currently in discussions with project development partners in the US and expects to develop a second, commercial scale system under a joint venture model in 2015.

1.5.3 AGILYX—TIGARD, OR, USA

In December 2013, Agilyx began operations at a pilot scale PTF facility in Tigard, OR, USA. The self-financed facility represents the Gen 6 technology, the company's feature offering. Agilyx's Gen 6 is a continuously fed non-catalytic pyrolysis system that includes a heated, self-cleaning dual-screw reactor. The facility is currently processing an average of 10 TPD of waste plastics on a continuous basis. The pilot facility is currently producing light sweet synthetic crude oil, of which it has sold 600,000 gallons to a local refinery. The system has an up-time of 92%. An independent study has reportedly been performed on the system, but it was not provided for review.

ORA conducted a site visit of the Tigard, Oregon facility in September 2014. During this visit, ORA observed pre-shred mixed rigid plastics being fed into the system and film plastic stored onsite. Agilyx indicated that film plastics would be blended with rigid plastics and processed at the site. ORA did not observe film plastics being processed at the time of its visit.

Table 14: Agilyx System Summary

Owner/Operator	Agilyx
Technology	Thermal Depolymerization, Continuous Flow
Technology Provider	Agilyx

System Location	Tigard, OR, USA
Commercialization Stage	Gen 5- Commercial Gen 6- Pilot
Design Capacity	PIlot Scale, 10 TPD
Operating Status	Continuous, At Capacity
Operating Throughput	10 TPD
Feedstocks Processed	Rigid #2,4,5,6,7 (Films reported but not observed at time of visit)
Feedstock Sources	Post-consumer plastics from a single stream MRF and post-industrial plastics
Liquid Petroleum Product/s	Light sweet synthetic crude oil
Liquid Petroleum Product Production Rate	5.14 – 5.26 barrels/ton reported
End User	Sold to Local Refinery
Site Visit Date	September 2014

Image 3 - Agilyx System, Tigard, OR, USA

1.5.3A Process Overview

Feedstock arrives at the system pre-prepared by feedstock suppliers. Feedstock is shredded to a dimension of ½". In future commercial applications, Agilyx will seek to co-locate near a MRF, where pre-processing systems are already in place to minimize front-end costs. Once at the system, plastic feedstock is placed in storage bags on the stock floor. Each batch is tested in a bench scale system onsite to determine feedstock composition. Prepared plastics feedstock is placed on a hopper and loaded onto conveyer belts.

Once on the conveyer, a magnet pulls most remaining ferrous metals out of the input stream. Material is continuously fed into the system at automated 30-40 second intervals. Input material enters the reactor where heated dual screws rotating forwards and backwards at slightly different speeds feed it through several different heating zones. The relative movement of the screws creates a self-cleaning action. Any residues scraped off of the cartridge flights in this stage are collected as char. Plastics move through several heating zones and are converted into hydrocarbon gases. These pass to a condensing tower chamber, which uses a cold water spray to condense the majority of the gases into heavy oil. The oil and water emulsion is sent to a coalescing tank, where the oil and water are separated. The light hydrocarbons exit from the top of the condenser as gases and are subsequently condensed in a chiller as light oil which is sent directly to storage. The heavy oil is conditioned to adjust pH, remove particulates and lower organic salts before it is sent to storage as well.

1.5.3B Feedstock Supply

Feedstock quality is critical to generate yields for economic feasibility. Agilyx' s process favors #2, 4, 5, 6 and 7. Agilyx asserts to target plastic film, although indicated that it must be combined with higher density plastics in order to facilitate processing. The pilot system is currently processing feedstock that comes from a clean, single-stream MRF that sorts recyclables from residential and commercial sources. The system also sources feedstock from haulers, manufacturers and a variety of distinct industrial markets. Agilyx operates a separate bench scale unit to test the quality and composition of incoming plastics.

1.5.3C Inputs

The Agilyx system requires natural gas for start-up, electricity and water in the condensing and oil conditioning stages. The company did not disclose the amount of inputs required by the system.

1.5.3D Outputs

Liquid Petroleum Product

The Agilyx system produces light sweet synthetic crude oil that is currently sent to a refinery for further processing. The company indicated that the oil must contain less than 1% residual matter in order for it to have value for a refinery. Agilyx and their end user both undertake testing to ensure the product meets specifications, which can differ according to the refinery. The process has a liquid oil conversion rate of 72-75%, or 211-221 gallons/ton.

Wastewater

The Agilyx system produces wastewater from condensation and the oil conditioning process, which is sent offsite for treatment. Wastewater generation rates were not disclosed.

Char, Non-condensable Gases and Other Byproducts

Char production rates range from 7-10% by weight of incoming feedstock depending on the quality of the incoming feedstock. Agilyx indicated that char is an inert material and is not considered hazardous. At present, the system is disposing of char in landfill, however, plans to explore other end markets in the future. Non-condensable gas production ranges from 7-15% by weight of incoming feedstock. Agilyx is thermally destructing these gases on-site, but in the future may return-feed them into the system to offset the systems parasitic load. The Agilyx system produces trace amounts of hazardous waste from filter cartridges in the wastewater treatment skid, which requires special disposal.

1.5.3E System Costs

Capital costs for the Agilyx pilot are not indicative of future commercial Generation 6 offerings and were therefore not provided. Capital costs for their 50 TPD commercial scale system range from $12 to $13 million. Capital cost estimates are exclusive of building, site development, pre-development (soft), and pre-processing costs. O&M costs are proprietary.

1.5.3F Outlook

Agilyx is in the process of commissioning a system in North America in early 2016. Details were not disclosed.

1.5.4 ADDITIONAL PTF SYSTEMS

Through desk research and conversations with PTF industry players, ORA identified and collected information on additional PTF systems. ORA did not verify the operations of these systems through independent site visits as either 1) they did not meet ORA's site visit criteria listed in Section B, or 2) they were discovered at the end of the Study Period and time did not permit a visit. Several systems were reported to be in operation by a Supplier but ORA was either not provided with contact information or the owner/operator was not reachable for comment.

Table 15: Additional Known PTF Systems

Location	Owner/ Operator	Technology Supplier	Scale	Design Capacity	Operating Period	Feedstocks Processed	Operating Status
Danville, PA, USA	Vadxx	Vadxx	Pilot	1 TPD	March 2010-August 2014 (Akron, OK), system relocated in August 2014	Post-industrial plastics, post-consumer plastics from clean and dirty MRFs[82]	Discontinuous Operations
Niagara Falls, NY, USA	JBI	JBI	Demonstration	25 TPD	March 2010 - 2014	Post-industrial plastics excluding PET and PVC	Not operational[83]
Lithia Springs, GA, USA	GenAgain Technologies	Agilyx- Gen 5	Commercial	50 TPD	Did not Disclose	Did not disclose	Did not disclose
Nantong, Jiangsu Province, China*	Nantong Tianyi Environmental Protection Energy Equipment Co., Ltd.	PARC	Demonstration	20 MTPD	July 2009 - Present	MSW plastic: PE-50%, PP-25%, PS-25% Papermaking waste plastic: PE, PP, PS Industrial plastic scraps: PE, PP, PS, PMMA etc. Scrap tires and oil sludge	Discontinuous Operations
Xinghua, Jiangsu Province, China*	Nantong Tianyi Environmental Protection Energy Equipment Co., Ltd.	PARC	Demonstration	15 MTPD	January 2006 - Present[84]	MSW plastic: PE-50%, PP-25%, PS-25% Papermaking waste plastic: PE, PP, PS Industrial plastic scraps: PE, PP, PS, PMMA etc.	Continuous Operations; Capacity unknown
Sapporo, Japan	Sapporo Plastics Recycling, Co.	Toshiba Corporation	Commercial	<40 TPD	2000 – September 2012	PE, PP, PS	Not operational[85]
Whitehorse, Yukon, Canada	P&M Recycling	Blest	Pilot	528 lbs/day[86]	Installed in 2012-Present	PP, PE and PS from various municipal and industrial	Discontinuous Operations

[82] Plastics can be rigid, flexible, varying densities, varying contamination levels, and can include tires.
[83] As of October 2014.
[84] Facility has reportedly been processing plastics since 2007.
[85] Information provided by Toshiba Corporation, December 2014.
[86] System throughput is 70-80% of stated design capacity.

						sources	
Perry, OH, USA	RES Polyflow	RES Polyflow	Demonstration	60 TPD	March 2013-August 2013	3 batch and 4 continuous feed trials performed with 50% post-consumer MSW and 50% mix of post-industrial plastics[87]	Not operational[88]
Portlaoise, Ireland	Cynar	Cynar	PIlot	10 MTPD	Jul 2010- Present	Trialed plastics from domestic (20%), commercial (10%), agricultural (20%), and construction (20%) waste.[89]	Discontinuous operations.
Tamil Nadu, India	MK Aromatics Limited	Polymer Energy	Commercial	10 MTPD	2009-Present	80% Post consumer 20% post industrial plastics #2,4,5,6,7; 30-35% film plastics, 65-70% rigid plastics	Continuous Operations, At Capacity

* Supplier reported data and/or information not verified by system owner/operator

[87] Post-industrial plastics included tires/ carpet/ agricultural plastics and other materials.
[88] Supplier has taken system offline in preparation for siting at new location.
[89] System can tolerate up to 50% contamination rates in domestic and agricultural feedstocks and 20% in commercial feedstocks.

1.5.5 OUTLOOK

According to Contributing and Participating Suppliers, 35 PTF systems ranging from pilot to commercial scale are reportedly constructed around the world[90]. ORA verified operating status via direct communication with the owner/operator of 14 of the 35 systems. 26 of the 35 systems are reported to be in various stages of operations ranging from discontinuous to continuous. ORA verified operating status via direct communication with the owner/operator of 8 of the 26 operating systems.

Of the total, 24 systems are constructed at the commercial scale. ORA verified operating status via direct communication with the owner/operator of 5 of 24 commercial scale systems. The MK Aromatics Limited system was reported as being fully operational since 2008, the SITA system in Bristol, UK and the Cynar/Plastic Energy SL system in Almeria, Spain are currently in commissioning, PARC is relocating their commercial scale system to a new site and the Sapporo system is no longer operational. The 16 commercial scale Pyrocrat Systems LLP facilities were reported to be fully operational, however did not meet the ORA site visit criteria, as the company did not disclose contact information for the owner/operators of their systems. The operating statuses of the remaining 3 systems are either unknown or were not disclosed by the Supplier or facility operator (Table 16 and Table 17).

It is unknown whether the commercial scale facilities that are reported to be operating on a continuous basis, at capacity, are economically self-sustaining at the present time.

Table 16: Number of PTF Systems Constructed and In Operation

	No. Reported	No. Verified via Direct Communications with System Owner/Operator
	SYSTEMS CONSTRUCTED	
No. of Pilot & Demonstration Scale Systems Constructed	11	9
No. of Commercial Scale Systems Constructed	24[91]	5
TOTAL No. of PTF Systems Constructed	35[92]	14
	SYSTEMS IN OPERATION	
No. of Pilot & Demonstration Scale Systems in Operation	9	7
No. of Commercial Scale Systems in Operation	17	1
TOTAL No. of PTF Systems in Operation	26	8
No. of PTF Systems with Unknown or Undisclosed Operating Status	3	1

Table 17: Constructed Commercial Scale PTF Systems

[90] Blest asserts to have sold more than 60 units worldwide. ORA was only able to identify the location and operating status of one system in Whitehorse, Canada, therefore additional units have not been included in this total.

[91] One facility is currently being relocated to a new site. This facility is not fully constructed at the new site but was constructed and reportedly operational at its previous location.

[92] See previous footnote.

No.	Technology Supplier	Owner/Operator	Location	Operating Status	Economic Status
1	Not Disclosed	SITA	Bristol, UK	In Commissioning	Not Applicable
2	Cynar	Plastic Energy SL*	Almeria, Spain*	In Commissioning*	Not Applicable
3	Agilyx	GenAgain Technologies LLC	Lithia Springs, Georgia, USA	Not Disclosed	Not Disclosed
4	Agilyx	Rational Energies*	Plymouth, Minnesota, USA*	Unknown*	Unknown
5	Agilyx	Waste Management*	North Portland, Oregon, USA*	Unknown*	Unknown
6	Toshiba Corporation	Sapporo Plastics Recycling, Co.	Sapporo, Japan	Not Operational	Not Applicable
7	Polymer Energy	MK Aromatics Limited	Tamil Nadu, India	Operational	Unknown
8	Pyrocrat Systems LLP	Not disclosed	Maharashtra Province, India*	Operational*	Unknown
9	Pyrocrat Systems LLP	Not disclosed	Rajasthan Province, India*	Operational*	Unknown
10	Pyrocrat Systems LLP	Not disclosed	Rajasthan Province, India*	Operational*	Unknown
11	Pyrocrat Systems LLP	Not disclosed	Maharashtra Province, India*	Operational*	Unknown
12	Pyrocrat Systems LLP	Not disclosed	Maharashtra Province, India*	Operational*	Unknown
13	Pyrocrat Systems LLP	Not disclosed	Karnataka Province, India*	Operational*	Unknown
14	Pyrocrat Systems LLP	Not disclosed	Tamil Nadu Province, India*	Operational*	Unknown
15	Pyrocrat Systems LLP	Not disclosed	Maharashtra Province, India*	Operational*	Unknown
16	Pyrocrat Systems LLP	Not disclosed	Maharashtra Province, India*	Operational*	Unknown
17	Pyrocrat Systems LLP	Not disclosed	Maharashtra Province, India*	Operational*	Unknown
18	Pyrocrat Systems LLP	Not disclosed	Maharashtra Province, India*	Operational*	Unknown
19	Pyrocrat Systems LLP	Not disclosed	Gujarat Province, India*	Operational*	Unknown
20	Pyrocrat Systems LLP	Not disclosed	Maharashtra Province, India*	Operational*	Unknown
21	Pyrocrat Systems LLP	Not disclosed	Andhra Pradesh Province, India*	Operational*	Unknown
22	Pyrocrat Systems LLP	Not disclosed	Gujarat Province, India*	Operational*	Unknown
23	Pyrocrat Systems LLP	Not disclosed	Not Disclosed, Europe	Operational*	Unknown

* Supplier reported data and/or information not verified by system owner/operator

Nearly all Contributing and Participating Suppliers have plans to commercialize operations in 2015 or early 2016, if they have not already done so. Several reported having secured operating permits, commitments from investors, and letters of intent (LOIs) for feedstock supply and fuel offtake. ORA identified 19 PTF systems with the potential to achieve full commercialization in 2015 or early 2016 and verified status via direct communication with the owner/operator of 7 of 19 planned systems. Two systems are currently in commissioning, 2 systems are currently under construction, 9 have equipment on order[93], 2 are undertaking site selection and 2 are in the planning stage. PK Clean is currently undertaking a capacity upgrade at their pilot facility in Salt Lake City, UT to achieve commercial scale operations and PARC is relocating its facility to Huaian, China (Table 18 and Table 19). Details on select systems with the potential to commercialize in 2015 or early 2016 are provided in Table 20.

Table 18: Number of Commercial Scale PTF Systems Planned for 2015/Early 2016

[93] Facility status not verified with system owner/operator

	No. Reported	No. Verified via Direct Communications with System Owner/Operator
No. of Commercial Scale Systems in Planning	2	1
No. of Commercial Scale Systems with Equipment On Order	9	0
No. Of Commercial Scale Systems Under Construction	2	1
No. of Commercial Scale Systems in Commissioning	2	1
No. of Commercial Scale Systems in Site Selection	2	2
No. of Systems Undertaking Equipment Transfer or Capacity Upgrade	2	2
TOTAL No. of PTF Systems Planned for 2015/Early 2016	19	7

Table 19: Commercial Scale PTF Systems Planned for 2015 or Early 2016

No.	Technology Supplier	Owner/Operator	Location	Status
1	Cynar	Plastic Energy SL*	Seville, Spain*	Under Construction*
2	Cynar	Plastic Energy SL*	Undisclosed location, South America*	In Planning*
3	Agilyx	Not disclosed	Not disclosed	In Planning
4	Vadxx	Vadxx/Liberation Capital	Akron, Ohio, USA	Under Construction
5	RES Polyflow	RES Polyflow	TBD, Ohio or Indiana, USA	Site Selection underway
6	Nexus Fuels	Nexus Fuels	TBD, Southeastern, USA	Site Selection underway
7	PARC	PARC	Huaian, China	Equipment transfer underway
8	Pyrocrat Systems LLP	Not disclosed	Madhya Pradesh Province, India*	Equipment on order*
9	Pyrocrat Systems LLP	Not disclosed	Maharashtra Province, India*	Equipment on order*
10	Pyrocrat Systems LLP	Not disclosed	Gujarat Province, India*	Equipment on order*
11	Pyrocrat Systems LLP	Not disclosed	Maharashtra Province, India*	Equipment on order*
12	Pyrocrat Systems LLP	Not disclosed	Maharashtra Province, India*	Equipment on order*
13	Pyrocrat Systems LLP	Not disclosed	Maharashtra Province, India*	Equipment on order*
14	Pyrocrat Systems LLP	Not disclosed	Madhya Pradesh Province, India*	Equipment on order*
15	Pyrocrat Systems LLP	Not disclosed	Tamil Nadu Province, India*	Equipment on order*
16	Pyrocrat Systems LLP	Not disclosed	Maharashtra Province, India*	Equipment on order*
17	PK Clean	PK Clean	Salt Lake City, Utah	Capacity upgrade underway

* Supplier reported data and/or information not verified by system owner/operator

Vadxx recently announced a partnership with Liberation Capital, a US-based private equity fund specializing in project finance for small renewable energy, water and wastewater projects, to own/operate multiple PTF systems. Rockwell Automation is the company's EPC. Construction is scheduled for completion on their first commercial scale 60 TPD system in Akron, OH in December 2014 with equipment installation planned for January 2015 and operations for March/April 2015. The system will process pre-sorted, pre-processed rigid and film polymer feedstocks (plastics #2,4,5,6, 7 and select rubbers) from industry and municipal single-stream MRFs to produce a middle distillate on-spec #2 diesel fuel blendstock that meets ASTM D975. Vadxx is projecting a refined fuel production rate of 250 gallons/ton of feedstock entering the reactor and indicated that their fuel product will be sold to a blender for direct terminal blending with diesel. The system has been approved as a de minimis air pollution source (OAC 3745-15-05) in the state of Ohio designating that it emits less than 10 lbs/day of any air contaminant and less than 1 TPY of any hazardous air pollutant and has an operating permit in place. Feedstock supply is secured for the Akron, OH site and Vadxx is currently negotiating an offtake agreement for the sale of fuel products produced. Vadxx holds permits for three more PTF systems and is seeking additional feedstock within the hauling range of Chicago IL, Louisville KY, Toronto ON, and Easton PA for the development of future sites.

In 2013, Cynar Plc signed a contract with Project Developer, Plastic Energy SL, for the development of 8 PTF systems in Spain and Portugal and 15-20 PTF systems in South America, Florida and the Caribbean. Construction on the first commercial scale system in Almeria, Spain is complete and the system is currently in commissioning. Inerco is the company's EPC. The system will process a blend of post-consumer and post-industrial rigid and film plastic #2,4,5,6 from a co-located single stream MRF and other MRFs to produce a middle distillate on-spec #2 diesel fuel blendstock meeting ASTM D975 and

Image 4 - Cynar/Plastic Energy Sl System in Almeria, Spain

EN590 (CynDiesel™), light oil (CynLite™) and kerosene (CynKero™). All feedstock is secured for the facility. Cynar is projecting a refined fuel production rate of 275 gallons/ton and indicated that an offtake

is in the place with an oil distributor for the purchase of the fuels produced. A second commercial system is currently concluding construction in Seville, Spain with equipment installation scheduled to begin in December 2014 and a third plant is being planned at an undisclosed location in South America.

Table 20: Detail on Select Known PTF Systems with Potential to Fully Commercialize Operations in 2015/Early 2016 (Design Capacity >=1 TPD)

Location	Akron, OH, USA	Almeria, Spain	Seville, Spain	Bristol, England, UK	TBD- OH or IN	TBD- South Eastern US
Owner/ Operator	Liberation Capital, Vadxx	Plastic Energy	Plastic Energy	SITA	RES Polyflow	Nexus Fuels and Undisclosed strategic investor
Technology Supplier	Vadxx	Cynar Plc	Cynar Plc	Not disclosed	RES PolyFlow	Nexus Fuels
Scale	Commercial	Commercial*	Commercial*	Commercial	Commercial	Commercial
Design Capacity	60 TPD	20 MTPD*	20 MTPD*	20 MTPD	60 TPD	50 TPD
Planned Feedstocks	Blend of post consumer and post industrial rigid and film plastics	Blend of post-consumer and post industrial rigid and film plastics*	Blend of post-consumer and post industrial rigid and film plastics*	Blend of post consumer and post industrial rigid and film plastics	Post industrial scrap, post consumer #3-7 bales, agricultural film, marina and vehicle shrink wrap, contaminated/ off spec compounds	Blend of post industrial and post consumer plastics
Feedstock Source	Single stream MRF	Supply from co-located single stream MRF and other regional MRFs*	Single stream MRF*	Supply from co-located MRF owned/operated by SITA	TBD	TBD
Oil Product	On Spec Middle Distillate #2 Diesel	CynDiesel™, CynLite™ and CynKero™*	CynDiesel™, CynLite™ and CynKero™*	Not disclosed	Naphtha blendstock, Distillate blendstock, Heavy Oil	Blend of light sweet crude, Fuel Oil #2 fractionated diesel blendstock, gasoline blendstock, kerosene blendstock, wax
End Use	Direct Terminal Blending	Bulk Sales to oil distributor, End use unknown*	Bulk Sales to oil distributor, End use unknown*	Not disclosed	Blendstock sales to fuel blenders, Heavy oil sales to consolidator or direct to end user	Light sweet crude sales to broker, fuel Oil #2 sales to strategic investor, fractionated fuel sales into local markets for blending into transportation fuels
Status	In Construction. Equipment delivery scheduled for Jan 2015	In Commissioning*	In Construction. Equipment delivery schedule for Dec	In Commissioning	Site Selection Underway, (existing demonstration scale	Site Selection Underway

			2014*		system will be re-located)	
Feedstock Agreements in Place? (% of Feedstock Covered)	100% secured	100% secured*	100% secured*	100% provided by own internal supply	LOIs in place (100%)	No
Off Take Agreements in Place? (% of End Product Covered)	Negotiations Underway	100% under contract*	100% under contract*	100% under contract	LOIs in place (<100%)	For #2 heating oil only
Financing in Place?	Yes	Yes*	Yes*	Yes	Equity raise underway	No
Permits in Place?	Yes	Yes*	Yes*	Yes	No	No
Anticipated Operations Start Date	March/April 2015	Q1 2015*	Q2 2015*	Q2 2015	Early 2016	Q4 2015

* Supplier reported data and/or information not verified by system owner/operator

1.6 KEY CHALLENGES, OPPORTUNITIES AND OBSERVATIONS

1.6.1 CHALLENGES AND OPPORTUNITIES

Along the path to PTF commercialization, stakeholders have highlighted key challenges to the development and future success of PTF systems.

Feedstock Quality – One salient challenge for companies is securing access to consistently high quality feedstock. Feedstock variability can have economic implications given that certain resins produce higher liquid petroleum product yields than others, and high contamination rates can lead to greater char management costs, reduced liquid petroleum product yields, and the production of chlorines. The composition of plastic bales differs considerably from MRF to MRF, and PTF systems may require that material suppliers undertake additional and potentially costly pre-sorting measures in order to adhere to feedstock requirements. Some PTF systems may also require that material suppliers shred, dry or chip feedstock prior to delivery. Additional costs incurred by the feedstock supplier are then passed on to the PTF system operator, leading to an increase in material acquisition costs.

Chlorine contamination is another challenge. Although PVC makes up a small percentage of the plastic waste stream and companies are intent on its removal, there are other sources of chlorine contamination in plastics, such as applied flame-retardants, in less easily detected sources. Suppliers reported conducting visual inspections, periodic burn tests and using instrumentation to assess incoming feedstock quality as well as testing chloride levels at the back end.

Feedstock Volume – Unlike other MSW management facilities that are able to enter into long-term feedstock supply agreements, the PTF market is challenged by the need for a relatively desirable feedstock whose market price fluctuates with the value of crude oil. Feedstock suppliers are reluctant to commit to long-term binding agreements, as they often hedge on market fluctuations and future price expectations to yield higher profit margins. Furthermore, as recycling rates for PS, PP, HDPE and other resins continue to rise, PTF operators may see reduced access to feedstock and have to pay higher acquisition costs. While PTF targets some resins that are not readily recycled, PTF may end up competing with traditional recycling markets for plastic feedstock raising environmental, economic and technical questions about whether the systems are sustainable. In locations where recycling markets and collection and sorting infrastructure are not well developed, opportunities exist to establish dedicated drop off centers for target feedstocks whereby citizens would deliver plastics to a centralized location in exchange for a small fee. This model is said to be successfully supplying feedstock for the MK Aromatics Limited system in India.

Wastewater Generation and Energy Requirements – Some companies generate wastewater as a byproduct of the process, especially for technologies that are desalting and conditioning oils. This is an additional back-end processing requirement for projects and may also require additional permitting. Electricity requirements vary across Suppliers. In regions where electricity is produced with diesel generators and costs are high, supplemental renewable energy sources may need to be developed in parallel or a portion of the liquid petroleum product may need to be used to meet onsite electricity demand.

Offtake Agreements and Access to End Users– Given that PTF is still an emerging industry, it has yet to establish a robust market for synthetic crude oil and distillate fuel oils. With variations in feedstock quality come variations in liquid petroleum product quality, which can lead to unpredictability and unnecessary risk for buyers. Furthermore, small quantities of liquid petroleum product produced compared with larger scale refineries may make it difficult to place into the market. In order for offtake agreements to be secured, it is necessary to identify end users that assign value to local waste-derived fuel supply. Additionally, developers in remote locations may be limited by their access to distribution networks and refineries, which may confine them to certain Suppliers.

Access to financing – Currently, there are a limited number of financing players due to high levels of perceived investment risk, a limited understanding of the technology's capabilities and performance and a lack of long-term offtake and feedstock supply agreements. As a result, traditional debt structures are difficult to access or are not appropriate to finance the development of PTF systems.

In spite of these challenges, Suppliers and Project Developers are responding with strategies to increase system efficiency, improve system siting and system economics.

Improved Processing Efficiency – In order to maximize technological efficiency, many Suppliers are configuring their technology solution to a continuous feed system and phasing out batch feed system designs. Suppliers are also undertaking system modifications to improve system economics by reducing energy and water inputs, increasing onsite electricity generation, and reducing system downtime. Although some system operators have experienced technical and operational challenges delaying immediate scale up and commercialization, operators and Suppliers are rising to the challenge with innovative engineering to overcome process bottlenecks and improve performance.

System Sizing – Given the availability of suitable plastic feedstock in a defined area and the associated costs with sourcing plastic feedstock for a PTF system, many Suppliers are tending towards smaller, more compact modular system designs (10-60 TPD). Suppliers are tending towards these design capacities to meet current demand, optimize economic performance and facilitate siting. RES Polyflow is also proposing a spoke and wheel system where they would operate decentralized pre-processing facilities and a centralized PTF system.

Permitting – Some Suppliers are shifting towards business models that incorporate pre-processing off-site. This not only reduces system footprint, capital and operating costs, but may also facilitate permitting as a manufacturing facility rather than a waste processing facility. Other Suppliers have made a strategic decision to pursue a solid waste permit and undertake pre-processing onsite, thereby increasing access to feedstock and decreasing material acquisition costs. One Supplier with plans to seek a solid waste permit for a future commercial system reported the need to revise regulations to increase material storage limits on-site to allow for preemptive feedstock acquisition prior to system startup. Stakeholders interviewed cited no public opposition to the development of their systems and reported an unchallenged permitting process.

Co-location of PTF Systems with Materials Recovery Facilities – In order to ensure a consistent supply of high quality feedstock and to reduce costs associated with feedstock transportation, many Suppliers are co-locating PTF systems with MRFs.

1.6.2 OBSERVATIONS AND CONCLUSIONS

As the industry marches forward on the path to commercialization, the future outlook of PTF is promising. In particular, several operational successes were noted:

- ***System Operations at Scale*** - ORA did not observe commercial scale operations during the Study Period however it verified operations at the 1.5-2, 5 and 10 TPD scale across three different pilot scale systems. PK Clean and Agilyx are currently operating their systems on a continuous basis, at capacity, while Nexus Fuels is operating on a discontinuous basis.
- ***Feedstocks Processed*** - ORA observed the processing of shredded rigid HDPE and a shredded blend of rigid post-consumer plastics from a single stream MRF and post-industrial plastics. ORA did not observe the processing of film plastics although films were visible onsite at the Agilyx site. Several Participating Suppliers reported on their ability and interest in processing films in combination with rigid plastics.[94] ORA was not able to independently verify whether evaluated facilities are processing end-of-life plastics.
- ***Liquid Petroleum Production*** - ORA observed a liquid petroleum product being produced at the systems visited.[95] PK Clean and Agilyx reported successfully marketing their synthetic crude oil to refineries in the US while Nexus Fuels is utilizing and storing their end product onsite. Several additional Suppliers reported on successfully marketing liquid petroleum products when their systems were operational.

In addition to operational achievements of the PTF industry to date, the following policy and contextual factors will contribute to the future advancement of PTF:

- With the introduction of the "Green Fence" in February 2013, US mixed rigid bale exports to China have decreased due to tighter contamination standards. With a limited but growing domestic market for these materials, and few plastic separation systems that can process mixed bales,[96] PTF systems may be able to absorb materials that were previously targeted for export, presuming they meet feedstock requirements and cannot be absorbed by recycling markets.
- In Europe and the US where environmental permitting standards are stringent, all systems were reportedly permitted in the lowest category of air emissions. While a detailed assessment of the potential greenhouse gas benefits of PTF was not undertaken as part of this study, Vadxx noted that a 60 TPD system was expected to produce an estimated 13 tons of CO2e/year.

Looking ahead to how the PTF industry will continue to take shape, there are several considerations and trends to note:

- Opportunities for system deployment are greatest around population centers where volumes are high and transportation distances low. For Suppliers that produce synthetic crude oil, proximity to a refinery end user is also preferable. All Suppliers indicated a willingness to purchase feedstock, signaling that system economics are competitive.
- The PTF industry is currently dominated by the private sector. While municipalities may play a role in feedstock supply, they are more risk adverse and unlikely to pursue the development of

[94] ORA did not independently test the composition of feedstock processed by the systems.
[95] ORA did not independently test the quality of petroleum products produced.
[96] Moore Recycling Associates, Inc. 2012 National Post-consumer Non-Bottle Rigid Plastic Recycling Report. March 2014

publically owned and operated PTF systems until a site has been operating for 10,000 consecutive hours.

- Given that securing feedstock supply and offtake are some of the greatest challenges in deploying a PTF system, facility deployment could be expedited through the facilitation of a hospitable regulatory environment that promotes the landfill diversion of plastics and the production of alternative energy sources. Concerns exist around whether PTF may compete for plastic feedstock with traditional recycling systems, particularly given high liquid petroleum product yields from HDPE. Feedstock acquisition practices vary by Supplier and facility location however Supplier willingness to pay for feedstock may be predictive of a competitive landscape.
- With current fluctuations in oil prices, system economics may be negatively impacted with sustained low prices for crude oil and refined fuels. At the time of publication, crude oil prices reached $55.26/Barrel[97] and the retail price of ultra-low sulfur diesel fuel was $3.281/gallon[98]. Consequently, it is expected that PTF Suppliers will invest in additional R&D to improve the efficiency of existing systems and become more selective around feedstock quality to ensure greater resiliency to future drops in petroleum product prices.
- Despite the small number of commercial scale systems online at this time, investors are committing to multi-plant investments and Project Developers are committing to multi-plant orders signaling that the technology has successfully met or exceeded preliminary financial and technical expectations. The PTF landscape is competitive as Suppliers compete for first mover advantage with further advancements towards full commercialization expected in 2015 and 2016.
- With 80% of marine plastics originating from land-based sources, programs, policies and processing systems that stimulate demand for end-of-life plastics are essential to curbing the flow of plastic to the oceans. PTF systems have the potential to create incentive structures that increase the amount of plastics collected and converted for beneficial use, if systems are developed in conjunction with collection systems that target otherwise indiscriminately discard or landfill dispose plastic waste.

[97] http://www.oil-price.net Date: December 23, 2014 Price for WTI Crude Oil
[98] http://www.eia.gov/dnav/pet/pet_pri_gnd_dcus_nus_w.htm Date: December 23, 2014 Price for ULSD

PART II: PROJECT DEVELOPMENT GUIDELINES AND RECOMMENDATIONS

The successful development of a PTF system is influenced by many factors – technical, financial, policy-environment, among others. PTF Suppliers indicated that permitting, siting, securing feedstocks and offtake, etc. (Project Planning Steps) can span 6 to 18 months with lead times on equipment delivery and construction also ranging from 6 to 18 months for a total development timeline of 12 to 36 months. Once an entity decides to pursue the development of a PTF system, the process of developing a system requires several key steps:

1. Determining Project Development Structure
2. Assessing Technical Viability
3. Assessing Financial Viability
4. Partnership Development
5. Mobilizing Project Finance
6. Siting and Permitting
7. Risk Mitigation Strategies

The sections below describe each step in detail.

2.1 DETERMINING PROJECT DEVELOPMENT STRUCTURE

Prior to the development of a PTF system, interested parties must coordinate with Suppliers to determine the most appropriate project development structure. Project development structure may be determined by the Supplier's current business model offering. Current project development structures available from companies contacted for this report are described below. In "4. Partnership Development", we detail the process and types of strategic partnerships for the development of PTF systems.

Design Build Own Operate– At present, the most prevalent of existing project development structures are DBOO. Among the companies that ORA contacted, Nexus Fuels, Vadxx, Agilyx, Golden Renewables and RES Polyflow are currently operating under this project development structure. Many Suppliers are electing to develop their first plants under this model to achieve proof of concept. This model is a vertical integration of all aspects of project development through which the Suppliers take on exclusive risk for the development and operations of a plant.

Joint Venture – Under a joint venture, Suppliers select Strategic Project Partners to help fund 50% (or other meaningful percentage) of capital expenditures, provide guaranteed feedstock agreements, guaranteed offtake agreements and/or land. Suppliers provide technology, operating expertise as well as service and maintenance. The partnership usually entails a profit sharing agreement for net revenues from the sale of the liquid petroleum product. Suppliers offering this project development structure have mutable terms that may be negotiated as needed. Companies contacted that are operating under this project development structure include Agilyx and PK Clean.

Equipment Sales and Service – Equipment sales and service agreements entail a purchase of the complete turnkey equipment by an interested party. Suppliers only provide the technology package and necessary training to configure a system ready for use. In these project development structures, technology vendors will sell PTF units for a fixed price. This includes capital infrastructure, configuration and set up, preliminary testing and training. Long-term service and maintenance agreements can also be offered through the equipment sales model as a percentage of revenues. Companies currently offering this project development structure include: PK Clean, Agilyx, JBI, Pyrocrat Systems LLP, Golden Renewables and Blest.

Licensing – Some Suppliers offer a licensing arrangement, through which they provide the intellectual property for the development of a PTF system for a fee (fixed or yearly). A trailing royalty estimated as a percentage of revenues from the sale of liquid petroleum products may also be required. Cynar, Vadxx, RES Polyflow, Golden Renewables and Agilyx offer licensing agreements with qualified third parties.

Public Private Partnership - In a public private partnership (PPP), each party contributes financial, human and technical resources and has shared responsibility for the decision-making process. There are 5 primary types of PPPs: service contracts, management contracts, lease contracts, build-operate-transfer contracts, and concessions. Under each contract structure, the project owner is able to enter into contract with an independent operator for the day-to-day management of the project. MK Aromatics Limited is the only Supplier that reported developing systems under a PPP project structure.

2.2 ASSESSING TECHNICAL VIABILITY

Technical viability is defined by the fit between the Supplier and other the project partners' desired outcomes for the system. Interested Project Developers must define goals for the liquid petroleum product produced from a PTF system and identify which Suppliers can provide compatible offerings. Assessing technical viability and understanding input and output markets is a critical step for Project Developers to undertake in order to determine the most suitable output offering.

Assess the sources, composition and quantities of available plastic feedstock - Project Developers must assess the sources and quantities of plastic feedstock available. Plastics targeted for PTF systems can originate from municipal, agricultural, commercial or industrial sources, and be sourced directly from the generator or from a MRF. As transportation costs for input materials can significantly affect the financial viability of the system, it is important to determine whether the source of plastic feedstock is close to or co-located to the projected site of the PTF system.

In addition to identifying potential sources of plastic feedstock, Project Developers must also be able to demonstrate that the quality of plastic feedstock is compatible with the processing system and is an appropriate composition to produce the liquid petroleum yields required to meet financial returns. Key feedstock characteristics evaluated are:

- <u>Plastic resin composition</u> - Most PTF technologies have higher liquid petroleum product yields with clean #2, 4, 5 and 6 although a small number of vendors accept #1-7 with low levels of #1 and #3 and/or with the addition of pre-processing equipment.
- <u>Contamination Level</u> - Contamination can include non-target plastics such as PVC and PET and other wastes such as paper, metal, wood, etc. Contamination levels impact overall system throughput and therefore liquid petroleum product yields and char production rates.
- <u>Particle size/Pre-sorting</u> - Many PTF technology vendors prefer that plastics be delivered to the system pre-sorted and shred. Doing so reduces onsite capital and operating costs but may result

in higher material acquisition costs. In the US, off site pre-processing allows for permitting as a manufacturing system rather than a waste processing system. Suppliers that have made a strategic decision to pre-process materials onsite have done so with the expectation that it will increase access to low-cost, target feedstocks.

- Moisture Level - According to PTF Suppliers, moisture levels are not problematic for processing, however do reduce the conversion efficiency during the pyrolytic process. When moisture levels increase, higher quantities of feedstock are required to produce the desired amount of liquid petroleum product output.

Lastly, Project Developers must determine whether available sources of target plastics can produce quantities consistent with system design capacity. Participating Suppliers offer PTF systems in design capacities of 10, 20, 24, 30, 50 and 60 TPD and 3, 6, 12, 15, 20, 25 and 60 MTPD. While systems can be installed in parallel to increase throughput capacity, additional R&D would be required to scale down capacity; therefore system economics are optimized when feedstock quantities are matched to these throughputs or multipliers thereof. As the most advanced technologies operate on a continuous basis, it is also important to have a secured supply of consistent, high-quality plastic feedstock. Some Suppliers recommend stockpiling feedstock in advance of system start-up to ensure a steady supply of material.

Complete plastics feedstock analysis for quality control – Suppliers typically require that interested parties provide feedstock samples or composition analyses. Many PTF Suppliers test feedstock samples to produce an oil assay, which is then used as a basis for estimating liquid petroleum product yields and quality.

Assess Availability of Markets for Petroleum Products- Given that PTF systems are economically driven by the sale of liquid petroleum products, it is essential to identify potential end markets. Given the desired output – such as fuel blendstocks or synthetic crude oil – it is important to identify potential offtake buyers for the output produced and select a Supplier that has demonstrated experience producing the desired quality of end product. Some Suppliers have the ability to customize back end configurations to fractionate some or all of the liquid petroleum output to meet the demand of local markets, although this varies by Supplier. Therefore, it is important to identify Suppliers that can produce the desired end product that matches the demand of local markets.

2.3 ASSESSING FINANCIAL VIABILITY

The financial evaluation of a potential PTF system involves developing a business plan and comparing projected expenses and revenues.

Estimate Revenues — Once the quantity of liquid petroleum product/s and additional end products (i.e. char, syngas, wax, non-target plastic rejects, etc.) are estimated, the revenues from the sale of these products can be calculated. Potential markets for liquid petroleum products include: heating oil companies, refineries, industrial users, oil brokers, and blenders. Potential markets for secondary end products include: road construction companies, industrial end users, cement kilns, and recyclers. In the absence of available markets for secondary end products, developers are typically responsible for transportation and proper disposal. Revenues are calculated as the estimated quantity of product produced multiplied by the contract price paid by the customer. Suppliers contacted for this report indicated that they are selling their liquid petroleum products at prevailing market prices. With this in mind, assumptions about projected revenues for petroleum products will tend to be consistent with global market prices. Additionally, depending on local conditions, incentives such as state or federally subsidized renewable energy credits can also become project revenues.

Quantify Capital and Operations and Maintenance (O&M) Expenses — Each PTF system has its own unique capital and O&M costs. Suppliers also have individual business models that impact overall costs. Capital cost considerations can include: equipment, installation, building/land purchase and soft costs. Operating costs considerations can include: debt service/equity returns, labor, water and wastewater, supplemental fuel and electricity, lease expense, feedstock acquisition, residue management, liquid petroleum product delivery/transportation, trailing royalties and maintenance. Certain technologies require the use of a catalyst or additive, such as hydrogen, which comes at an additional cost.

Compare Cash Flows — Expenses and revenues must be calculated and compared on an annualized basis over the expected life of the project, which is typically 10 to 20 years, and should take into consideration: project performance over time, fluctuations in expenses and product sale prices, financing costs, depreciation, and taxes.

Assess Economic Feasibility —Economic feasibility can be measured by the annual net cash flows, the net present value, and/or the investor's internal rate of return. If these indicators are below the project development criteria, it may be necessary to re-evaluate project feasibility under a different set of utilization alternatives. If liquid petroleum products can have multiple utilization options, a direct comparison of cash flows is possible to determine the best alternative.

2.4 STRATEGIC PARTNERSHIP DEVELOPMENT

Suppliers typically seek partnerships with entities that can mobilize financing, have access to quality plastic feedstock, have access to land available to site a system and/or can enter into offtake agreements for the purchase of liquid petroleum products (Strategic Project Partners). Depending on the company's chosen business model, Suppliers may also seek partners to jointly develop projects, purchase equipment, or license their technology (Project Developers). Suppliers that follow a DBOO model are also considered Project Developers. Under an equipment purchase or license agreement, the Project Developer is responsible for identifying and developing relationships with Strategic Project Partners. Suppliers that choose to own/operate PTF systems may or may not have existing relationships with financing and offtake partners but are almost always seeking Strategic Project Partners that can provide land, feedstock supply agreements and local project development support.

Suppliers are selective about the Strategic Project Partners and Project Developers they engage with and typically conduct extensive due diligence. This can include requiring that prospective partners provide some or all of the following:

- A site with all necessary utility connections

- Site design and layout
- Local contractors
- Feedstock supply agreements
- Offtake agreements
- Site permitting
- Regional regulatory compliance
- Management of community and stakeholder relations
- Pre-processing equipment
- Investment capital
- Grants, tax or labor incentives

The role of the Strategic Project Partner is defined by the technology supplier in a DBOO model or the Project Developer in an equipment sales or licensing agreement model and may be dictated by pre-existing relationships (i.e. long term financing partners or regional off take agreements). For example, Vadxx seeks Project Developers that can fulfill the following responsibilities in exchange for a baseline share of free cash flow: the selection of a technology integrator, provision of site with necessary utility connections, the identification of and documented commitment of waste polymers, site permitting, providing a local project engineering firm and general contractor, managing community and stakeholder relations, and ensuring regional regulatory compliance. Cash flow sharing amounts can be increased if the Project Developer elects to contribute project capital, undertake operations or execute feedstock supply agreements. Under Cynar's licensing model, Project Developers are required to demonstrate a 5-year minimum feedstock supply agreement, provide a site with a waste processing permit, provide all pre-processing equipment, and agree to multi-plant orders (5+) in strategic regions. Nexus Fuels requires that a Strategic Project Partner provide a feedstock guarantee, with tax incentives, grants and labor provisions considered beneficial.

The selection of a Strategic Project Partner can also be driven by a projects anticipated return on investment. Given that economic performance is driven by liquid petroleum product yields, and that some Suppliers have commitments to investors, special attention is paid to feedstock quantity, quality, composition, and feedstock proximity to the PTF system.

Suppliers have different approaches to selecting Strategic Project Partners for project development. For example, RES Polyflow issued a self-declared Request for Proposals in 2013 to vet, pre-qualify and advance licensing opportunities with third-party partners while Agilyx solicits applications of interest from potential partners.

Feedstock Agreements- As feedstock quality and quantity is a principal determinant of the success of any PTF system, Project Developers seek to establish feedstock supply agreements. Prior to executing feedstock supply agreements, Project Developers solicit letters of intent (LOI) from feedstock suppliers. LOIs indicate a commitment to direct feedstock to a proposed system. Once the system has begun commissioning, LOIs can be moved to binding contracts. Due to the fluctuating nature of recycling markets, stakeholders interviewed cited supplier willingness to enter into agreements spanning 3-4 years. One PTF vendor requires feedstock supply agreements that mirror system payback at around 5-6 years.

Generally speaking, the terms of these agreements are legally and financially binding, and may include, but are not limited to:

- *Material Quality* – This may include requirements that the composition of feedstock not exceed contamination or moisture thresholds and be prepared (in all cases: pre-sorted from non-polymer feedstocks and in some cases: shredded, chipped, and dried). Contamination limits may also apply to non-target polymers such as PVC and PET.
- *Material Quantity* – This may include minimum weight or volume requirements over a specified duration (day, week, month, year).
- *Logistics and Transportation for Delivery* – There is much variability across known PTF sites for terms for transportation and logistics for feedstock supply.
- *Tipping Fee or Materials Purchase Fee* – Project Developers may be able to charge a tipping fee for select feedstocks. Alternatively, some Project Developers may be willing to consider revenue sharing in exchange for feedstock supplied. In other cases, Project Developers are willing to purchase feedstock from suppliers at current market prices of ~$0.02-0.04/lb. Some PTF systems accepted waste with no financial conditions – neither payment nor charge – as the arrangement was deemed mutually beneficial for both parties. However, this may not be a long-term strategy for securing feedstock as demand for materials increase.
- *Penalty Provisions for Non-Compliance*— Penalty provisions were not readily disclosed however Suppliers noted the ability to reject deliveries that upon visual inspection, did not meet feedstock requirements.
- *Term of validity* – Feedstock agreements will indicate period of validity for supply.
- *Other Conditions – Exclusivity and Confidentiality* – PTF developers may consider requesting exclusive supply of feedstock and confidentiality agreements.

Offtake Agreements- Once markets for liquid petroleum products have been identified, it is critical to establish offtake agreements. LOIs may precede the execution of a contract between a Project Developer and a buyer(s). Offtake agreements can take a significant amount of time to execute. Relatively small quantities of liquid petroleum product compared with refineries, and variations in end product quality by system and over time as feedstocks change, can make the product challenging to place. Ongoing testing is required to verify quality and provide reassurance to prospective buyers. While long-term agreements may not be possible, some of the surveyed PTF Suppliers and their Project Developers are currently engaged in multi-year offtake agreements with refineries, oil distributors and heating oil suppliers, while others are selling smaller quantities of petroleum product as it is produced or providing it to prospective buyers for trial and testing.

Offtake agreements typically include:

- ***Commercial Terms***-
  - *Production*- Offtake agreements will specify product purchase volume
  - *Pricing and Payment* – Terms will also include unit or volume pricing as well as payment schedules.
  - *Transportation*- Logistics for transportation, storage and delivery will be defined

- ***Technical Terms***- The agreement will establish oil or refined fuel specifications. These vary but can include: flash point, pour point, chloride level, styrene level, TAN (total acid number), and sulfur. Limits are set at the discretion of the buyer.
- ***Penalty Provisions***- Provisions for non-compliance typically reflect a rejection of the liquid petroleum product.

2.5 MOBILIZING PROJECT FINANCE

Financing a PTF system is one of the most important and challenging tasks facing a Project Developer. It is particularly difficult for emerging PTF technologies given that they do not fit a traditional project finance model. Project finance firms' desire projects with:

1. Proven technology with multiple commercially operational reference facilities,
2. Long-term supply agreements,
3. Long-term offtake agreements, and
4. High investment costs ($100-200Million).

PTF technology is inherently high risk due to the limited number applications. Full project costs are generally $20 million or less, making fixed transaction costs a higher percentage of the total and more difficult to absorb. Additionally, the duration of feedstock supply and offtake agreements that Project Developers are able to secure are short compared with other large-scale waste processing systems. This is due to the fluctuating market prices for petroleum products compared with MSW streams and the variability in end product by technology and feedstock composition.

The predominant method for financing a PTF system is by direct equity investment. Under this model, an equity investor will provide a portion or all of the capital required to develop a plant in exchange for a share in the company. After the project meets the desired internal rate of return (IRR), the percent of free cash flow to the Project Developer increases. Stakeholders interviewed cited unlevered IRR requirements in the mid 20's to 30% range (excluding government subsidies). Once the system is commercially operational for 6-9 months, the project can be debt financed as an operating asset. Of the systems nearing commercialization in early 2015, the Vadxx/Liberation Capital system in Akron, OH was financed with 100% equity while the Cynar/Plastic Energy systems in Almeria and Seville, Spain have been developed with a blend of debt financing from the ***Joint European Resources for Micro to Medium Enterprises*** of the European Investment Bank and the sale of equity shares in Plastic Energy. Debt financing for the Almeria Plant was replaced by a grant from the European Regional Development Fund in February 2014 followed by a second grant for the Seville plant in June 2014. MK Aromatics Limited reported that their system was financed with a blend of 50% gap funding from their PPP government partner, 30% low interest 3% APR, 15 year loan from a corporate partner and 20% internal funds.

Alternative debt financing structures exist but can be complicated and take longer to execute. Debt providers can require a sovereign guarantee or investment grade backer and can have stringent repayment requirements in the event of a default. Banks typically have similar requirements for long-term supply and offtake agreements and therefore may have a limited role in the financing of PTF systems even after the technology is commercially established.

Equity investors assess qualities such as: proximity and quantity of target feedstock, financial standing of prospective feedstock and offtake partners, quality of the project development team, experience of the Engineering Procurement and Construction (EPC) company, location risk (geopolitical, logistical, etc.) and proven performance of the technology when deciding whether to invest in a PTF project. Investors may or may not cover costs associated with undertaking Project Planning Steps.

2.6 SITING AND PERMITTING

Many Suppliers will require that Strategic Project Partners or Project Developers identify sites available to develop a system. It is recommended that PTF systems are sited adjacent or near the source of plastic feedstock to minimize the costs of transport. Alternatively, PTF systems can also be sited near end users. Many of the PTF companies surveyed recommended some or all the following siting requirements:

- Proximity to feedstock source or offtake purchaser;
- Covered building and storage tanks; and
- Access to water, electricity and wastewater utilities and other required inputs (i.e. - hydrogen).

Project Developers may consider hiring an EPC firm to facilitate the site development and construction of the PTF system.

In addition to siting considerations, it is equally important to identify and understand the regulatory obligations that govern the development of a PTF system. Regulations may apply to waste and water management, system operations, system siting, air emissions and on-site energy generation from generators in addition to more traditional laws regarding labor, health and regulatory compliance. Regulations and standards can be issued by municipal, state or national agencies and must all be taken into consideration when developing a PTF project.

In the United States, permits are issued by the State. Permit conditions often affect project design and typically, neither construction nor operation can begin until all permits are in place. The type of operating permit required is determined by whether pre-processing occurs onsite. In the US, when feedstock is sorted and shred offsite, the system can be permitted as a manufacturing system. Additionally, when a PTF system is co-located with a MRF, it can be covered under an existing solid waste management or recycling permit. Some Suppliers have made strategic decisions requiring that material be delivered to their site pre-processed or have opted to co-locate with a MRF to ease the permitting process and improve system economics. Other Suppliers are willing to undertake pre-processing onsite in order to increase access to target feedstocks, despite any added challenges associated with siting a solid waste processing or recycling system. Of all of the known systems that have been permitted to date in the US and Europe, all have been classified as small air pollutant emitter. Certain Suppliers may require wastewater permits; however, ORA is not aware of any systems that currently demand one.

Engaging the public is also an important consideration. While this may not be a required step in all projects, promoting the environmental, economic, job creation and energy benefits to the general public can help to avoid public opposition to not in my backyard (NIMBY) issues that can create significant delays in the project’s implementation timeline.

2.7 RISK MITIGATION STRATEGIES

The development of a PTF system is a complex undertaking that can be costly and require the involvement of multiple stakeholders. Drawing on the experience of other projects, Project Developers should anticipate that they may encounter a variety of risks, such as project delays, cost overruns, financing obstacles, etc. In order to best safeguard the development of a PTF system, it is recommended that project stakeholders create a risk mitigation strategy at all stages: 1) Planning, 2) Construction and Development, and 3) Operations. In many cases, Project Developers choose to work in a consortium of Strategic Project Partners to mitigate project risks. One key advantage to strategic partnership agreements is the efficient distribution of project risks across multiple parties.

APPENDIX A: STATUS OF PTF TECHNOLOGY VENDORS IDENTIFIED

Technology Supplier	Location	Status

1	Agilyx	USA	Study Participant
2	Anhui Oursun Environ	China	Did not respond to request for participation
3	Blest	Japan	Study Contributor
4	High Wave Energy (Formerly Climax Global Energy)	USA	Declined to Participate
5	Cynar Plc	Ireland	Study Participant
6	Ecocreations	Korea	Did not respond to request for participation
7	ECO-Int'l Marketing	Korea	Did not respond to request for participation
8	Enviro-hub Singapore	Singapore	Did not respond to request for information
9	Environment System (Technology Provider)/ Shonan Trading	Japan	Declined to Participate
10	GEEP	USA	Declined to Participate
11	GGE Americas	USA	Did not respond to request for participation
12	Global Clean Energy	USA	Did not respond to request for participation
13	Golden Renewables	USA	Study Participant
14	Green Envirotech	USA	Did not respond to request for participation
15	JBI	USA	Study Participant
16	Klean Industries	Canada	Study Contributor
17	MK Aromatics Limited	India	Study Contributor
18	Natural State Research, Inc.	USA	Undertaking R&D

19	Nexus Fuels LLC	USA	Study Participant
20	P-fuel, Ltd.		Did not respond to request for participation
21	Plastics Advanced Recycling Corp (PARC)	USA	Study Participant
22	PlastOil/Diesoil	Czech Republic	Declined to Participate
23	Poly Green	Thailand	Did not respond to request for participation
24	Polymer Energy	Thailand	Did not respond to request for participation
25	Polymer Energy	USA	Did not respond to request for participation
26	Promeco/Cimelia	Italy	Did not respond to request for participation
27	Pyrocrat Systems LLC	India	Study Participant
28	Recarbon Corp		Did not respond to request for participation
29	Regen	USA	Unconfirmed Status of System Operations
30	RES Polyflow	USA	Study Participant
31	Royco		Did not respond to request for participation
32	Samki Group	India	Did not respond to request for participation
33	Shonan Trading Co.	China	Declined to Participate
34	Smart E2 Solutions	USA	Undertaking R&D
35	Splainex	Netherlands	Did not respond to request for participation
36	T Technology	Poland	Did not respond to request for participation
37	Vadxx	USA	Study Participant
38	Ventana Cleantech	USA	Did not respond to request for participation

APPENDIX B: FUELS

Oil and Fractionated Fuel Properties and Classifications

Oil, generally speaking, is a liquid substance made of hydrocarbon matter that can be combusted. Fossil fuel derived crude oil consists of carbon (83 – 87%), hydrogen (10-14%), sulfur (up to 6%), nitrogen (up to 2%), oxygen (up to 1.5 %) and metals (less than 1,000 parts per million).S[99] Crude oils can vary widely with different physical and chemical properties and are classified based on their American Petroleum Institute (API) gravity- light, medium or heavy- and sulfur content – sweet or sour (Table 21).

Table 21: Properties of Crude Oils[100]

Oil Classification	Light	Medium	Heavy
API Gravity[101] (Light or Heavy)	**Light >** 31.1°	**Medium**: ~22.3° - 31.1°	**Heavy** < 22.3°
Sulfur Content (Sweet or Sour)	**Sweet** <0.5%	**Sweet/Sour** > 0.5% & <1%	**Sour** > 1%
Volatility[102]	-Moderately volatile -Moderately evaporative -Moderately Toxic	-Low volatility -Low evaporative -High toxicity	-Very low volatility -Very low evaporative -High toxicity
Examples	West Texas Intermediate (WTI) Brent Blend	Russian Export Blend Dubai Crude	Saudi Heavy Venezuela Heavy
Value	Commands higher market prices	Commands medium market prices	Commands lowest market prices

Synthetic crude oil derived from plastics is considered a substitute for fossil fuel derived crude. Oil quality may vary by PTF Supplier, input feedstock and technological configuration; however, all surveyed Suppliers producing a synthetic crude oil indicated that their product meets the specifications of light sweet crude. Depending on plant configuration, synthetic crude oil can either be a principal or intermediary output of a PTF system. Synthetic crude oil can be sold to a refinery for further processing into petroleum products such as diesel and gasoline, or can be fractionated onsite into distillates that can be marketed directly to industrial end users, blenders, or distributors.

PTF companies often use assays to characterize and demonstrate the quality, composition and distillate yields of their end product. Lighter oils produce higher fractions of hydrocarbon mixtures with lower boiling points, and heavier oils tend to produce higher fractions of hydrocarbon mixtures with higher boiling points.[103] Crude oil assays typically test for the following specifications in Table 22.

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[99] Centre for Energy, http://www.centreforenergy.com/AboutEnergy/ONG/Oil/Overview.asp?page=2. Accessed: September 2014.

[100] US EPA, http://www.epa.gov/hpv/pubs/summaries/crdoilct/c14858ca.pdf Accessed September 2014.

[101] American Petroleum Institute measure of specific gravity of crude oil or condensate in degrees. An arbitrary scale expressing the gravity or density of liquid petroleum products. The measuring scale is calibrated in terms of degrees API; it is calculated as follows: Degrees API = (141.5 / sp.gr.60 deg.F/60 deg.F) - 131.5

[102] Volatility is defined by the rapidity in which the oil evaporates into the air.

[103] US EPA, http://www.epa.gov/region6/6en/xp/longhorn_nepa_documents/lppapp6a.pdf , Accessed: September 2014.

Table 22. U.S. Department of Energy Strategic Petroleum Reserves Crude Oil Specifications, SPR 2008[104]

Characteristic	Sour	Sweet	Primary ASTM Test Method
API Gravity [°API]	30 – 45	30 – 45	D1298 or D5002
Total Sulfur [Mass %], max.	1.99	0.50	D4294
Pour Point [°C], max.	10	10	D5853-A
Salt Content [Mass %], max.	0.050	0.050	D6470
Viscosity [cSt @ 15.6°C], max. [cSt @ 37.8°C], max.	32 13	32 13	D445
Reid Vapor Pressure [kPa @ 37.8°C], max.	76	76	D6377
Total Acid Number [mg KOH/g], max.	1.00	1.00	D664
Water and Sediment [Vol. %], max.	1.0	1.0	D473 or D4928
Yields [Vol. %] Naphtha [28-191°C] Distillate [191-327°C] Gas Oil [327-566°C] Residuum [>566°C]	24 - 30 17 - 31 26 - 38 10 – 19	21 - 42 19 - 45 20 - 42 14 max.	D2892 & D5236c

[104] US Department of Energy, Strategic Petroleum Reserve, http://www.spr.doe.gov/reports/docs/CrudeOilAssayManual.pdf, Accessed: September 2014.