Comparison of Pyrolysis-Based Advanced Recycling Air Emissions to Common Manufacturing Emissions

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March 2021

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Advanced recycling technologies are helping to expand the circular economy by converting waste plastics that cannot be recycled mechanically back into valuable feedstocks for new plastics and products like waxes, lubricants and lower-environmental-footprint fuels. These technologies offer a unique way to recover the building blocks for new materials and can do so in a more environmentally friendly way, helping to keep plastics out of oceans and landfills and reduce the use of virgin fossil-based energy.

The emissions from these technologies are well regulated and controlled through technological and operational practices to be kept low. This new analysis finds that pyrolysis-based advanced recycling technologies are not only better for our planet by avoiding virgin resource extraction but are also well regulated by the federal Clean Air Act and state and local regulatory authorities. In fact, these advanced recycling facilities are so finely tuned that materials which do not meet strict requirements are automatically rejected.

Most importantly, every category of air emissions from these technologies was shown to be well below regulated levels and below typical well-known everyday industries and institutions that are often located right in our own communities.

This report compares the emissions of pyrolysis-based advanced recycling (advanced recycling) emissions to common industries throughout the United States. The data demonstrate that the site-based emissions produced by pyrolysis-based advanced recycling technologies are lower when compared to many other common industrial and institutions facilities found in communities across the country. This report diagrams all the sources and types of emissions from an average advanced recycling operation and compares them to similar emissions from hospitals, universities, housing, and manufacturing facilities of various sizes. This paper also analyzes why emissions of dioxin are not a concern for pyrolysis-based advanced recycling facilities.

The data demonstrate that the site-based emissions produced by pyrolysis-based advanced recycling technologies are lower when compared to many other common industrial and institutional facilities found in communities across the country

METHODOLOGY

Good Company completed the analysis included in this whitepaper by interviewing advanced recycling technology and operating companies, reviewing their air emissions data, and comparing it to publicly available the U.S. Environmental Protection Agency (EPA) air quality standards and federally reported air emissions data.

Four advanced recycling companies provided data on their operating facilities that ranged from 3 to 136 KTA (kiltonnes per annum) facilities, with an average of 55 KTA. Advanced recycling facility run data and permitting data provided to Good Company covered 2019 to 2020 and provided the number of run days and tons of emissions per year. Advanced recycling facility emissions were compared to emissions of other manufacturers subject to mandatory reporting for hazardous air and primary criteria air pollutants.

For each pollutant, the range of emissions and reference examples were included for industrial manufacturing operations, hospitals and universities using the EPA's 2017 National Emissions Inventory (published April 2020). While not every facility has the same emissions profiles, Good Company sought comparable facility types that share common air emissions.

More information on the methodology is available in the criteria air pollutant section and Appendix.

CONTEXT: THE RECYCLING LANDSCAPE

In the pursuit of recovering materials with economic value from difficult-to-recycle plastics (such as flexibles, films, and small rigid plastics), a wide range of technology innovators are taking on the challenge with new and repurposed technologies. These technologies take many forms from pulverization with high-pressure water jets into microscopic particles to the conversion of the materials into new compounds through heat and/or catalyst reactions such as pyrolysis. This broad category of technology has an emerging name — advanced recycling. Advanced recycling, sometimes called chemical recycling, is different from traditional material, sometimes called mechanical, recycling in that it is more than simply melting the material and reforming it.

Pyrolysis-based advanced recycling facilities produce chemistry products such as feedstocks for new chemicals and plastics, basic chemicals, products such as waxes and lubricants as well as transportation fuels for road, air and marine travel. The raw materials for this process are post-use plastics that are not traditionally recycled by mechanical recycling due to food contamination or other properties that make them impractical for mechanical recycling. Other advanced recycling technologies include gasification, depolymerization and solvolysis. For this report, we focus on the pyrolysis technologies as they are the largest and fastest emerging subcategory of the technologies.

Pyrolysis-based advanced recycling technologies can complement the traditional recycling of post-use plastics and enable communities and businesses to divert greater quantities of valuable plastics from landfills and bring the matter back into commerce. The production of chemical feedstocks, monomers and fuels from post-use plastics can offset the need for some virgin material extraction and production. The U.S. Department of Energy's Argonne National Laboratory has determined that there are quantifiable environmental benefits to converting post-use plastics to an ultra-low sulfur diesel instead of sending these plastics to landfill.[1]

PYROLYSIS: HOW DOES IT WORK?

An advanced recycling facility using pyrolysis receives plastic feedstock that has been source separated and/or sorted from other materials (e.g. metals, glass, and other non-desirable materials). These plastics are then processed into a specification feedstock via shredding, drying, and clearing of any residual contamination. Next, this "post-processed" feedstock is heated in the absence of oxygen until it melts, and the polymer molecules break down to form gaseous vapors. The condensable gases are cooled and converted to products while the non-condensable gases are collected separately and combusted for process energy/heat to displace methane used to heat the pyrolysis vessels. Destruction of non-condensable gases occurs in the pollution control device, but the value of utilizing these gases to reduce energy requirements is the primary approach. Some of the products the technology can make include waxes, lubricants, feedstocks (such as naphtha or monomers) to produce new chemicals and plastics, or fuels for transportation.

The ideal plastic resin feedstock depends on the intended end product. Generally speaking, resins that yield greater amounts of useful end products include high density polyethylene (HDPE), low density polyethylene (LDPE), linear low-density polyethylene (LLDPE), polypropylene (PP), polystyrene (PS), and some engineered resins labeled as #7 (Other) via the Resin Identification Code (RIC). By contrast, companies that provided data for this report noted that polyethylene terephthalate (PET) has lower yields, and more importantly, it generally has strong traditional mechanical recycling markets. Destruction of non-condensable gases occurs in the pollution control device, but the value of utilizing these gases to reduce virgin energy requirements is the primary approach. Other non-pyrolysis advanced recycling technologies such as dissolution processes can dissolve plastics and recover them for conversion back into useful products.

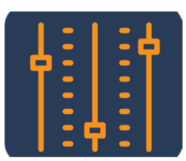
1 "Life-cycle analysis of fuels from post-use, non-recycled plastics." Fuel. Volume 203, 1 September 2017. Pahola Thathiana Benavides, Pingping Sun, Jeongwoo Han, Jennifer B. Dunn, Michael Wang.

PYROLYSIS-BASED ADVANCED RECYCLING:
WHAT ARE THE PRIMARY SOURCES OF EMISSIONS?

First and foremost, pyrolysis of plastics is not combustion of plastics. The materials are not destroyed through heat in concert with oxygen as they would be in combustion or incineration. Instead, difficult-to-recycle plastics are often sorted and separated up to three times (at the curb or commercial generator, at the recycling facility and once more to remove non-plastic contamination) and then **processed in a closed system that is heated in the absence of oxygen to produce saleable liquid products**. The bulk of advanced recycling facility emissions come from producing the heat through combustion of natural gas and the non-condensable gases. The primary steps in the pyrolysis-based advanced recycling process include:

FEEDSTOCK DELIVERY:

Sorting and Preparation: The site is visited by trucks delivering post-use plastic feedstocks. These materials are unloaded by a forklift that could be powered by gasoline, diesel, propane or electricity. In some cases, the feedstocks are shredded to reduce the size and densified. If shredded, the grinded product is pulled through cutting screens from a blower vacuum then to a standard cyclone and baghouse to collect dust for disposal.



OXYGEN AND AIR POLLUTION DEVICE CONTROLS:

The pyrolysis vessels are sealed and starved of oxygen (nitrogen flush), then heated with electricity, natural gas, propane or non-condensable gases. Because air pollution control devices are employed, the external emissions from heating pyrolysis vessels are similar to a home stove or water heater on a per unit basis of methane combustion.

TEMPERATURE CONTROLS:

The newly formed vapors/gases are then cooled and condensed into liquid hydrocarbons (hydrogen and carbon molecules that are liquids at room temperatures) and air pollution control devices are used to prevent additional emissions at this stage.

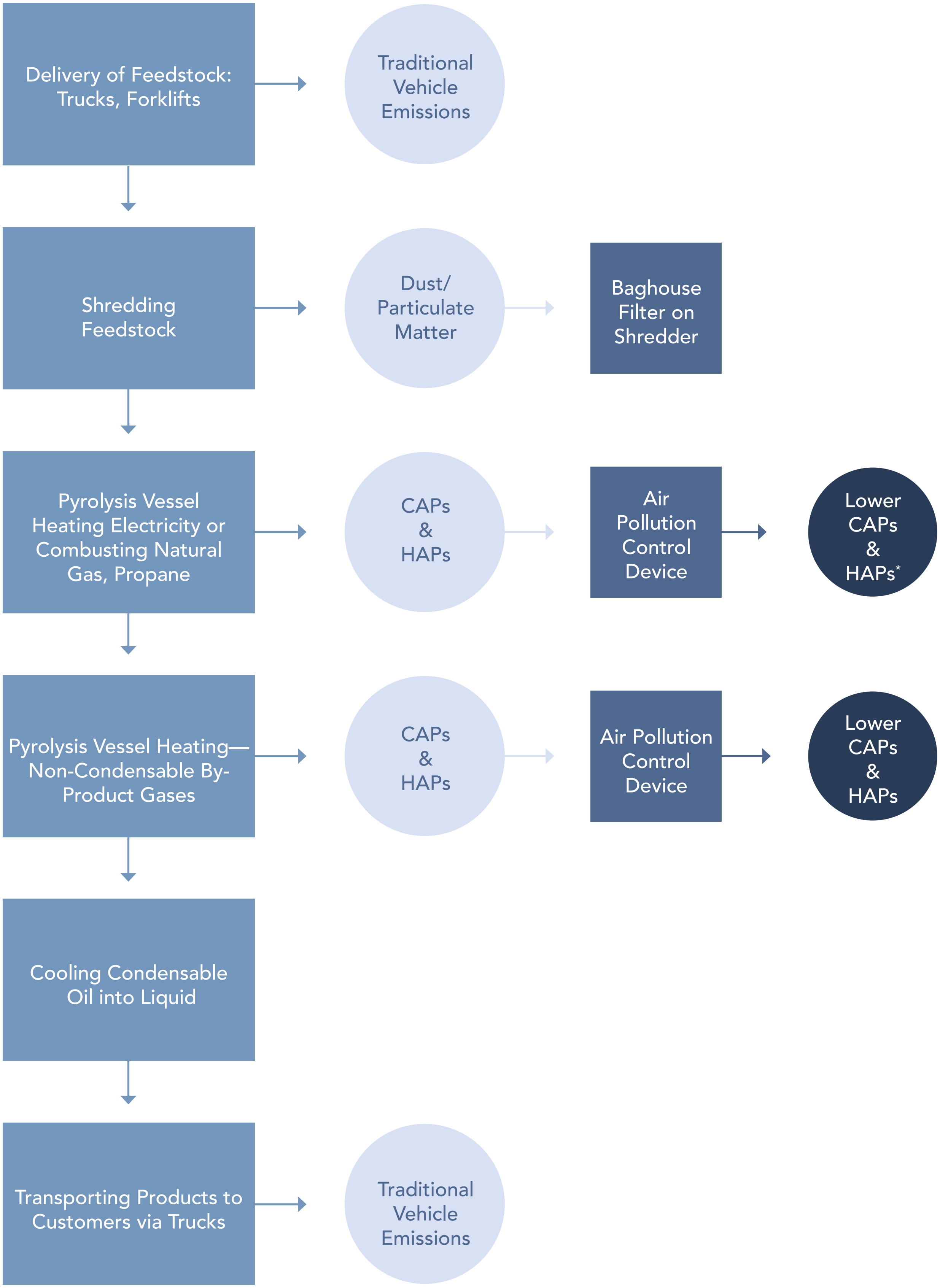
FACILITY-LEVEL PROCESSES:

The non-condensable gases such as methane and hydrogen are generally co-fired with natural gas or propane to heat the vessels. This produces CO_2 and water. The gas is very clean and does not contain any heteroatoms such as chlorine, bromine or sulfur. Using the non-condensable gases as process energy displaces the need for additional methane or propane and that displacement has quantifiable environmental benefits. Depending on local regulations, a scrubber can be installed as an additional best practice.

CUSTOMER DELIVERY:

The gaseous vapors are condensed into the desired end products including a pyrolysis oil that is similar to crude oil. This oil can be sent for further processing or fractionated on site to waxes, lubricants, monomers, basic chemicals, chemical and plastic feedstocks, or liquid fuels and fuel blendstocks. The products are shipped offsite via rail, trucks, or barge that are most likely running on diesel fuel with emissions typical of that fuel. Generally, pyrolysis facilities convert 75-80% of their inbound feedstock into liquid hydrocarbons, ~10% remains as non-condensable gases and are used as process energy and ~10% remains a solid carbon char. (Benavides, 2017)

GENERALIZED PROCESS FLOW DIAGRAM TO SHOW EMISSION SOURCES AND TYPES:



*Below the EPA Title V air permit thresholds

WHAT ADVANCED RECYCLING EMISSIONS ARE REGULATED BY THE U.S. EPA?

Like other types of manufacturing operations, advanced recycling facilities are subject to regulatory controls governing their activities. Importantly, there are both federal and state programs that strictly monitor emissions from manufacturing facilities and protect communities' safety and well-being. For any advanced recycling manufacturer to establish operations, it must first seek a permit from the environmental regulators and continue to operate in compliance with the Clean Air Act (CAA).

Under its authority via the CAA, the U.S. Environmental Protection Agency regulates both Hazardous Air Pollutants (HAPs) and Criteria Air Pollutants (CAPs) and sets thresholds for emissions via the National Ambient Air Quality Standards (NAAQS). Sources of HAP emissions exceeding 10 tons/year for a single HAP or 25 tons/year for any combination of HAP are subject to federal regulation and require a Title V permit. Sources of CAP emissions exceeding 100 tons per year also require a Title V permit. In some communities where air quality is poor ("out of attainment") the thresholds for permits are lower. However, sources of any significant amount of CAP emissions must report the emission levels. Local jurisdictions (State Departments of Environment, Air Quality Management Districts, etc.) are delegated the responsibility for enforcement and often require more stringent reporting and limits on emissions than the EPA. Those firms that exceed their permitted emissions are subject to strict penalties, including being fined daily and risk the loss of their permits, meaning they can no longer legally operate.

The EPA also lists and regulates 187 HAPs under the CAA. HAPs are toxic air pollutants that cause or may cause serious harm to human health and the environment. The following is a list of the primary contributing HAPs that could be produced by pyrolysis-based advanced recycling facilities:

1. Benzene
2. Toluene
3. Ethyl benzene
4. Xylenes

CAPs are commonly found pollutants that are detrimental to human health, and include these six compounds:

1. Surface Ozone (O3)/ Volatile Organic Compounds (VOCs)
2. Particulate Matter (PM)
3. Sulfur Dioxide (SO2)
4. Nitrogen Oxides (NOx)
5. Carbon Monoxide (CO)
6. Lead (Pb) - Not a process emission from advanced recycling and thus omitted from this report.

WHAT IS A TITLE V PERMIT?

Title V, which is the Environmental Protection Agency's permit program for stationary sources of air pollution, requires a list of provisions that must be met to ensure compliance with the Clean Air Act.

HAP emissions exceeding 10 tons per year for a single HAP or 25 tons per year for any combination of HAP are subject to federal regulation and require a Title V Permit. CAP emissions exceeding 100 tons per year also require a Title V permit.

COMBINED HAP EMISSIONS

Permitting data indicates that pyrolysis-based advanced recycling facilities are expected to create very few HAP emissions and are likely to be well below federal permitting requirements. In fact, very little to no HAP emissions are expected at some pyrolysis-based advanced recycling facilities with lower scales of production.

WHAT ARE THE EMISSIONS OF ADVANCED RECYCLING FACILITIES AND WHAT ARE THEY COMPARABLE TO?

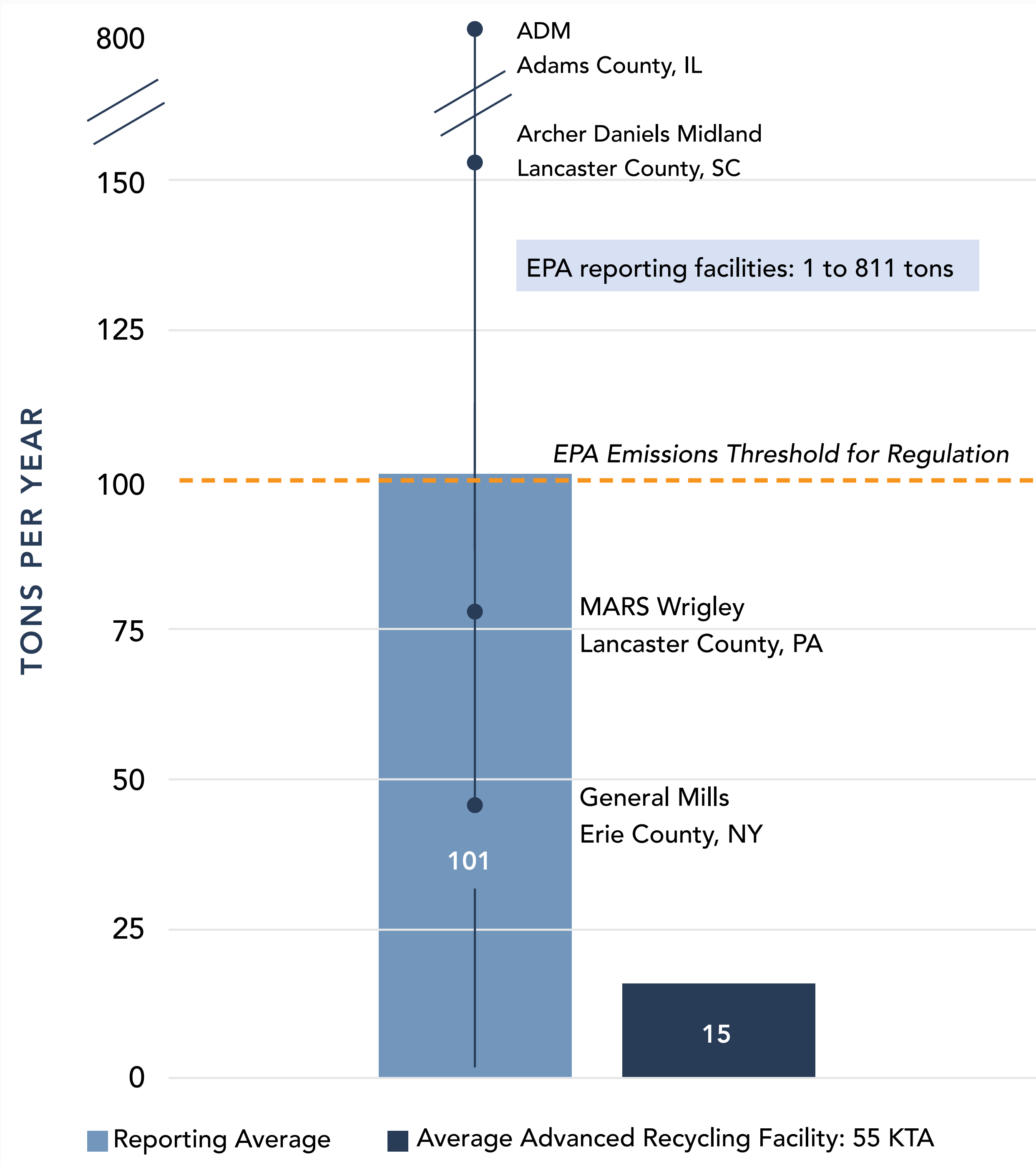
Like other industrial manufacturing facilities, a pyrolysis facility will generate some CAPs, and this paper provides context for these emissions by benchmarking them to other common manufacturing and institutional facilities. For this paper, we have modeled the "average current advanced recycling facility" as one that processes 55,000 tons per year of inbound plastics or a 55 KTA (kilotonnes per annum) facility. This "average facility" volume represents an average projected input capacity of multiple facilities in the U.S. based on public announcements. KTA references one million kilograms of difficult-to-recycle plastics and equates to 1,102 short tons.

An average facility's CAP emissions as a group are not comparable in all respects to any single industry. However, several of its individual CAP emissions are comparable to those of numerous specific, well-regulated facilities that are required to report to the EPA under the CAA. Average pyrolysis-based advanced recycling facilities were only found to have higher emissions profiles, relative to the industries of comparison, in NOx and CO and this is due primarily to the combustion of natural gas with ambient air for process energy and heat.

- VOC (Volatile Organic Compounds) and PM10 (Particulate Matter under 10 microns) emissions from an average pyrolysis-based advanced recycling facility are roughly comparable to those from smaller than average food processing plants.
- SO_2 (Sulfur Dioxide) emissions are roughly comparable to those from smaller than average institutions (hospitals, universities and prisons).
- NO_x (Nitrogen Oxides) emissions are roughly comparable to those from larger than average institutions (hospitals, universities and prisons).
- CO (Carbon Monoxide) emissions are comparable to those from larger than average auto manufacturing operations.
- While lead is also a CAP, there are no measurable lead emissions from pyrolysis-based advanced recycling facilities and so it is omitted from this paper.

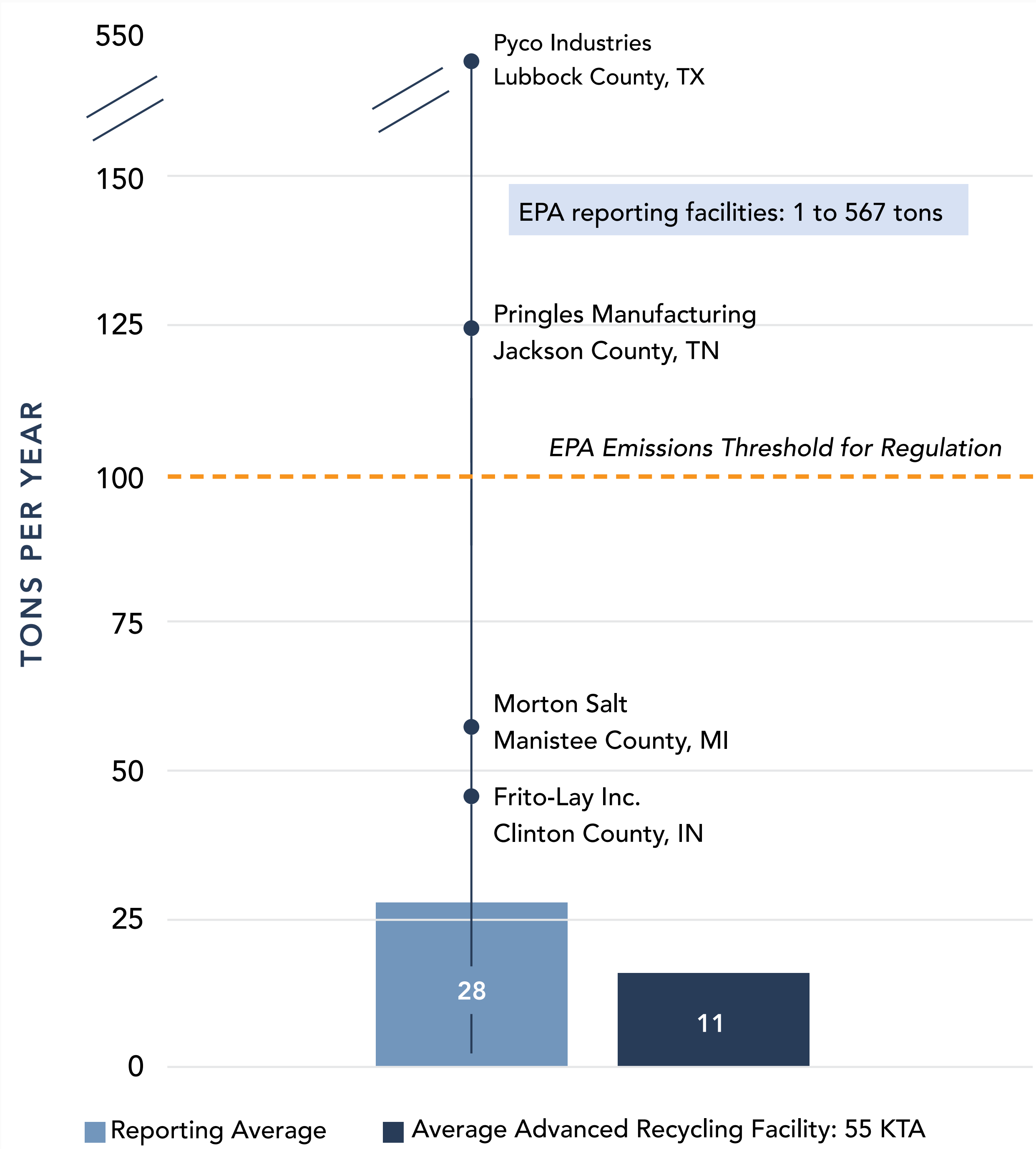
VOLATILE ORGANIC COMPOUNDS (VOCS)

The average pyrolysis-based advanced recycling facility emits less than 20 tons of VOCs annually, which is below the EPA emissions threshold for regulation. The average reporting facility in the U.S. (excluding those facilities with less than 1 ton of emissions) reports 101 tons of VOCs emitted annually with a range between 1 to 811 tons. Facilities reporting for this CAP are predominantly food processing facilities. For comparison, the average pyrolysis-based advanced recycling facility emits roughly as much as a Frito-Lay facility in Windham, CT.



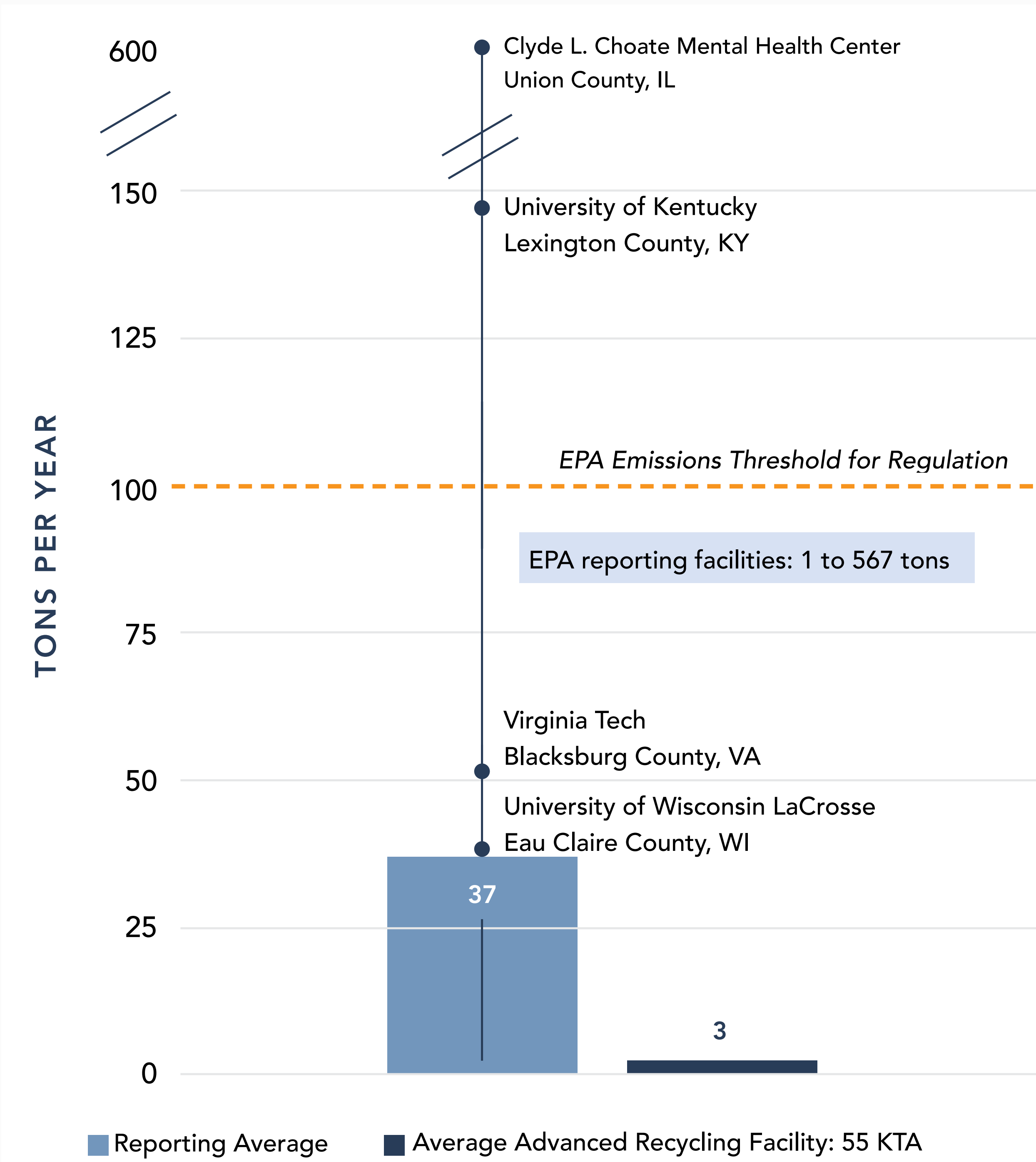
PARTICULATE MATTER, UNDER 10 MICRONS (PM_{10})

The average pyrolysis-based advanced recycling facility emits less than 15 tons of particulate matter under 10 microns (PM10) annually. The average reporting facility in the U.S. (excluding those facilities with less than 1 ton of emissions) reports 28 tons of PM10 emitted annually with a range between 1 to 567 tons. Facilities reporting for this CAP are predominantly food processing facilities and select oil and gas companies. For comparison, the average pyrolysis-based advanced recycling facility emits roughly as much as a Land O'Lakes cheese production facility in Spencer, WI.



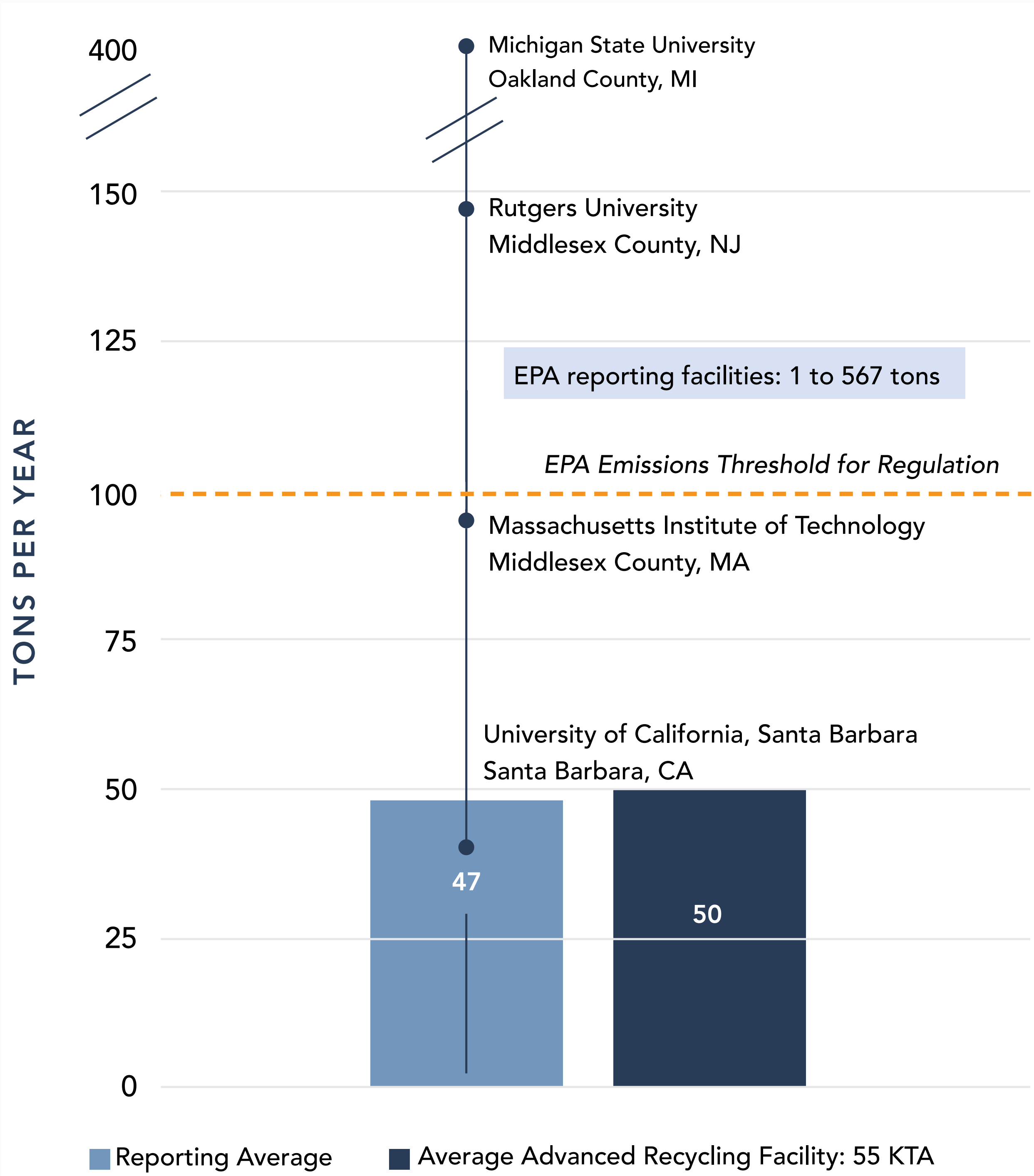
SULFUR DIOXIDE (SO_2)

The average pyrolysis-based advanced recycling facility emits less than 5 tons of SO_2 annually. The average reporting facility in the U.S. (excluding those facilities with less than 1 ton of emissions) reports 38 tons of SO_2 emitted annually with a range between 1 to 615 tons. Facilities reporting to EPA for this CAP are predominantly hospitals, colleges/universities and prisons. For comparison, the average pyrolysis-based advanced recycling facility emits roughly as much as the 15 megawatt combined heat and power (CHP) power plant providing energy to the Yale School of Medicine in New Haven, CT.



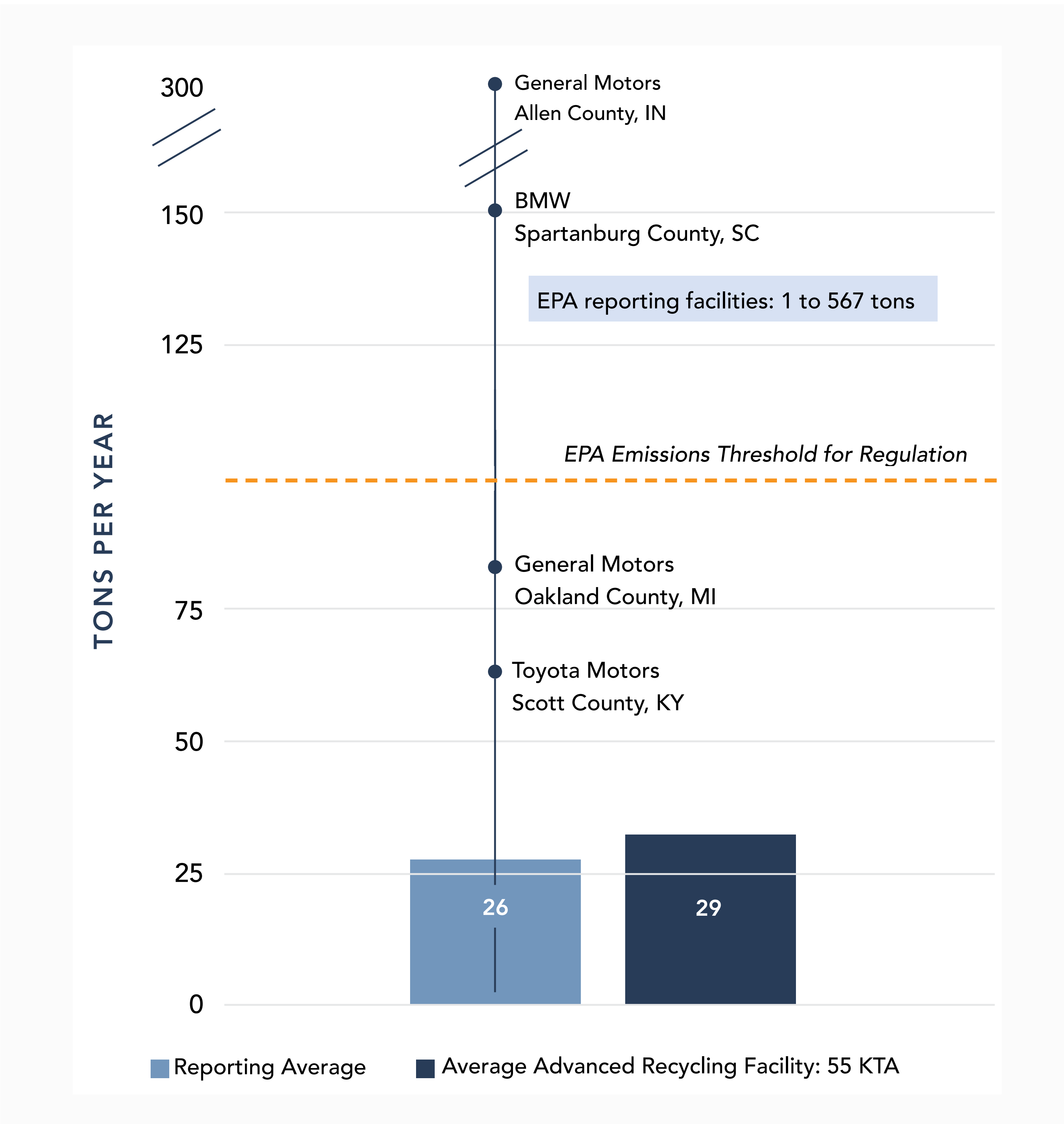
NITROGEN OXIDES (NO_X)

The average pyrolysis-based advanced recycling facility emits 50 tons of nitrogen oxides annually. Facilities reporting to EPA for this CAP are predominantly colleges and universities (excluding those facilities with less than 1 ton of emissions). Major public and private universities and colleges report 47 tons of nitrogen oxides emitted annually with a range between 1 to 391 tons. These emissions typically come from an onsite power plant or generator. For comparison, the average pyrolysis-based advanced recycling facility emits roughly as much as the University of California, Santa Barbara in Santa Barbara, CA.



CARBON MONOXIDE (CO)

The average pyrolysis-based advanced recycling facility emits less than 35 tons of CO annually. The average reporting facility in the U.S. (excluding those facilities with less than 1 ton of emissions) reports 26 tons of CO emitted annually with a range between 1 to 293 tons. For comparison, the average pyrolysis-based advanced recycling facility emits roughly as much as the General Motors (GM) Lordstown manufacturing plant in Trumbell, OH.



WHY DIOXIN IS NOT A CONCERN FOR PYROLYSIS FACILITIES

Dioxins are a serious and genuine health concern. Therefore, advanced recycling technology providers have controls to prevent dioxins from forming and are subject to regular product testing. Why are they working hard to prevent dioxins from occurring? The simple answer is – they couldn't operate in the United States according to U.S. environmental and health laws if they or their partners brought the products to market with dioxin contamination.

Where are dioxins and why are they a problem? Dioxins are persistent pollutants (that stay potent for a long time) and bioaccumulate in fatty tissues of the food chain. Per the World Health Organization, "Dioxins are highly toxic and can cause reproductive and developmental problems, damage the immune system, interfere with hormones and also cause cancer." More than 90% of human exposure is through food, mainly meat and dairy products, fish and shellfish. Many national authorities have programs in place to monitor the food supply. Their half-life in the body is estimated to be 7 to 11 years. In the environment, dioxins tend to accumulate in the food chain. The higher an animal is in the food chain, the higher the concentration of dioxins.[2]

For 40 years, it has been known that poorly controlled waste combustion gives rise to dioxins, furans, and other products of incomplete combustion. Most dioxins found in the environment today are human-made and were created before 1990. Historically, incinerators, the manufacture of certain herbicides, and pulp and paper bleaching were among the largest industrial sources of dioxins.

Since then, regulation and subsequent technical advances have led to drastic decreases in dioxin emissions. Between 1987 and 2000, dioxin emissions declined 90% in the United States[3].

As dioxin emissions from industry declined, unregulated sources such as forest fires, backyard burning of garbage and residential wood burning have risen in significance as contributors to dioxin emissions. "Backyard burning of waste materials creates higher levels of dioxins than industrial incinerators and is particularly dangerous because it releases pollutants at the ground level where they are more readily inhaled or incorporated into the food chain."[4] In fact, backyard burning of waste is currently the largest source of dioxins at 35% of the U.S. total.

The U.S. EPA has actively regulated dioxins via these five laws:

1. Comprehensive Environmental Response, Compensation and Liability Act (CERCLA)/ Resource Conservation and Recovery Act (RCRA)
2. Hazardous Air Pollutants for Hazardous Waste Combustors and Clean Air Act
3. Toxic Substances Control Act (TSCA)
4. Emergency Planning and Community Right-to-Know Act (EPCRA)
5. Safe Drinking Water Act (SDWA)

How do pyrolysis operations and technologies prevent dioxin formation? Given the strict U.S. EPA prohibitions against producing dioxins, pyrolysis facilities are engineered and operated to not produce dioxins. In addition to their commitment to operational and product safety, these facilities would also be subject to significant fines for each violation and/or risk their permission to operate. Therefore, proper at-scale commercial operations of pyrolysis facilities are not expected to result in the production of dioxins.

2 https://www.who.int/news-room/fact-sheets/detail/dioxins-and-their-effects-on-human-health
3 U.S. Environmental Protection Agency (EPA), 2006. An inventory of sources and environmental releases of dioxin-like compounds in the United States for the years 1987, 1995, and 2000. National Center for Environmental Assessment https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=159286
4 U.S. Environmental Protection Agency (EPA). Dioxins Produced by Backyard Burning. https://www.epa.gov/dioxin/dioxins-produced-back-yard-burning Retrieved June 2020.

Advanced recycling facilities avoid dioxins with many interventions, the primary one being that the plastic material is heated in a closed, oxygen-deprived environment that causes a thermo-chemical reaction that is not combustion.

Of course, if these technologies are operated incorrectly — in a way that would both damage the equipment and make the products unsaleable — it is possible to produce dioxins. However, this scenario would be unexpected given that pyrolysis technologies are designed to recover valuable, saleable products and are strictly monitored by air emissions authorities, these technologies are engineered, designed and operated to prevent dioxins.

THE MAIN METHODS FOR PREVENTING DIOXIN FORMATION AT MULTIPLE STAGES OF THE PYROLYSIS PROCESS INCLUDE THE FOLLOWING:

FEEDSTOCK DELIVERY, SORTING AND PREPARATION	OXYGEN CONTROLS	TEMPERATURE CONTROLS	FACILITY-LEVEL PROCESSES	EMISSION RECORDS AND TESTING	CUSTOMER CONTROLS AND OVERARCHING REGULATIONS
prevents contaminants	prevents combustion and air emissions	avoiding formation temperatures	removal of chlorine and additional emissions controls (e.g., activated carbon "scrubbers")	quality control and assurance	final assurance that regulations are met

DETAILED PRACTICES FOR DIOXIN PREVENTION IN OPERATIONS OF ADVANCED RECYCLING FACILITIES

Given the potential for permits being revoked for producing dioxin, pyrolysis-based advanced recycling technologies have built in several redundant quality controls to help ensure dioxins are not produced.

FEEDSTOCK DELIVERY, SORTING AND PREPARATION:

Specifications enforced with scanners and contractual penalties — Plant operators sort the inbound material so their feedstocks are predominantly composed of carbon and hydrogen. Chlorinated plastics are generally excluded from advanced recycling technologies because those resins have very low yields of marketable petroleum products and can produce acidic byproducts that corrode the equipment and cause the marketable products to fail to meet strict customer specifications.

Records are kept on each feedstock batch, and industry standard testing allows for preventing materials that could generate chlorine. For these reasons, feedstock specifications are strictly enforced using optical scanners and hand-held scanners to determine the makeup of the inbound plastic materials.

Further, contracts with the feedstock provider often require the specification to be met or providers are subject to financial penalties from both the advanced recycling operating companies and purchasers of the final product.

Additional quality controls — Many operators spot check the purveyors of the feedstocks at the source (usually plastics recyclers). Finally, some of the technology operators pay their staff a bounty on off-spec material and reward them for reducing contamination.

OXYGEN CONTROLS:

Absence of oxygen to ensure pyrolysis, not combustion — Generally, the vessel where the primary thermal reaction occurs is flushed with nitrogen to eliminate oxygen to not only prevent combustion, but also the formation of dioxins and furans.

TEMPERATURE CONTROLS:

Right temperature environment — Pyrolysis products spend virtually no time at the dioxin formation temperature range of 200–400°C (392–752°F). Pyrolyzing plastics without oxygen does not create dioxins and is different than combustion in incinerators. Pyrolyzing plastics yields new gases that can be condensed into fuels and non-condensable gases that may contain chlorine, which are destroyed with combustion.

Controlled cooling of the product — The condensable gases are rapidly cooled to prevent the formation of dioxins that could occur if they were to sit for an extended period in the temperature range of 200–400°C (392–752°F).

Non-condensable gases combusted for process energy – For generating process energy/heat, the technologies use the non-condensable gases mixed with natural gas (methane) or propane to heat the closed vessels with the emissions flowing to the pollution control device. The combustion of those gases ranges from 600–800°C (1,202–1,472°F). This aligns with the meta study[5] that showed that 99.9% of 29 dioxins are destroyed at 700°C.

Additional controls post destruction of emissions — Any number of controls are used by the pyrolysis-based advanced recycling companies including controlled cooling of the emissions out of the stack, using copper catalysts and using an activated charcoal scrubber.

FACILITY-LEVEL PROCESSES:

Additional processes — Some pyrolysis technologies employ hydrotreating and/or guard beds to treat the non-condensable gases. Guard beds draw out unwanted chemicals and catalysts.

PRODUCT TESTING:

Testing to comply with regulations and customer requirements — Pyrolysis facilities keep careful air emission records in accordance with EPA requirements, even though the pyrolysis-based advanced recycling process is closed loop with lower emissions than many other industrial processes. Plant level quality control programs are used to test liquid fuels via American Society for Testing and Materials (ASTM) methods to meet TSCA standards. Analytical lab samples are tested on site or by third-party labs to meet customer specifications and verify that there is no chlorine or dioxins.

5 Gullett, B. and Seeker, R. 1997. "Chlorinated Dioxin and Furan Control and Monitoring." In Paper Presented at the ICCR Meeting Research Triangle Park, NC. https://www.tandfonline.com/doi/full/10.3155/1047-3289.61.5.511

CUSTOMER SPECIFICATIONS, CONTROLS AND OVERARCHING REGULATIONS:

The products of pyrolysis must meet strict performance specifications, otherwise their outputs are of little use or unsaleable to downstream customers. Further, if the product is a fuel, it must meet the EPA standards or it is illegal to sell. Downstream chemical manufacturing, refinery or fuel blending customers must meet strict specifications for their customers and will not put billions of dollars of infrastructure at risk by adding contaminated and off-specification hydrocarbons, chemicals, monomers and fuels to their facilities.

The standard practice in the industry is that customers of pyrolysis-based advanced recycling — chemical manufacturers and fuel wholesale buyers — are required as fuel suppliers to submit fuel samples to internal and third-party independent lab testing. Generally, third-party testing of fuel and additive fuel products adheres to ASTM related fuel standards (ASTM D975 and ASTM D4814) and ISO standards. If applicable, state-specific testing requirements are also applied to the testing and verification process. Included in the battery of tests is a gas chromatographic (GC) and high-resolution mass spectrometric (MS) analysis to identify the concentration of specific materials.

These testing parameters and methods are capable of identifying the presence and quantity of dioxins and furans in parts per trillion (ppt) and satisfy the EPA's Tier 1 data requirements for a "chemical analysis to characterize the emissions of fuels or additive/base fuel mixtures." Advanced recycling fuel and chemical recycling customers are bound to meet the U.S. EPA's 40 CFR Part 79 of the EPA Registered Fuels and Fuels Additives program.[6]

Advanced recycling fuel customers test fuel and additive fuel products to ASTM and ISO standards, and relevant state-specific testing requirements.[7] To meet these guidelines, fuel customers submit to internal and third-party independent lab testing. In other words, fuels derived from pyrolysis must meet the regulatory and customer specification to be saleable. The final onus on proving fuel quality and the non-existence of dioxins is directed to advanced recycling customers that blend, sell or use the fuels.

6 U.S. Gov Info. 40 CFR 79 - Registration of Fuels and Fuel Additives. https://www.govinfo.gov/app/details/CFR-2014-title40-vol17/CFR-2014-title40-vol17-part79/summary

7 Pace Analytical. Dioxin Testing Certifications. https://www.pacelabs.com/environmental-services/specialty-services/dioxins-furans/dioxin-certifications.html

DETAILED PRACTICES FOR DIOXIN PREVENTION IN OTHER ADVANCED RECYCLING FACILITIES THAT DO NOT USE PYROLYSIS

Some advanced recycling companies use different technologies that represent competitive advantages, therefore most the details provided in this section are provided in such a way that they do not share sensitive, proprietary data or information.

Facility-level processes and equipment for advanced recycling companies that prevent the formations of dioxins:

FEEDSTOCK CONTROLS AND SORTING	At the front end, advanced recycling companies eliminate materials that could be problematic to the system and have the potential for dioxin formation.
EQUIPMENT AND PROCESSES	Advanced recycling facilities pair specific equipment and processes to reduce and eliminate potential volatile organic compounds. For instance, select advanced recyclers use a thermal oxidizer to eliminate potential dioxins via a high-temperature process. Other facilities run syngas or recycled fuel gas through guard beds. Some facilities use cooling and isolation at different stages of the process allows for the identification and measurement of potential emissions to confirm that they are addressed before moving on to the next stage.
THIRD-PARTY TESTING AND ADHERENCE TO LOCAL AND NATIONAL REGULATIONS	Select advanced recycling companies have completed third-party environmental testing and reporting on emissions data to demonstrate their performance and compliance with state or federal laws for air and water in the U.S. and Canada.

CONCLUSION

Advanced recycling technologies provide significant potential to create a circular economy for plastics by converting low value plastics that cannot be recycled mechanically back into valuable feedstocks for new plastics and chemicals, basic chemicals, monomers, products like waxes and lubricants and lower-environmental-footprint fuels.

These technologies help keep plastics out of landfills and the marine environment and displace the use of additional fossil energy resources.

However, the potential of these technologies will not be met if policymakers and key stakeholders are not confident that the emissions of these technologies are well regulated and minimized. This analysis finds that pyrolysis technologies are being well regulated by the Clean Air Act (CAA) and state/local regulatory authorities, and are expected to have air emissions that are well below regulated levels and even below well-known industries and community institutions in every category of emissions, or in most cases, both. Furthermore, the production of dioxins is not an expected concern for these technologies.

Pyrolysis-based advanced recycling technologies manage their feedstock, do not combust plastics and redundantly engineer their technologies to prevent dioxin production. Finally, the ability to produce on-spec outputs for sale into the marketplace is also paramount. Products that do not meet specifications are rendered unsaleable and places an existential requirement on pyrolysis facilities to manage their inbound materials, saleable products and emissions into the environment. These technologies offer a unique way to recover matter, energy and polymer feedstocks and can do so in an environmentally friendly way.

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APPENDIX:
METHODOLOGY

NORMALIZING EMISSIONS DATA

Data from permits have been scaled to incoming feedstock (which is reported in permitting applications). This allows for a calculation to normalize emissions per ton of incoming feedstock. Further, we set the capacity of the facilities at a near average capacity of 55,000 tons of inbound feedstock per year.

INDUSTRY EMISSIONS DATA

Industry emissions data are sourced from the EPA's 2017 National Emissions Inventory (published April 2020) — the most recent at the time of this analysis. EPA's inventory is a database made up of an aggregation of locally and federally reported CAP emissions. Any facility required to report any single CAP emissions at either level is included in this database. This leads to some facilities having near zero emissions of a single CAP because that facility is required to report substantial emissions in another CAP (and therefore all its CAP emissions).

Additionally, reporting thresholds (bottom of permit range) vary between local regulators, leading to possible inclusions of some facilities and exclusions of others, even if they have similar emissions profiles (this occurs when emissions fall beneath federal Title V permitting). The average emissions per industry reported in this paper is a straight average of emissions excluding facilities that reported under 1 ton of CAP emissions in that category. This exclusion is an attempt to remove incidental emissions that are included in the database as described in the above paragraph.

DISCLAIMER

APPENDIX:
GLOSSARY TERMS

Clean Air Act, established in 1970 by U.S. federal government regulates air emissions from stationary and mobile sources. These laws provided EPA the authority to establish National Ambient Air Quality Standards (NAAQS) to regulate emissions of hazardous air pollutants.[8]

Combustion or burning is a rapid, high temperature chemical reaction between a fuel and oxidant, typically oxygen, that generally produces heat, light and gaseous products.

Criteria Air Pollutants (CAPs) are the six common air pollutants covered by the Clean Air Act's National Ambient Air Quality Standards (NAAQS) because they can harm human and environmental health.[9] CAPs include: carbon monoxide, lead, ground-level ozone, nitrogen dioxide, particulate matter, and sulfur dioxide.

Depolymerization is a process that converts polymers into component monomers, essentially macromolecules into smaller molecules. In this process, plastics can be broken apart into their constituent compounds via pyrolysis. Later, these compounds can be reconstituted into polymers.

Hazardous Air Pollutants (HAPs) are air toxics (toxic air pollutants) known to cause cancer and other serious health impacts from certain categories of industrial facilities. There are 187 toxic air pollutants including asbestos, benzene, and 2,3,7,8-Tetrachlorodibenzo-p-dioxin.

Hydrotreating is a common refinery practice used in blend stock production that removes impurities like sulfur and chlorine from the liquid hydrocarbon stream post conversion.

Liquid Hydrocarbons or Hydrogen Gas Liquids (HGLs) are organic compounds consisting of molecules of carbon and hydrogen in various combinations. These compounds are a primary product of advanced recycling facilities. These compounds occur as liquids under high pressures, gases at atmospheric pressure, and liquefied via cooling processes.

Non-Condensable Gases are created through pyrolysis that when cooled, will not become a liquid. These are used to displace methane and/or propane for process heat and are often combined with methane and/or propane to ensure the combustion temperature is high enough to prevent dioxin formation.

Post-Use Recyclable Plastics are materials that have been used once and can be recycled if the economics work based on commodity prices. If markets or prices are not adequate, these plastic streams are good candidates for advanced recycling.

Purification is a dissolution process where the plastics are dissolved in a solvent, separated and purified and then additives are extracted and used for new plastics.

Pyrolysis is a thermal decomposition process at high elevated temperatures in an inert atmosphere, devoid of oxygen that changes the chemical composition of the materials.

8 USEPA. Summary of the Clean Air Act. https://www.epa.gov/laws-regulations/summary-clean-air-act
9 USEPA. Criteria Air Pollutants. https://www.epa.gov/criteria-air-pollutants#self