February 26, 2025

Comments before House Environment & Transportation Committee

FAVORABLE WITH AMENDMENTS

House Bill 1092

Recycling - Prohibition on the Chemical Conversion of Plastic

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Good afternoon. My name is Mike Ewall and I'm the founder and director of a national organization, Energy Justice Network. Energy Justice works at the local level with grassroots community groups in Maryland and the rest of the country to support efforts to promote zero waste, and to stop polluting and unnecessary energy and waste industry facilities.

Energy Justice Network strongly supports House Bill 1092 and recommends the following amendment

> "A PERSON MAY NOT BUILD **OR OPERATE** IN THE STATE A FACILITY THAT CONVERTS16 PLASTIC TO FUEL OR FEEDSTOCK THROUGH…"

This amendment would ensure that no facilities slip through the cracks by being quickly constructed before this bill goes into effect.

This bill protects Maryland communities against a toxic scam of an industry that many communities have had to organize themselves to fight. Plastics pyrolysis is a failed industry that dresses up an incineration process as if it's recycling.

One of the most alarming things we've seen is that plastics pyrolysis chemicals have been found to have a shocking 1 in 4 cancer risk. Standards are usually set at one in one million.[1]

Most of the materials in plastics, when put into a pyrolysis process, are ultimately burned, whether on-site or off-site. When burned on-site, this is essentially an incineration process, though it is broken into two stages.

To illustrate, if you light a piece of paper on fire, and look closely, you'll notice a small gap between the paper and the flame. It is the heat that gasifies the paper, and the gases that burn. This takes place in any sort of incinerator. Technically, all incineration is gasification. However, in a gasification or pyrolysis type of incinerator, they basically put a pipe in the middle, between the paper and the flame, making it a two-stage incineration process. In the first stage, temperature and sometimes pressure are used to make the material into a gas. They call this "syngas," short for "synthesis gas" and describe it as hydrogen (H_2) and carbon monoxide (CO). However, there are many more elements in waste than just hydrogen, carbon, and oxygen, so there will be many other chemicals in syngas than what is typically described.

The second stage is typically burning the gas, which is why EPA, when these processes are done in the same facility, still sees the full process as incineration, even though it's broken into a two-stage process. Claims that gasification and pyrolysis are not incineration or do not involve combustion depend on a limited analysis that focuses on the first stage and ignores the second.

[1] Sharon Lerner, "This 'climate-friendly' fuel comes with an astronomical cancer risk," ProPublica, Feb. 23, 2023. https://www.theguardian.com/environment/2023/feb/23/climate-friendly-us-program-plastics-fuel-cancer

There are a few important differences between convention incineration and pyrolysis.

First, pyrolysis provides the *opportunity* to filter the syngas before burning it, which theoretically allows for better pollution control than putting the filters after the flame. However, pyrolysis facilities are more experimental and often operated at small, pilot scales where such filtering is not required by regulation as permits for larger facilities would require.

Second, gasification and pyrolysis allow for the gas to be used in different ways than simply burning it on-site. In some more complex proposals (and most are proposals… few exist in commercial operation), the syngas is to be fed into a second stage that separates out gases for certain industrial uses, or converts gases to liquid fuels to be burned off-site in motor vehicles or other applications.

The most telling assessment of these technologies is from the waste industry consultants who evaluate and even recommend them to local governments they consult for. While all traditional, major solid waste consulting firms (Arcadis, CDM Smith, Geosyntec, HDR, MSW Consultants, SCS, etc.) tend to be enamored with incinerators, none are bigger cheerleaders for the industry than Gershman, Brickner & Bratton, Inc. (GBB). GBB is the only consulting outfit that joins the incinerator industry players in funding the New York City-based academic research outfit that routinely puts out pro-incinerator academic research (similar to how the tobacco industry became popular for "tobacco science"). They are the go-to outfit to present the state of the "waste-to-energy"[2] industry at solid waste and utility conferences.

In these presentations, GBB typically shows a slide on various "waste-to-energy" technologies and their risks. GBB does not consider there to be any health or environmental risk to any of these technologies, but is presenting to industry audiences about the financial investment risk. In that context, GBB characterizes both gasification and pyrolysis as high risk investments due to "previous failures at scale" and "no operating experience with large-scale operations in the U.S."[3] GBB has continuously presented variations of this high-risk assessment for the past decade, as these technologies are relegated to small-scale demonstration plants that typically fail technically and/or economically. Plants that continue to operate do so by abandoning mixed municipal solid waste and switching to very homogeneous feedstocks.

Examples from 2012 and 2017 presentations by GBB follow on the next page.

While GBB has a long history of urging communities to explore all "waste-to-energy" technologies, including those they describe as high risk when talking within the industry, various reports from other solid waste consultants continue to this day to dismiss the technology as unproven.

Arcadis, a consultant currently working for Montgomery County, recently describes pyrolysis as a type of gasification for a county client in Florida and summarizes it, saying "Unproven technology. Can be equipped for electrical generation, counts as recycling in Florida, fire hazards from syngas production."[4]

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[2] "Waste-to-energy" is in quotes because it is an unscientific public relations term for waste incineration technologies, and does not literally turn matter into energy, violating the laws of physics, but turns waste into air pollution and ash. See: https://www.energyjustice.net/incineration/waste-to-energy

[3] "Waste Conversion Technologies for Minnesota," GBB presentation to SWANA, October 17, 2017. See slide 30 in http://gbbinc.com/wp-content/uploads/2017/10/SimmonsRAM-SWANA2017.pdf See also, slide 43 in "The Latest Updates on Waste-to-Energy and Conversion Technologies; Plus Projects Under Development," GBB presentation to WasteCon 2012. http://www.gbbinc.com/speaker/GershmanWASTECON2012.pdf

[4] Arcadis, "Miami-Dade County Department of Solid Waste Management – Preliminary Solid Waste System Siting Alternatives Report," August 2023, Table 3.4, pp. 71-72. https://www.miamidade.gov/solidwaste/library/final-preliminary-future-wte-siting-report.pdf

Technologies and Risk

Source: Gershman, Brickner & Bratton, Inc. August 2012

Alternative	Risks/Liability	Risk Summary
Mass Burn/WaterWall	Proven commercial technology	Very Low
Mass Burn/Modular	Proven commercial technology	Low
RDF/ Dedicated Boiler	Proven commercial technology	Low
RDF/Fluid Bed	Proven technology; limited U.S. commercial experience	Moderate to Low
Anaerobic Digestion	Proven technology; limited U.S. commercial experience	Moderate to Low
Mixed-Waste Composting	Previous large failures; No large-scale commercially viable plants in operation; subject to scale-up issues	Moderate to high
Pyrolysis	Previous failures at scale, uncertain commercial potential; no operating experience with large - scale operations	High
Gasification	Limited operating experience at only small scale; subject to scale-up issues	High
Chemical Decomposition/ Depolymerization	Technology under development; not a commercial option at this time	High

Conversion Technologies have Different Risk Profiles

Alternative	Risks/Liability	Risk Summary
Processing for Recyclables and Fuel	Proven commercial technology	Low
Composting	Proven commercial technology	Low
Mass Burn Combustion	Proven commercial technology	Low
RDF Combustion	Proven technology; limited U.S. commercial experience	Moderate to Low
Anaerobic Digestion	Proven technology; limited U.S. commercial experience	Moderate to Low
Pyrolysis and Gasification	Previous failures at scale; no operating experience with large -scale operations in the U.S.; full-scale demonstrations nearing operation	High

Source: Gershman, Brickner & Bratton, Inc. 2017

In over 30 years of our own experience across the nation, we can affirm that gasification facilities are generally more hype than reality. They cannot operate continuously, do not work with feedstocks that are not very homogenous, they tend to be pilot scale efforts that cannot scale up to commercial facilities, and they typically fall apart technically, economically, or both, if they even get as far as permitting and construction.

As far as pollution levels go, there is little data because gasification facilities are typically not working or lasting long, and are often flying below regulatory thresholds for testing and reporting. However, data we've seen shows that emissions are comparable to traditional incinerators, though some pollutants can be emitted at lower levels, while others at higher levels. Robust data to make generalizations about how they compare is simply unavailable, though select data points can be found here and there.

In its greenhouse gas comparison study for Miami-Dade County, Arcadis writes:

> **"1.5.2 Gasification Facility**
> There is no emission factor for the gasification process provided by USEPA. Based on our understanding of the process and professional knowledge, GHG emissions for gasification facilities would be comparable and on par with GHG emissions from a [trash incinerator] with the same carbon content of fuel."[5]

In other words, gasification is just as much a carbon emitter as conventional incinerators. Greenhouse gas emissions from conventional incinerators are 65% worse than coal per unit of energy, according to EPA data.[6]

In the face of this history, we see communities typically spend money on consultants to evaluate gasification and other "waste-to-energy" technologies just to ultimately throw up their hands and return to landfilling. In 2011, Prince George's County, Maryland hired GBB to review alternatives to landfilling. After extensive analysis of options including municipal solid waste combustion, gasification, waste-to-fuels, and mixed waste processing, GBB narrowed the list of qualified vendors from 16 to seven before Prince George's County abandoned all of them in 2016 in favor of a plan to extend the life of its landfill and adopt zero waste measures. Vendors with pyrolysis and gasification technologies didn't make the short-list of seven.

In 2014, the world's largest waste corporation, Waste Management, Inc., sold off its investments in gasification, pyrolysis and other waste-to-fuels companies.[7]

In June 2020, consultant Geosyntec completed a $450,000 Solid Waste and Recycling Master Plan for the City of Baltimore, which looked at options for replacing its aging trash incinerator. Their final report states:

> *Gasification is also an emerging and untested technology for waste processing in the U.S., which may make it difficult to permit and build such a facility. . . Based on the very high capital costs for a MWP facility using gasification technology, and the fact that gasification is a largely untested technology for processing organics separated from a mixed waste stream, a MWP facility configuration with a gasifier is not recommended.*[8]

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[5] Arcadis, "Miami-Dade County Department of Solid Waste Management – Greenhouse Gas Emissions Study," October 14, 2024, p.2. https://www.miamiherald.com/latest-news/article296016704.ece/BINARY/Levine%20Cava%20memo%20on%20incinerator%20site.pdf#page=31

[6] https://www.energyjustice.net/incineration/worsethancoal

[7] Big Waste Hauler Rethinks Startups," Wall Street Journal, Jan 3, 2014.

[8] "Draft Master Plan, City of Baltimore, Recycling and Solid Waste Management Master Plan," Geosyntec, June 2020. See pages 57 and 60: https://publicworks.baltimorecity.gov/sites/default/files/LWBB_Draft%20Master%20Plan_6-5-20.pdf

MWP stands for mixed waste processing, which involves sorting trash to remove materials such as glass and metal before preparing what remains to be burned, composted or digested. Although proponents of gasification and pyrolysis claim these technologies can effectively process a wide variety of materials, they cannot process them as a heterogenous mixture. Extensive use of MWP is required to produce an acceptable feedstock and even when such sorting methods are in place, what comes off the back end is often still too diverse for the highly sensitive mechanical components that comprise these systems.

In their more detailed "Managing What's Left" report leading up to the Master Plan, Geosyntec elaborates on gasification, stating:

> *Geosyntec is not aware of any commercial scale MSW gasification project currently in operation in the U.S. It is not a mature technology and thus analyses presented in this section are based on extrapolation from pilot projects that may not be scalable or projects currently under construction (which are unproven). This adds an extra dimension of uncertainty to the findings discussed here.*[9]

Please find the article in the first footnote, and other relevant materials attached:

Attachments:

1) Sharon Lerner, "This 'climate-friendly' fuel comes with an astronomical cancer risk," ProPublica, Feb. 23, 2023. https://www.theguardian.com/environment/2023/feb/23/climate-friendly-us-program-plastics-fuel-cancer

2) Declaration of Dr. Ranajit (Ron) Sahu relating to pyrolysis (followed by his CV)

3) Zero Waste Europe, "El Dorado of Chemical Recycling: State of play and policy challenges"

Please also review:

4) The Delusion of Advanced Plastic Recycling Using Pyrolysis, ProPublica https://www.propublica.org/article/delusion-advanced-chemical-plastic-recycling-pyrolysis [best viewed online]

5) Natural Resources Defense Council, "Recycling Lies: 'Chemical Recycling' of Plastic is Just Greenwashing Incineration" https://www.nrdc.org/resources/recycling-lies-chemical-recycling-plastic-just-greenwashing-incineration [protected; cannot attach]

[9] "Managing What's Left, City of Baltimore, Recycling and Solid Waste Management Master Plan," Geosyntec, April 2020. See page 36: https://publicworks.baltimorecity.gov/sites/default/files/LWBBTask7ReportFINAL4-15-20.pdf

https://www.theguardian.com/environment/2023/feb/23/climate-friendly-us-program-plastics-fuel-cancer

This ‘climate-friendly’ fuel comes with an astronomical cancer risk

Almost half of products cleared so far under a new US federal ‘biofuels’ program are not, in fact, biofuels

This article is co-published with ProPublica, a nonprofit newsroom that investigates abuses of power

Sharon Lerner
Thu 23 Feb 2023 11.00 GMT

The Environmental Protection Agency (EPA) recently gave a Chevron refinery the green light to create fuel from discarded plastics as part of a climate-friendly initiative to boost alternatives to petroleum. But, according to agency records obtained by ProPublica and the Guardian, the production of one of the fuels could emit air pollution that is so toxic, one out of four people exposed to it over a lifetime could get cancer.

“That kind of risk is obscene,” said Linda Birnbaum, former head of the National Institute of Environmental Health Sciences. “You can’t let that get out.”

That risk is 250,000 times greater than the level usually considered acceptable by the EPA division that approves new chemicals. Chevron hasn’t started making this fuel yet, the EPA said. When the company does, the cancer burden will disproportionately fall on people who have low incomes and are Black because of the population that lives within three miles of the refinery that will produce the fuel in Pascagoula, Mississippi.

ProPublica and the Guardian asked Maria Doa, a scientist who worked at the EPA for 30 years, to review the document laying out the risk. Doa, who once ran the division that managed the risks posed by chemicals, was so alarmed by the cancer threat that she initially assumed it was a typographical error. “EPA should not allow these risks in Pascagoula or anywhere,” said Doa, who now is the senior director of chemical policy at Environmental Defense Fund.

In response to questions from ProPublica and the Guardian, an EPA spokesperson wrote that the agency’s lifetime cancer risk calculation is “a very conservative estimate with ‘high uncertainty’”, meaning the government erred on the side of caution in calculating such a high risk.

That kind of risk is obscene. EPA should not allow these risks in Pascagoula or anywhere
Linda Birnbaum, former head of the National Institute of Environmental Health Sciences

Under federal law, the EPA can’t approve new chemicals with serious health or environmental risks unless it comes up with ways to minimize the dangers. And if the EPA is unsure, the law allows the agency to order lab testing that would clarify the potential health and environmental harms. In the case of these new plastic-based fuels, the agency didn’t do either of those things. In approving the fuel, the EPA didn’t require any lab tests, air monitoring or controls that would reduce the release of the cancer-causing pollutants or people’s exposure to them.

In January 2022, the EPA announced the initiative to streamline the approval of petroleum alternatives in what a press release called “part of the Biden-Harris administration’s actions to confront the climate crisis”. While the program cleared new fuels made from plants, it also signed off on fuels made

from plastics even though they are petroleum-based and contribute to the release of planet-warming greenhouse gases.

Although there's no mention of discarded plastics in the press release or on the EPA website's description of the program, an agency spokesperson told ProPublica and the Guardian that it allows their production because the initiative also covers fuels made from waste. The spokesperson said that 16 of the 34 fuels the program approved so far are made from waste. She would not say how many of those are made from plastic and stated that such information was confidential.

All of the waste-based fuels are the subject of consent orders, documents the EPA issues when it finds that new chemicals or mixtures may pose an "unreasonable risk" to human health or the environment. The documents specify those risks and the agency's instructions for mitigating them.

But the agency won't turn over these records or reveal information about the waste-based fuels, not even their names or chemical structures. Without those basic details, it is nearly impossible to determine which of the thousands of consent orders on the EPA website apply to this program. In keeping this information secret, the EPA cited a legal provision that allows companies to claim as confidential any information that would give their competitors an advantage in the marketplace.

Nevertheless, ProPublica and the Guardian did obtain one consent order that covers a dozen Chevron fuels made from plastics that were reviewed under the program. Although the EPA had blacked out sections, including the chemicals' names, the document showed that the fuels that Chevron plans to make at its Pascagoula refinery present serious health risks, including developmental problems in children and cancer and harm to the nervous system, reproductive system, liver, kidneys, blood and spleen.

Aside from the chemical that carries a 25% lifetime risk of cancer from smokestack emissions, another of the Chevron fuels ushered in through the program is expected to cause cancer in 1.2 of 10,000 people – a rate also far higher than the agency allows for the general population. The EPA division that screens new chemicals typically limits cancer risk from a single air pollutant to one case of cancer per million people. The agency also calculated that air pollution from one of the fuels is expected to cause cancer in 7.1 of every 1,000 workers – more than 70 times the level the EPA's new chemicals division usually considers acceptable for workers.

In addition to the chemicals released through the creation of fuels from plastics, the people living near the Chevron refinery are exposed to an array of other cancer-causing pollutants, as ProPublica reported in 2021. In that series, which mapped excess cancer risk from lifetime exposure to air pollution across the US, the greatest risk was one cancer case per 53 people, in Port Arthur, Texas.

A refinery in Port Arthur, Texas, where the risk of cancer from lifetime exposure to air pollution is the greatest in the US. Photograph: Eric Gay/AP

The one-in-four lifetime cancer risk from breathing the emissions from the Chevron fuel is higher even than the lifetime risk of lung cancer for current smokers.

In an email Chevron spokesperson Ross Allen wrote: “It is incorrect to say there is a one-in-four cancer risk from smoke-stack emissions. I urge you [to] avoid suggesting otherwise.” Asked to clarify what exactly was wrong with the statement, Allen wrote that Chevron disagrees with ProPublica and the Guardian’s “characterization of language in the EPA consent order”. That document, signed by a Chevron manager at its refinery in Pascagoula, quantified the lifetime cancer risk from the inhalation of smokestack air as 2.5 cancers per 10 people, which can also be stated as one in four.

In a subsequent phone call, Allen said: “We do take care of our communities, our workers and the environment. Generally, this is job one for Chevron.” In a separate written statement, Chevron said it followed the EPA’s process under the Toxic Substances Control Act: “The TSCA process is an important first step to identify risks and if EPA identifies unreasonable risk, it can limit

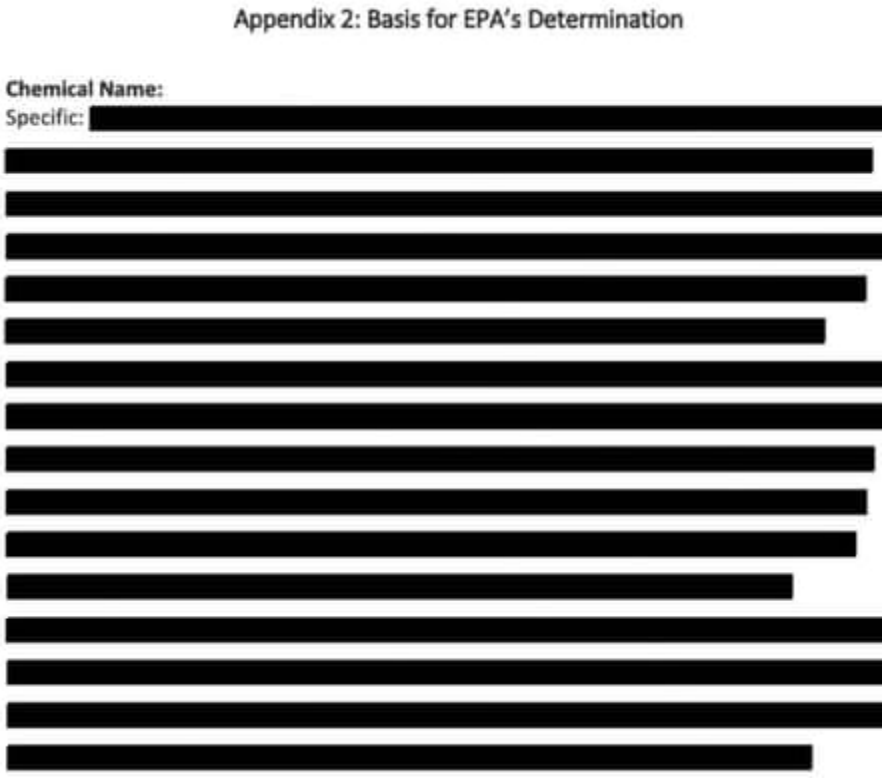
or prohibit manufacture, processing or distribution in commerce during applicable review period."

The Chevron statement also said: "Other environmental regulations and permitting processes govern air, water and handling hazardous materials. Regulations under the Clean Water, Clean Air and Resource Conservation and Recovery Acts also apply and protect the environment and the health and safety of our communities and workers."

Similarly, the EPA said that other federal laws and requirements might reduce the risk posed by the pollution, including Occupational Safety and Health Administration (Osha) regulations for worker protection, the Clean Water Act, the Clean Air Act and rules that apply to refineries.

But Osha has warned the public not to rely on its outdated chemical standards. The refinery rule calls for air monitoring only for one pollutant: benzene. The Clean Water Act does not address air pollution. And the new fuels are not regulated under the Clean Air Act, which applies to a specific list of pollutants. Nor can states monitor for the carcinogenic new fuels without knowing their names and chemical structures.

We asked Scott Throwe, an air pollution specialist who worked at the EPA for 30 years, how existing regulations could protect people in this instance. Now an independent environmental consultant, Throwe said the existing testing and monitoring requirements for refineries couldn't capture the pollution from these new plastic-based fuels because the rules were written before these chemicals existed. There is a chance that equipment designed to limit the release of other pollutants may incidentally capture some of the emissions from the new fuels, he said. But there's no way to know whether that is happening.



A redacted section of an EPA consent order covering plastic-derived fuels. Photograph: EPA

Under federal law, companies have to apply to the EPA for permission to introduce new chemicals or mixtures. But manufacturers don't have to supply any data showing their products to be safe. So the EPA usually relies on studies of similar chemicals to anticipate health effects. In this case, the EPA used a mixture of chemicals made from crude oil to gauge the risks posed by the new plastic-based fuels. Chevron told the EPA the chemical components of its new fuel but didn't give the precise proportions. So the EPA had to make some assumptions, for instance that people absorb 100% of the pollution emitted.

Asked why it didn't require tests to clarify the risks, a spokesperson wrote that the "EPA does not believe these additional test results would change the risks identified nor the unreasonable risks finding".

In her three decades at the EPA, Maria Doa of the Environmental Defense Fund had never seen a chemical with that high of a cancer risk that the agency allowed to be released into a community without restrictions.

“The only requirement seems to be just to use the chemicals as fuel and have the workers wear gloves,” she said.

While companies have made fuels from discarded plastics before, this EPA program gives them the same administrative break that renewable fuels receive: a dedicated EPA team that combines the usual six regulatory assessments into a single report.

The irony is that Congress created the Renewable Fuel Standard Program, which this initiative was meant to support, to reduce greenhouse gas emissions and boost the production of renewable fuels. Truly renewable energy sources, such as plants or algae, can be regenerated in a short period of time. While there is significant debate about whether ethanol, which is made from corn, and other plant-based renewable fuels are really better for the environment than fossil fuels, there is no question that plastics are not renewable and that their production and conversion into fuel releases climate-harming pollution.

Under the EPA’s Renewable Fuel Standard, bio-based fuels must meet specific criteria related to their biological origin as well as the amount by which they reduce greenhouse gas emissions compared with petroleum-based fuels. But under this new approach, fuels made from waste don’t have to meet those targets, the agency said.

In its written statement, Chevron said that “plastics are an essential part of modern life and plastic waste should not end up in unintended places in the environment. We are taking steps to address plastic waste and support a circular economy in which post-use plastic is recycled, reused or repurposed.” But environmentalists say such claims are just greenwashing.

Whatever it’s called, the creation of fuel from plastic is in some ways worse for the climate than simply making it directly from fossil fuels. Over 99% of all plastic is derived from fossil fuels, including coal, oil and gas. To produce fuel from plastics, additional fossil fuels are used to generate the heat that converts them into petrochemicals that can be used as fuel.

“It adds an extra step,” said Veena Singla, a senior scientist at the Natural Resources Defense Council. “They have to burn a lot of stuff to power the process that transforms the plastic.”

Less than 6% of plastic waste is recycled in the US. Scientists estimate that more than a million tons of that unrecycled plastic ends up in the environment each year, killing marine mammals and polluting the world.

Plastic does not fully decompose; instead it eventually breaks down into tiny bits, some of which wind up inside our bodies. As the public's awareness of the health and environmental harm of plastic grows, the industry has found itself under increasing pressure to find a use for the waste.

The idea of creating fuel from plastic offers the comforting feeling that plastics are sustainable. But the release of cancer-causing pollution is just one of several significant problems that have plagued attempts to convert discarded plastic into new products. One recent study by scientists from the Department of Energy found that the economic and environmental costs of turning old plastic into new resources using a process called pyrolysis were 10 to 100 times higher than those of making new plastics from fossil fuels. The lead author said similar issues plague the use of this process to create fuels from plastics.

Chevron buys oil that another company extracts from discarded plastics through pyrolysis. Though the parts of the consent order that aren't redacted don't mention that this oil came from waste plastics, a related EPA record makes this clear. The cancer risks come from the pollution emitted from Chevron's smokestacks when the company turns that oil into fuel.

The EPA attributed its decision to embark on the streamlined program in part to its budget, which it says has been "essentially flat for the last six years". The EPA spokesperson said that the agency "has been working to streamline its new chemicals work wherever possible".

The New Chemicals Division, which houses the program, has been under particular pressure because updates to the chemicals law gave it additional responsibilities and faster timetables. That division of the agency is also the subject of an ongoing EPA inspector general investigation into whistleblowers' allegations of corruption and industry influence over the chemical approval process.

This story was updated on 1 March 2023. A previous version misstated what happens to unrecycled plastic in the US. Scientists estimate that more than a million tons of it end up in the environment each year. It is not known precisely how much of this plastic from the US winds up in the oceans.

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Declaration of Dr. Ranajit (Ron) Sahu

1. My name is Dr. Ranajit (Ron) Sahu. A copy of my resume is provided in Attachment A to this Declaration. I have a Bachelor's of Technology degree in Mechanical Engineering from the Indian Institute of Technology (IIT) followed by M.S and Ph.D degrees in Mechanical Engineering from the California Institute of Technology (Caltech). My Ph.D work focused on pyrolysis and combustion, which are directly relevant to this Declaration.

2. In my opinion, all gasification and pyrolysis of waste necessarily involves the combustion of at least some of the material being gasified or pyrolyzed (i.e., the waste materials).

3. Broadly, combustion is a subset of a broader set of chemical reactions, called oxidation. While typically oxidation involves oxygen, from a chemistry standpoint oxidation is defined more broadly where the agent causing oxidation can be different than oxygen.

4. Combustion is the "burning" that occurs for various materials in the presence of oxygen. Most commonly the source of the oxygen is ambient air. Typically combustion releases heat – i.e., it is exothermic. The most common form of oxidation and combustion that takes place in pyrolysis and gasification units is the reaction of carbon with oxygen to create a combination of carbon dioxide (CO_2) and also some carbon monoxide (CO), accompanied with a release of heat.

5. Other examples of oxidation include formation of rust (or oxidation of iron, but not carbon) which is a very slow form of oxidation. At the other end in terms of speed, explosions are also often caused by rapid oxidation of fuels which can contain carbon. Combustion, in terms of speed, falls somewhere in between. Within the set of oxidation reactions that involve the combination of carbon with oxygen, all reactions that are not explosions are combustion..

6. Combustion typically requires the presence of a source of carbon (i.e., the materials to be combusted either intentionally or not), the oxidant (i.e., typically oxygen or air), and the presence of sufficient energy. A flame is not necessary for combustion because, if the temperature of a material is raised significantly it can "autoignite" and there is no need for a separate ignition source. Thus, in simple terms combustion can occur when there is a source of carbon, a source of oxygen and an energy source either from an ignitor or due to the material temperature being high enough to cause auto-ignition.

7. Theoretically, pyrolysis is the chemical decomposition of typically organic (i.e., carbon-based) materials via the application of heat but in the absence of oxygen. The absence of oxygen, however, is an aspirational goal, because it is not possible to eliminate the presence of all oxygen in real-world pyrolysis units.

8. In general terms all materials that can be pyrolyzed/gasified contain some oxygen or oxygen compounds. Also, if the pyrolysis chamber or container is not perfectly sealed and maintained at greater than atmospheric pressure, external oxygen can be introduced into the pyrolysis process. For both reasons, it is impossible to operate a pyrolysis unit in the absence of all oxygen.

9. As the temperature of organic material that is to be pyrolyzed/gasified is increased in order to effect the pyrolysis/gasification, the presence of some of the inherent oxygen in the material and/or

any externally introduced oxygen will initiate combustion reactions while pyrolysis/gasification is going on. Thus, some combustion is impossible to avoid in pyrolysis/gasification units.

10. Pyrolysis/gasification is often the first stage or first step in combustion. Heat causes the waste materials to release volatile organic materials which then react with available oxygen (always present to some degree), releasing more heat and causing the formation of carbon dioxide and carbon monoxide along with other products of complete and incomplete combustion.

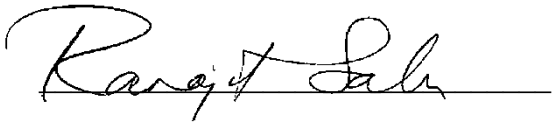
11. Because some oxygen is always unavoidably present in organic materials (which consist of carbon, hydrogen, oxygen, and other elements such as sulfur, nitrogen, etc.), some combustion is inevitable during pyrolysis/gasification and always occurs.

12. Further proof that some combustion always occurs in pyrolysis/gasification units is the invariable presence of products of complete combustion (such as carbon dioxide and water vapor as well as sulfur oxides, if sulfur compounds are present in the "fuel") as well as the products of incomplete combustion such as carbon monoxide in the product gases from pyrolysis. These products of complete combustion would not be present if at least some materials had not been combusted.

13. Based on the inevitable and unavoidable aspects of both gasification/pyrolysis and some combustion occurring simultaneously, it is futile to artificially "separate" these processes into idealized forms where only one of these processes can occur to the exclusion of the other(s). Thus, in a practical incinerator, including one designed to first pyrolyze/gasify substances, followed by the subsequent combustion of the gaseous products, some combustion is inevitable in the first or pyrolysis chamber. It is impossible to separate such multi-component devices and call them separate names. They are collectively as a whole an incinerator. They work together to combust the substances in the waste that is fed into them.

I declare under penalty of perjury that the foregoing is true and correct to the best of my knowledge.

Executed this 17th day of December, 2021.



Ranajit Sahu, Ph.D.

ATTACHMENT A

RANAJIT (RON) SAHU, Ph.D, QEP, CEM (Nevada)

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EXPERIENCE SUMMARY

Dr. Sahu has over thirty one years of experience in the fields of environmental, mechanical, and chemical engineering including: program and project management services; design and specification of pollution control equipment for a wide range of emissions sources including stationary and mobile sources; soils and groundwater remediation including landfills as remedy; combustion engineering evaluations; energy studies; multimedia environmental regulatory compliance (involving statutes and regulations such as the Federal CAA and its Amendments, Clean Water Act, TSCA, RCRA, CERCLA, SARA, OSHA, NEPA as well as various related state statutes); transportation air quality impact analysis; multimedia compliance audits; multimedia permitting (including air quality NSR/PSD permitting, Title V permitting, NPDES permitting for industrial and storm water discharges, RCRA permitting, etc.), multimedia/multi-pathway human health risk assessments for toxics; air dispersion modeling; and regulatory strategy development and support including negotiation of consent agreements and orders.

He has over twenty eight years of project management experience and has successfully managed and executed numerous projects in this time period. This includes basic and applied research projects, design projects, regulatory compliance projects, permitting projects, energy studies, risk assessment projects, and projects involving the communication of environmental data and information to the public.

He has provided consulting services to numerous private sector, public sector and public interest group clients. His major clients over the past twenty six years include various trade associations as well as individual companies such as steel mills, petroleum refineries, chemical plants, cement manufacturers, aerospace companies, power generation facilities, lawn and garden equipment manufacturers, spa manufacturers, chemical distribution facilities, land development companies, and various entities in the public sector including EPA, the US Dept. of Justice, several states (including Oregon, New Mexico, Pennsylvania, and others), various agencies such as the California DTSC, and various municipalities. Dr. Sahu has performed projects in all 50 states, numerous local jurisdictions and internationally.

In addition to consulting, for approximately twenty years, Dr. Sahu taught numerous courses in several Southern California universities including UCLA (air pollution), UC Riverside (air pollution, process hazard analysis), and Loyola Marymount University (air pollution, risk assessment, hazardous waste management). He also taught at Caltech, his alma mater (various engineering courses), at the University of Southern California (air pollution controls) and at California State University, Fullerton (transportation and air quality).

Dr. Sahu has and continues to provide expert witness services in a number of environmental areas discussed above in both state and Federal courts as well as before administrative bodies (please see Annex A).

EXPERIENCE RECORD

2000-present **Independent Consultant.** Providing a variety of private sector (industrial companies, land development companies, law firms, etc.), public sector (such as the US Department of Justice), and public interest group clients with project management, environmental

consulting, project management, as well as regulatory and engineering support consulting services.

1995-2000 Parsons ES, **Associate, Senior Project Manager and Department Manager for** Air Quality/Geosciences/Hazardous Waste Groups, Pasadena. Responsible for the management of a group of approximately 24 air quality and environmental professionals, 15 geoscience, and 10 hazardous waste professionals providing full-service consulting, project management, regulatory compliance and A/E design assistance in all areas.

Parsons ES, **Manager for Air Source Testing Services**. Responsible for the management of 8 individuals in the area of air source testing and air regulatory permitting projects located in Bakersfield, California.

1992-1995 Engineering-Science, Inc. **Principal Engineer and Senior Project Manager** in the air quality department. Responsibilities included multimedia regulatory compliance and permitting (including hazardous and nuclear materials), air pollution engineering (emissions from stationary and mobile sources, control of criteria and air toxics, dispersion modeling, risk assessment, visibility analysis, odor analysis), supervisory functions and project management.

1990-1992 Engineering-Science, Inc. **Principal Engineer and Project Manager** in the air quality department. Responsibilities included permitting, tracking regulatory issues, technical analysis, and supervisory functions on numerous air, water, and hazardous waste projects. Responsibilities also include client and agency interfacing, project cost and schedule control, and reporting to internal and external upper management regarding project status.

1989-1990 Kinetics Technology International, Corp. **Development Engineer.** Involved in thermal engineering R&D and project work related to low-NOx ceramic radiant burners, fired heater NOx reduction, SCR design, and fired heater retrofitting.

1988-1989 Heat Transfer Research, Inc. **Research Engineer**. Involved in the design of fired heaters, heat exchangers, air coolers, and other non-fired equipment. Also did research in the area of heat exchanger tube vibrations.

EDUCATION

1984-1988 Ph.D., Mechanical Engineering, California Institute of Technology (Caltech), Pasadena, CA.

1984 M. S., Mechanical Engineering, California Institute of Technology (Caltech), Pasadena, CA.

1978-1983 B. Tech (Honors), Mechanical Engineering, Indian Institute of Technology (IIT) Kharagpur, India

TEACHING EXPERIENCE

Caltech

"Thermodynamics," Teaching Assistant, California Institute of Technology, 1983, 1987.

"Air Pollution Control," Teaching Assistant, California Institute of Technology, 1985.

"Caltech Secondary and High School Saturday Program," - taught various mathematics (algebra through calculus) and science (physics and chemistry) courses to high school students, 1983-1989.

"Heat Transfer," - taught this course in the Fall and Winter terms of 1994-1995 in the Division of Engineering and Applied Science.

“Thermodynamics and Heat Transfer,” Fall and Winter Terms of 1996-1997.

U.C. Riverside, Extension

"Toxic and Hazardous Air Contaminants," University of California Extension Program, Riverside, California. Various years since 1992.

"Prevention and Management of Accidental Air Emissions," University of California Extension Program, Riverside, California. Various years since 1992.

"Air Pollution Control Systems and Strategies," University of California Extension Program, Riverside, California, Summer 1992-93, Summer 1993-1994.

"Air Pollution Calculations," University of California Extension Program, Riverside, California, Fall 1993-94, Winter 1993-94, Fall 1994-95.

"Process Safety Management," University of California Extension Program, Riverside, California. Various years since 1992-2010.

"Process Safety Management," University of California Extension Program, Riverside, California, at SCAQMD, Spring 1993-94.

"Advanced Hazard Analysis - A Special Course for LEPCs," University of California Extension Program, Riverside, California, taught at San Diego, California, Spring 1993-1994.

“Advanced Hazardous Waste Management” University of California Extension Program, Riverside, California. 2005.

Loyola Marymount University

"Fundamentals of Air Pollution - Regulations, Controls and Engineering," Loyola Marymount University, Dept. of Civil Engineering. Various years since 1993.

"Air Pollution Control," Loyola Marymount University, Dept. of Civil Engineering, Fall 1994.

“Environmental Risk Assessment,” Loyola Marymount University, Dept. of Civil Engineering. Various years since 1998.

“Hazardous Waste Remediation” Loyola Marymount University, Dept. of Civil Engineering. Various years since 2006.

University of Southern California

"Air Pollution Controls," University of Southern California, Dept. of Civil Engineering, Fall 1993, Fall 1994.

"Air Pollution Fundamentals," University of Southern California, Dept. of Civil Engineering, Winter 1994.

University of California, Los Angeles

"Air Pollution Fundamentals," University of California, Los Angeles, Dept. of Civil and Environmental Engineering, Spring 1994, Spring 1999, Spring 2000, Spring 2003, Spring 2006, Spring 2007, Spring 2008, Spring 2009.

International Programs

“Environmental Planning and Management,” 5 week program for visiting Chinese delegation, 1994.

“Environmental Planning and Management,” 1 day program for visiting Russian delegation, 1995.

“Air Pollution Planning and Management,” IEP, UCR, Spring 1996.

“Environmental Issues and Air Pollution,” IEP, UCR, October 1996.

PROFESSIONAL AFFILIATIONS AND HONORS

President of India Gold Medal, IIT Kharagpur, India, 1983.

Member of the Alternatives Assessment Committee of the Grand Canyon Visibility Transport Commission, established by the Clean Air Act Amendments of 1990, 1992.

American Society of Mechanical Engineers: Los Angeles Section Executive Committee, Heat Transfer Division, and Fuels and Combustion Technology Division, 1987-mid-1990s.

Air and Waste Management Association, West Coast Section, 1989-mid-2000s.

PROFESSIONAL CERTIFICATIONS

EIT, California (#XE088305), 1993.

REA I, California (#07438), 2000.

Certified Permitting Professional, South Coast AQMD (#C8320), since 1993.

QEP, Institute of Professional Environmental Practice, since 2000.

CEM, State of Nevada (#EM-1699). Expiration 10/07/2021.

PUBLICATIONS (PARTIAL LIST)

"Physical Properties and Oxidation Rates of Chars from Bituminous Coals," with Y.A. Levendis, R.C. Flagan and G.R. Gavalas, *Fuel*, **67**, 275-283 (1988).

"Char Combustion: Measurement and Analysis of Particle Temperature Histories," with R.C. Flagan, G.R. Gavalas and P.S. Northrop, *Comb. Sci. Tech.* **60**, 215-230 (1988).

"On the Combustion of Bituminous Coal Chars," PhD Thesis, California Institute of Technology (1988).

"Optical Pyrometry: A Powerful Tool for Coal Combustion Diagnostics," *J. Coal Quality*, **8**, 17-22 (1989).

"Post-Ignition Transients in the Combustion of Single Char Particles," with Y.A. Levendis, R.C. Flagan and G.R. Gavalas, *Fuel*, **68**, 849-855 (1989).

"A Model for Single Particle Combustion of Bituminous Coal Char." Proc. ASME National Heat Transfer Conference, Philadelphia, **HTD-Vol. 106**, 505-513 (1989).

"Discrete Simulation of Cenospheric Coal-Char Combustion," with R.C. Flagan and G.R. Gavalas, *Combust. Flame*, **77**, 337-346 (1989).

"Particle Measurements in Coal Combustion," with R.C. Flagan, in "**Combustion Measurements**" (ed. N. Chigier), Hemisphere Publishing Corp. (1991).

"Cross Linking in Pore Structures and Its Effect on Reactivity," with G.R. Gavalas in preparation.

"Natural Frequencies and Mode Shapes of Straight Tubes," Proprietary Report for Heat Transfer Research Institute, Alhambra, CA (1990).

"Optimal Tube Layouts for Kamui SL-Series Exchangers," with K. Ishihara, Proprietary Report for Kamui Company Limited, Tokyo, Japan (1990).

"HTRI Process Heater Conceptual Design," Proprietary Report for Heat Transfer Research Institute, Alhambra, CA (1990).

"Asymptotic Theory of Transonic Wind Tunnel Wall Interference," with N.D. Malmuth and others, Arnold Engineering Development Center, Air Force Systems Command, USAF (1990).

"Gas Radiation in a Fired Heater Convection Section," Proprietary Report for Heat Transfer Research Institute, College Station, TX (1990).

"Heat Transfer and Pressure Drop in NTIW Heat Exchangers," Proprietary Report for Heat Transfer Research Institute, College Station, TX (1991).

"NOx Control and Thermal Design," Thermal Engineering Tech Briefs, (1994).

“From Purchase of Landmark Environmental Insurance to Remediation: Case Study in Henderson, Nevada,” with Robin E. Bain and Jill Quillin, presented at the AQMA Annual Meeting, Florida, 2001.

“The Jones Act Contribution to Global Warming, Acid Rain and Toxic Air Contaminants,” with Charles W. Botsford, presented at the AQMA Annual Meeting, Florida, 2001.

PRESENTATIONS (PARTIAL LIST)

"Pore Structure and Combustion Kinetics - Interpretation of Single Particle Temperature-Time Histories," with P.S. Northrop, R.C. Flagan and G.R. Gavalas, presented at the AIChE Annual Meeting, New York (1987).

"Measurement of Temperature-Time Histories of Burning Single Coal Char Particles," with R.C. Flagan, presented at the American Flame Research Committee Fall International Symposium, Pittsburgh, (1988).

"Physical Characterization of a Cenospheric Coal Char Burned at High Temperatures," with R.C. Flagan and G.R. Gavalas, presented at the Fall Meeting of the Western States Section of the Combustion Institute, Laguna Beach, California (1988).

"Control of Nitrogen Oxide Emissions in Gas Fired Heaters - The Retrofit Experience," with G. P. Croce and R. Patel, presented at the International Conference on Environmental Control of Combustion Processes (Jointly sponsored by the American Flame Research Committee and the Japan Flame Research Committee), Honolulu, Hawaii (1991).

"Air Toxics - Past, Present and the Future," presented at the Joint AIChE/AAEE Breakfast Meeting at the AIChE 1991 Annual Meeting, Los Angeles, California, November 17-22 (1991).

"Air Toxics Emissions and Risk Impacts from Automobiles Using Reformulated Gasolines," presented at the Third Annual Current Issues in Air Toxics Conference, Sacramento, California, November 9-10 (1992).

"Air Toxics from Mobile Sources," presented at the Environmental Health Sciences (ESE) Seminar Series, UCLA, Los Angeles, California, November 12, (1992).

"Kilns, Ovens, and Dryers - Present and Future," presented at the Gas Company Air Quality Permit Assistance Seminar, Industry Hills Sheraton, California, November 20, (1992).

"The Design and Implementation of Vehicle Scrapping Programs," presented at the 86th Annual Meeting of the Air and Waste Management Association, Denver, Colorado, June 12, 1993.

"Air Quality Planning and Control in Beijing, China," presented at the 87th Annual Meeting of the Air and Waste Management Association, Cincinnati, Ohio, June 19-24, 1994.

Annex A

Expert Litigation Support

A. Occasions where Dr. Sahu has provided Written or Oral testimony before Congress:

1. In July 2012, provided expert written and oral testimony to the House Subcommittee on Energy and the Environment, Committee on Science, Space, and Technology at a Hearing entitled "Hitting the Ethanol Blend Wall – Examining the Science on E15."

B. Matters for which Dr. Sahu has provided affidavits and expert reports include:

2. Affidavit for Rocky Mountain Steel Mills, Inc. located in Pueblo Colorado – dealing with the technical uncertainties associated with night-time opacity measurements in general and at this steel mini-mill.

3. Expert reports and depositions (2/28/2002 and 3/1/2002; 12/2/2003 and 12/3/2003; 5/24/2004) on behalf of the United States in connection with the Ohio Edison NSR Cases. *United States, et al. v. Ohio Edison Co., et al.*, C2-99-1181 (Southern District of Ohio).

4. Expert reports and depositions (5/23/2002 and 5/24/2002) on behalf of the United States in connection with the Illinois Power NSR Case. *United States v. Illinois Power Co., et al.*, 99-833-MJR (Southern District of Illinois).

5. Expert reports and depositions (11/25/2002 and 11/26/2002) on behalf of the United States in connection with the Duke Power NSR Case. *United States, et al. v. Duke Energy Corp.*, 1:00-CV-1262 (Middle District of North Carolina).

6. Expert reports and depositions (10/6/2004 and 10/7/2004; 7/10/2006) on behalf of the United States in connection with the American Electric Power NSR Cases. *United States, et al. v. American Electric Power Service Corp., et al.*, C2-99-1182, C2-99-1250 (Southern District of Ohio).

7. Affidavit (March 2005) on behalf of the Minnesota Center for Environmental Advocacy and others in the matter of the Application of Heron Lake BioEnergy LLC to construct and operate an ethanol production facility – submitted to the Minnesota Pollution Control Agency.

8. Expert Report and Deposition (10/31/2005 and 11/1/2005) on behalf of the United States in connection with the East Kentucky Power Cooperative NSR Case. *United States v. East Kentucky Power Cooperative, Inc*., 5:04-cv-00034-KSF (Eastern District of Kentucky).

9. Affidavits and deposition on behalf of Basic Management Inc. (BMI) Companies in connection with the BMI vs. USA remediation cost recovery Case.

10. Expert Report on behalf of Penn Future and others in the Cambria Coke plant permit challenge in Pennsylvania.

11. Expert Report on behalf of the Appalachian Center for the Economy and the Environment and others in the Western Greenbrier permit challenge in West Virginia.

12. Expert Report, deposition (via telephone on January 26, 2007) on behalf of various Montana petitioners (Citizens Awareness Network (CAN), Women's Voices for the Earth (WVE) and the Clark Fork Coalition (CFC)) in the Thompson River Cogeneration LLC Permit No. 3175-04 challenge.

13. Expert Report and deposition (2/2/07) on behalf of the Texas Clean Air Cities Coalition at the Texas State Office of Administrative Hearings (SOAH) in the matter of the permit challenges to TXU Project Apollo's eight new proposed PRB-fired PC boilers located at seven TX sites.

14. Expert Testimony (July 2007) on behalf of the Izaak Walton League of America and others in connection with the acquisition of power by Xcel Energy from the proposed Gascoyne Power Plant – at the State of Minnesota, Office of Administrative Hearings for the Minnesota PUC (MPUC No. E002/CN-06-1518; OAH No. 12-2500-17857-2).

15. Affidavit (July 2007) Comments on the Big Cajun I Draft Permit on behalf of the Sierra Club – submitted to the Louisiana DEQ.

16. Expert Report and Deposition (12/13/2007) on behalf of Commonwealth of Pennsylvania – Dept. of Environmental Protection, State of Connecticut, State of New York, and State of New Jersey (Plaintiffs) in connection with the Allegheny Energy NSR Case. *Plaintiffs v. Allegheny Energy Inc., et al.,* 2:05cv0885 (Western District of Pennsylvania).

17. Expert Reports and Pre-filed Testimony before the Utah Air Quality Board on behalf of Sierra Club in the Sevier Power Plant permit challenge.

18. Expert Report and Deposition (October 2007) on behalf of MTD Products Inc., in connection with *General Power Products, LLC v MTD Products Inc*., 1:06 CVA 0143 (Southern District of Ohio, Western Division) .

19. Expert Report and Deposition (June 2008) on behalf of Sierra Club and others in the matter of permit challenges (Title V: 28.0801-29 and PSD: 28.0803-PSD) for the Big Stone II unit, proposed to be located near Milbank, South Dakota.

20. Expert Reports, Affidavit, and Deposition (August 15, 2008) on behalf of Earthjustice in the matter of air permit challenge (CT-4631) for the Basin Electric Dry Fork station, under construction near Gillette, Wyoming before the Environmental Quality Council of the State of Wyoming.

21. Affidavits (May 2010/June 2010 in the Office of Administrative Hearings))/Declaration and Expert Report (November 2009 in the Office of Administrative Hearings) on behalf of NRDC and the Southern Environmental Law Center in the matter of the air permit challenge for Duke Cliffside Unit 6. Office of Administrative Hearing Matters 08 EHR 0771, 0835 and 0836 and 09 HER 3102, 3174, and 3176 (consolidated).

22. Declaration (August 2008), Expert Report (January 2009), and Declaration (May 2009) on behalf of Southern Alliance for Clean Energy in the matter of the air permit challenge for Duke Cliffside Unit 6. *Southern Alliance for Clean Energy et al., v. Duke Energy Carolinas, LLC*, Case No. 1:08-cv-00318-LHT-DLH (Western District of North Carolina, Asheville Division).

23. Declaration (August 2008) on behalf of the Sierra Club in the matter of Dominion Wise County plant MACT.us

24. Expert Report (June 2008) on behalf of Sierra Club for the Green Energy Resource Recovery Project, MACT Analysis.

25. Expert Report (February 2009) on behalf of Sierra Club and the Environmental Integrity Project in the matter of the air permit challenge for NRG Limestone's proposed Unit 3 in Texas.

26. Expert Report (June 2009) on behalf of MTD Products, Inc., in the matter of *Alice Holmes and Vernon Holmes v. Home Depot USA, Inc., et al.*

27. Expert Report (August 2009) on behalf of Sierra Club and the Southern Environmental Law Center in the matter of the air permit challenge for Santee Cooper's proposed Pee Dee plant in South Carolina).

28. Statements (May 2008 and September 2009) on behalf of the Minnesota Center for Environmental Advocacy to the Minnesota Pollution Control Agency in the matter of the Minnesota Haze State Implementation Plans.

29. Expert Report (August 2009) on behalf of Environmental Defense, in the matter of permit challenges to the proposed Las Brisas coal fired power plant project at the Texas State Office of Administrative Hearings (SOAH).

30. Expert Report and Rebuttal Report (September 2009) on behalf of the Sierra Club, in the matter of challenges to the proposed Medicine Bow Fuel and Power IGL plant in Cheyenne, Wyoming.

31. Expert Report (December 2009) and Rebuttal reports (May 2010 and June 2010) on behalf of the United States in connection with the Alabama Power Company NSR Case. *United States v. Alabama Power Company*, CV-01-HS-152-S (Northern District of Alabama, Southern Division).

32. Pre-filed Testimony (October 2009) on behalf of Environmental Defense and others, in the matter of challenges to the proposed White Stallion Energy Center coal fired power plant project at the Texas State Office of Administrative Hearings (SOAH).

33. Pre-filed Testimony (July 2010) and Written Rebuttal Testimony (August 2010) on behalf of the State of New Mexico Environment Department in the matter of Proposed Regulation 20.2.350 NMAC – *Greenhouse Gas Cap and Trade Provisions,* No. EIB 10-04 (R), to the State of New Mexico, Environmental Improvement Board.

34. Expert Report (August 2010) and Rebuttal Expert Report (October 2010) on behalf of the United States in connection with the Louisiana Generating NSR Case. *United States v. Louisiana Generating, LLC*, 09-CV100-RET-CN (Middle District of Louisiana) – Liability Phase.

35. Declaration (August 2010), Reply Declaration (November 2010), Expert Report (April 2011), Supplemental and Rebuttal Expert Report (July 2011) on behalf of the United States in the matter of DTE Energy Company and Detroit Edison Company (Monroe Unit 2). *United States of America v. DTE Energy Company and Detroit Edison Company*, Civil Action No. 2:10-cv-13101-BAF-RSW (Eastern District of Michigan).

36. Expert Report and Deposition (August 2010) as well as Affidavit (September 2010) on behalf of Kentucky Waterways Alliance, Sierra Club, and Valley Watch in the matter of challenges to the NPDES permit issued for the Trimble County power plant by the Kentucky Energy and Environment Cabinet to Louisville Gas and Electric, File No. DOW-41106-047.

37. Expert Report (August 2010), Rebuttal Expert Report (September 2010), Supplemental Expert Report (September 2011), and Declaration (November 2011) on behalf of Wild Earth Guardians in the matter of opacity exceedances and monitor downtime at the Public Service Company of Colorado (Xcel)'s Cherokee power plant. No. 09-cv-1862 (District of Colorado).

38. Written Direct Expert Testimony (August 2010) and Affidavit (February 2012) on behalf of Fall-Line Alliance for a Clean Environment and others in the matter of the PSD Air Permit for Plant Washington issued by Georgia DNR at the Office of State Administrative Hearing, State of Georgia (OSAH-BNR-AQ-1031707-98-WALKER).

39. Deposition (August 2010) on behalf of Environmental Defense, in the matter of the remanded permit challenge to the proposed Las Brisas coal fired power plant project at the Texas State Office of Administrative Hearings (SOAH).

40. Expert Report, Supplemental/Rebuttal Expert Report, and Declarations (October 2010, November 2010, September 2012) on behalf of New Mexico Environment Department (Plaintiff-Intervenor), Grand Canyon Trust and Sierra Club (Plaintiffs) in the matter of *Plaintiffs v. Public Service Company of New Mexico* (PNM), Civil No. 1:02-CV-0552 BB/ATC (ACE) (District of New Mexico).

41. Expert Report (October 2010) and Rebuttal Expert Report (November 2010) (BART Determinations for PSCo Hayden and CSU Martin Drake units) to the Colorado Air Quality Commission on behalf of Coalition of Environmental Organizations.

42. Expert Report (November 2010) (BART Determinations for TriState Craig Units, CSU Nixon Unit, and PRPA Rawhide Unit) to the Colorado Air Quality Commission on behalf of Coalition of Environmental Organizations.

43. Declaration (November 2010) on behalf of the Sierra Club in connection with the Martin Lake Station Units 1, 2, and 3. *Sierra Club v. Energy Future Holdings Corporation and Luminant*

Generation Company LLC, Case No. 5:10-cv-00156-DF-CMC (Eastern District of Texas, Texarkana Division).

44. Pre-Filed Testimony (January 2011) and Declaration (February 2011) to the Georgia Office of State Administrative Hearings (OSAH) in the matter of Minor Source HAPs status for the proposed Longleaf Energy Associates power plant (OSAH-BNR-AQ-1115157-60-HOWELLS) on behalf of the Friends of the Chattahoochee and the Sierra Club).

45. Declaration (February 2011) in the matter of the Draft Title V Permit for RRI Energy MidAtlantic Power Holdings LLC Shawville Generating Station (Pennsylvania), ID No. 17-00001 on behalf of the Sierra Club.

46. Expert Report (March 2011), Rebuttal Expert Report (June 2011) on behalf of the United States in *United States of America v. Cemex, Inc.*, Civil Action No. 09-cv-00019-MSK-MEH (District of Colorado).

47. Declaration (April 2011) and Expert Report (July 16, 2012) in the matter of the Lower Colorado River Authority (LCRA)'s Fayette (Sam Seymour) Power Plant on behalf of the Texas Campaign for the Environment. *Texas Campaign for the Environment v. Lower Colorado River Authority,* Civil Action No. 4:11-cv-00791 (Southern District of Texas, Houston Division).

48. Declaration (June 2011) on behalf of the Plaintiffs MYTAPN in the matter of Microsoft-Yes, Toxic Air Pollution-No (MYTAPN) v. State of Washington, Department of Ecology and Microsoft Corporation Columbia Data Center to the Pollution Control Hearings Board, State of Washington, Matter No. PCHB No. 10-162.

49. Expert Report (June 2011) on behalf of the New Hampshire Sierra Club at the State of New Hampshire Public Utilities Commission, Docket No. 10-261 – the 2010 Least Cost Integrated Resource Plan (LCIRP) submitted by the Public Service Company of New Hampshire (re. Merrimack Station Units 1 and 2).

50. Declaration (August 2011) in the matter of the Sandy Creek Energy Associates L.P. Sandy Creek Power Plant on behalf of Sierra Club and Public Citizen. *Sierra Club, Inc. and Public Citizen, Inc. v. Sandy Creek Energy Associates, L.P.,* Civil Action No. A-08-CA-648-LY (Western District of Texas, Austin Division).

51. Expert Report (October 2011) on behalf of the Defendants in the matter of *John Quiles and Jeanette Quiles et al. v. Bradford-White Corporation, MTD Products, Inc., Kohler Co., et al.,* Case No. 3:10-cv-747 (TJM/DEP) (Northern District of New York).

52. Declaration (October 2011) on behalf of the Plaintiffs in the matter of *American Nurses Association et. al. (Plaintiffs), v. US EPA (Defendant)*, Case No. 1:08-cv-02198-RMC (US District Court for the District of Columbia).

53. Declaration (February 2012) and Second Declaration (February 2012) in the matter of *Washington Environmental Council and Sierra Club Washington State Chapter v. Washington State Department of Ecology and Western States Petroleum Association,* Case No. 11-417-MJP (Western District of Washington).

54. Expert Report (March 2012) and Supplemental Expert Report (November 2013) in the matter of *Environment Texas Citizen Lobby, Inc and Sierra Club v. ExxonMobil Corporation et al.,* Civil Action No. 4:10-cv-4969 (Southern District of Texas, Houston Division).

55. Declaration (March 2012) in the matter of *Center for Biological Diversity, et al. v. United States Environmental Protection Agency,* Case No. 11-1101 (consolidated with 11-1285, 11-1328 and 11-1336) (US Court of Appeals for the District of Columbia Circuit).

56. Declaration (March 2012) in the matter of *Sierra Club v. The Kansas Department of Health and Environment*, Case No. 11-105,493-AS (Holcomb power plant) (Supreme Court of the State of Kansas).

57. Declaration (March 2012) in the matter of the Las Brisas Energy Center *Environmental Defense Fund et al., v. Texas Commission on Environmental Quality,* Cause No. D-1-GN-11-001364 (District Court of Travis County, Texas, 261st Judicial District).

58. Expert Report (April 2012), Supplemental and Rebuttal Expert Report (July 2012), and Supplemental Rebuttal Expert Report (August 2012) on behalf of the states of New Jersey and Connecticut in the matter of the Portland Power plant *State of New Jersey and State of Connecticut (Intervenor-Plaintiff) v. RRI Energy Mid-Atlantic Power Holdings et al.,* Civil Action No. 07-CV-5298 (JKG) (Eastern District of Pennsylvania).

59. Declaration (April 2012) in the matter of the EPA's EGU MATS Rule, on behalf of the Environmental Integrity Project.

60. Expert Report (August 2012) on behalf of the United States in connection with the Louisiana Generating NSR Case. *United States v. Louisiana Generating, LLC*, 09-CV100-RET-CN (Middle District of Louisiana) – Harm Phase.

61. Declaration (September 2012) in the Matter of the Application of *Energy Answers Incinerator, Inc.* for a Certificate of Public Convenience and Necessity to Construct a 120 MW Generating Facility in Baltimore City, Maryland, before the Public Service Commission of Maryland, Case No. 9199.

62. Expert Report (October 2012) on behalf of the Appellants (Robert Concilus and Leah Humes) in the matter of Robert Concilus and Leah Humes v. Commonwealth of Pennsylvania Department of Environmental Protection and Crawford Renewable Energy, before the Commonwealth of Pennsylvania Environmental Hearing Board, Docket No. 2011-167-R.

63. Expert Report (October 2012), Supplemental Expert Report (January 2013), and Affidavit (June 2013) in the matter of various Environmental Petitioners v. North Carolina DENR/DAQ and Carolinas Cement Company, before the Office of Administrative Hearings, State of North Carolina.

64. Pre-filed Testimony (October 2012) on behalf of No-Sag in the matter of the North Springfield Sustainable Energy Project before the State of Vermont, Public Service Board.

65. Pre-filed Testimony (November 2012) on behalf of Clean Wisconsin in the matter of Application of Wisconsin Public Service Corporation for Authority to Construct and Place in Operation a New Multi-Pollutant Control Technology System (ReACT) for Unit 3 of the Weston Generating Station, before the Public Service Commission of Wisconsin, Docket No. 6690-CE-197.

66. Expert Report (February 2013) on behalf of Petitioners in the matter of Credence Crematory, Cause No. 12-A-J-4538 before the Indiana Office of Environmental Adjudication.

67. Expert Report (April 2013), Rebuttal report (July 2013), and Declarations (October 2013, November 2013) on behalf of the Sierra Club in connection with the Luminant Big Brown Case. *Sierra Club v. Energy Future Holdings Corporation and Luminant Generation Company LLC*, Civil Action No. 6:12-cv-00108-WSS (Western District of Texas, Waco Division).

68. Declaration (April 2013) on behalf of Petitioners in the matter of *Sierra Club, et al., (Petitioners) v Environmental Protection Agency et al. (Resppondents),* Case No., 13-1112, (Court of Appeals, District of Columbia Circuit).

69. Expert Report (May 2013) and Rebuttal Expert Report (July 2013) on behalf of the Sierra Club in connection with the Luminant Martin Lake Case. *Sierra Club v. Energy Future Holdings Corporation and Luminant Generation Company LLC*, Civil Action No. 5:10-cv-0156-MHS-CMC (Eastern District of Texas, Texarkana Division).

70. Declaration (August 2013) on behalf of A. J. Acosta Company, Inc., in the matter of *A. J. Acosta Company, Inc., v. County of San Bernardino*, Case No. CIVSS803651.

71. Comments (October 2013) on behalf of the Washington Environmental Council and the Sierra Club in the matter of the Washington State Oil Refinery RACT (for Greenhouse Gases), submitted to the Washington State Department of Ecology, the Northwest Clean Air Agency, and the Puget Sound Clean Air Agency.

72. Statement (November 2013) on behalf of various Environmental Organizations in the matter of the Boswell Energy Center (BEC) Unit 4 Environmental Retrofit Project, to the Minnesota Public Utilities Commission, Docket No. E-015/M-12-920.

73. Expert Report (December 2013) on behalf of the United States in *United States of America v. Ameren Missouri*, Civil Action No. 4:11-cv-00077-RWS (Eastern District of Missouri, Eastern Division).

74. Expert Testimony (December 2013) on behalf of the Sierra Club in the matter of Public Service Company of New Hampshire Merrimack Station Scrubber Project and Cost Recovery, Docket No. DE 11-250, to the State of New Hampshire Public Utilities Commission.

75. Expert Report (January 2014) on behalf of Baja, Inc., in *Baja, Inc., v. Automotive Testing and Development Services, Inc. et. al*, Civil Action No. 8:13-CV-02057-GRA (District of South Carolina, Anderson/Greenwood Division).

76. Declaration (March 2014) on behalf of the Center for International Environmental Law, Chesapeake Climate Action Network, Friends of the Earth, Pacific Environment, and the Sierra Club (Plaintiffs) in the matter of *Plaintiffs v. the Export-Import Bank (Ex-Im Bank) of the United States*, Civil Action No. 13-1820 RC (District Court for the District of Columbia).

77. Declaration (April 2014) on behalf of Respondent-Intervenors in the matter of *Mexichem Specialty Resins Inc., et al., (Petitioners) v Environmental Protection Agency et al.,* Case No., 12-1260 (and Consolidated Case Nos. 12-1263, 12-1265, 12-1266, and 12-1267), (Court of Appeals, District of Columbia Circuit).

78. Direct Prefiled Testimony (June 2014) on behalf of the Michigan Environmental Council and the Sierra Club in the matter of the Application of DTE Electric Company for Authority to Implement a Power Supply Cost Recovery (PSCR) Plan in its Rate Schedules for 2014 Metered Jurisdictional Sales of Electricity, Case No. U-17319 (Michigan Public Service Commission).

79. Expert Report (June 2014) on behalf of ECM Biofilms in the matter of the US Federal Trade Commission (FTC) v. ECM Biofilms (FTC Docket #9358).

80. Direct Prefiled Testimony (August 2014) on behalf of the Michigan Environmental Council and the Sierra Club in the matter of the Application of Consumers Energy Company for Authority to Implement a Power Supply Cost Recovery (PSCR) Plan in its Rate Schedules for 2014 Metered Jurisdictional Sales of Electricity, Case No. U-17317 (Michigan Public Service Commission).

81. Declaration (July 2014) on behalf of Public Health Intervenors in the matter of *EME Homer City Generation v. US EPA* (Case No. 11-1302 and consolidated cases) relating to the lifting of the stay entered by the Court on December 30, 2011 (US Court of Appeals for the District of Columbia).

82. Expert Report (September 2014), Rebuttal Expert Report (December 2014) and Supplemental Expert Report (March 2015) on behalf of Plaintiffs in the matter of *Sierra Club and Montana Environmental Information Center (Plaintiffs) v. PPL Montana LLC, Avista Corporation, Puget Sound Energy, Portland General Electric Company, Northwestern Corporation, and Pacificorp (Defendants)*, Civil Action No. CV 13-32-BLG-DLC-JCL (US District Court for the District of Montana, Billings Division).

83. Expert Report (November 2014) on behalf of Niagara County, the Town of Lewiston, and the Villages of Lewiston and Youngstown in the matter of CWM Chemical Services, LLC New York State Department of Environmental Conservation (NYSDEC) Permit Application Nos.: 9-2934-00022/00225, 9-2934-00022/00231, 9-2934-00022/00232, and 9-2934-00022/00249 (pending).

84. *Declaration (January 2015) relating to Startup/Shutdown in the MATS Rule (EPA Docket ID No. EPA-HQ-OAR-2009-0234) on behalf of the Environmental Integrity Project.*

85. Pre-filed Direct Testimony (March 2015), Supplemental Testimony (May 2015), and Surrebuttal Testimony (December 2015) on behalf of Friends of the Columbia Gorge in the matter of the Application for a Site Certificate for the Troutdale Energy Center before the Oregon Energy Facility Siting Council.

86. Brief of Amici Curiae Experts in Air Pollution Control and Air Quality Regulation in Support of the Respondents, On Writs of Certiorari to the US Court of Appeals for the District of Columbia, No. 14-46, 47, 48. *Michigan et. al., (Petitioners) v. EPA et. al., Utility Air Regulatory Group (Petitioners) v. EPA et. al., National Mining Association et. al., (Petitioner) v. EPA et. al.,* (Supreme Court of the United States).

87. Expert Report (March 2015) and Rebuttal Expert Report (January 2016) on behalf of Plaintiffs in the matter of *Conservation Law Foundation v. Broadrock Gas Services LLC, Rhode Island LFG GENCO LLC, and Rhode Island Resource Recovery Corporation (Defendants)*, Civil Action No. 1:13-cv-00777-M-PAS (US District Court for the District of Rhode Island).

88. Declaration (April 2015) relating to various Technical Corrections for the MATS Rule (EPA Docket ID No. EPA-HQ-OAR-2009-0234) on behalf of the Environmental Integrity Project.

89. Direct Prefiled Testimony (May 2015) on behalf of the Michigan Environmental Council, the Natural Resources Defense Council, and the Sierra Club in the matter of the Application of DTE Electric Company for Authority to Increase its Rates, Amend its Rate Schedules and Rules Governing the Distribution and Supply of Electric Energy and for Miscellaneous Accounting Authority, Case No. U-17767 (Michigan Public Service Commission).

90. Expert Report (July 2015) and Rebuttal Expert Report (July 2015) on behalf of Plaintiffs in the matter of *Northwest Environmental Defense Center et. al., v. Cascade Kelly Holdings LLC, d/b/a Columbia Pacific Bio-Refinery, and Global Partners LP (Defendants)*, Civil Action No. 3:14-cv-01059-SI (US District Court for the District of Oregon, Portland Division).

91. Declaration (August 2015, Docket No. 1570376) in support of "Opposition of Respondent-Intervenors American Lung Association, et. al., to Tri-State Generation's Emergency Motion;" Declaration (September 2015, Docket No. 1574820) in support of "Joint Motion of the State, Local Government, and Public Health Respondent-Intervenors for Remand Without Vacatur;" Declaration (October 2015) in support of "Joint Motion of the State, Local Government, and Public Health Respondent-Intervenors to State and Certain Industry Petitioners' Motion to Govern, *White Stallion Energy Center, LLC v. US EPA*, Case No. 12-1100 (US Court of Appeals for the District of Columbia).

92. Declaration (September 2015) in support of the Draft Title V Permit for Dickerson Generating Station (Proposed Permit No 24-031-0019) on behalf of the Environmental Integrity Project.

93. Expert Report (Liability Phase) (December 2015) and Rebuttal Expert Report (February 2016) on behalf of Plaintiffs in the matter of *Natural Resources Defense Council, Inc., Sierra Club, Inc., Environmental Law and Policy Center, and Respiratory Health Association v. Illinois Power Resources LLC, and Illinois Power Resources Generating LLC (Defendants)*, Civil Action No. 1:13-cv-01181 (US District Court for the Central District of Illinois, Peoria Division).

94. Declaration (December 2015) in support of the Petition to Object to the Title V Permit for Morgantown Generating Station (Proposed Permit No 24-017-0014) on behalf of the Environmental Integrity Project.

95. Expert Report (November 2015) on behalf of Appellants in the matter of *Sierra Club, et al. v. Craig W. Butler, Director of Ohio Environmental Protection Agency et al.,* ERAC Case No. 14-256814.

96. Affidavit (January 2016) on behalf of Bridgewatch Detroit in the matter of *Bridgewatch Detroit v. Waterfront Petroleum Terminal Co., and Waterfront Terminal Holdings, LLC.*, in the Circuit Court for the County of Wayne, State of Michigan.

97. Expert Report (February 2016) and Rebuttal Expert Report (July 2016) on behalf of the challengers in the matter of the Delaware Riverkeeper Network, Clean Air Council, et. al., vs. Commonwealth of Pennsylvania Department of Environmental Protection and R. E. Gas Development LLC regarding the Geyer well site before the Pennsylvania Environmental Hearing Board.

98. Direct Testimony (May 2016) in the matter of Tesoro Savage LLC Vancouver Energy Distribution Terminal, Case No. 15-001 before the State of Washington Energy Facility Site Evaluation Council.

99. Declaration (June 2016) relating to deficiencies in air quality analysis for the proposed Millenium Bulk Terminal, Port of Longview, Washington.

100. Declaration (December 2016) relating to EPA's refusal to set limits on PM emissions from coal-fired power plants that reflect pollution reductions achievable with fabric filters on behalf of Environmental Integrity Project, Clean Air Council, Chesapeake Climate Action Network, Downwinders at Risk represented by Earthjustice in the matter of *ARIPPA v EPA, Case No. 15-1180*. (D.C. Circuit Court of Appeals).

101. Expert Report (January 2017) on the Environmental Impacts Analysis associated with the Huntley and Huntley Poseidon Well Pad on behalf citizens in the matter of the special exception use Zoning Hearing Board of Penn Township, Westmoreland County, Pennsylvania.

102. Expert Report (January 2017) on the Environmental Impacts Analysis associated with the Apex Energy Backus Well Pad on behalf citizens in the matter of the special exception use Zoning Hearing Board of Penn Township, Westmoreland County, Pennsylvania.

103. Expert Report (January 2017) on the Environmental Impacts Analysis associated with the Apex Energy Drakulic Well Pad on behalf citizens in the matter of the special exception use Zoning Hearing Board of Penn Township, Westmoreland County, Pennsylvania.

104. Expert Report (January 2017) on the Environmental Impacts Analysis associated with the Apex Energy Deutsch Well Pad on behalf citizens in the matter of the special exception use Zoning Hearing Board of Penn Township, Westmoreland County, Pennsylvania.

105. Affidavit (February 2017) pertaining to deficiencies water discharge compliance issues at the Wood River Refinery in the matter of *People of the State of Illinois (Plaintiff) v. Phillips 66 Company, ConocoPhillips Company, WRB Refining LP (Defendants)*, Case No. 16-CH-656, (Circuit Court for the Third Judicial Circuit, Madison County, Illinois).

106. Expert Report (March 2017) on behalf of the Plaintiff pertaining to non-degradation analysis for waste water discharges from a power plant in the matter of *Sierra Club (Plaintiff) v. Pennsylvania Department of Environmental Protection (PADEP) and Lackawanna Energy Center*, Docket No. 2016-047-L (consolidated), (Pennsylvania Environmental Hearing Board).

107. Expert Report (March 2017) on behalf of the Plaintiff pertaining to air emissions from the Heritage incinerator in East Liverpool, Ohio in the matter of *Save our County (Plaintiff) v. Heritage Thermal Services, Inc. (Defendant), Case No. 4:16-CV-1544-BYP*, (US District Court for the Northern District of Ohio, Eastern Division).

108. Rebuttal Expert Report (June 2017) on behalf of Plaintiffs in the matter of *Casey Voight and Julie Voight (Plaintiffs) v Coyote Creek Mining Company LLC (Defendant),* Civil Action No. 1:15-CV-00109 (US District Court for the District of North Dakota, Western Division).

109. Expert Affidavit (August 2017) and Penalty/Remedy Expert Affidavit (October 2017) on behalf of Plaintiff in the matter of *Wildearth Guardians (Plaintiff) v Colorado Springs Utility Board (Defendant,)* Civil Action No. 1:15-cv-00357-CMA-CBS (US District Court for the District of Colorado).

110. Expert Report (August 2017) on behalf of Appellant in the matter of *Patricia Ann Troiano (Appellant) v. Upper Burrell Township Zoning Hearing Board (Appellee)*, Court of Common Pleas of Westmoreland County, Pennsylvania, Civil Division.

111. Expert Report (October 2017), Supplemental Expert Report (October 2017), and Rebuttal Expert Report (November 2017) on behalf of Defendant in the matter of *Oakland Bulk and Oversized Terminal (Plaintiff) v City of Oakland (Defendant,)* Civil Action No. 3:16-cv-07014-VC (US District Court for the Northern District of California, San Francisco Division).

112. Declaration (December 2017) on behalf of the Environmental Integrity Project in the matter of permit issuance for ATI Flat Rolled Products Holdings, Breckenridge, PA to the Allegheny County Health Department.

113. Expert Report (Harm Phase) (January 2018), Rebuttal Expert Report (Harm Phase) (May 2018) and Supplemental Expert Report (Harm Phase) (April 2019) on behalf of Plaintiffs in the matter of *Natural Resources Defense Council, Inc., Sierra Club, Inc., and Respiratory Health Association v. Illinois Power Resources LLC, and Illinois Power Resources Generating LLC (Defendants)*, Civil Action No. 1:13-cv-01181 (US District Court for the Central District of Illinois, Peoria Division).

114. Declaration (February 2018) on behalf of the Chesapeake Bay Foundation, et. al., in the matter of the Section 126 Petition filed by the state of Maryland in *State of Maryland v. Pruitt (Defendant)*, Civil Action No. JKB-17-2939 (Consolidated with No. JKB-17-2873) (US District Court for the District of Maryland).

115. Direct Pre-filed Testimony (March 2018) on behalf of the National Parks Conservation Association (NPCA) in the matter of *NPCA v State of Washington, Department of Ecology and BP West Coast Products, LLC*, PCHB No. 17-055 (Pollution Control Hearings Board for the State of Washington.

116. Expert Affidavit (April 2018) and Second Expert Affidavit (May 2018) on behalf of Petitioners in the matter of *Coosa River Basin Initiative and Sierra Club (Petitioners) v State of Georgia Environmental Protection Division, Georgia Department of Natural Resources (Respondent) and Georgia Power Company (Intervenor/Respondent)*, Docket Nos: 1825406-BNR-WW-57-Howells and 1826761-BNR-WW-57-Howells, Office of State Administrative Hearings, State of Georgia.

117. Direct Pre-filed Testimony and Affidavit (December 2018) on behalf of Sierra Club and Texas Campaign for the Environment (Appellants) in the contested case hearing before the Texas State Office of Administrative Hearings in Docket Nos. 582-18-4846, 582-18-4847 (Application of GCGV Asset Holding, LLC for Air Quality Permit Nos. 146425/PSDTX1518 and 146459/PSDTX1520 in San Patricio County, Texas).

118. Expert Report (February 2019) on behalf of Sierra Club in the State of Florida, Division of Administrative Hearings, Case No. 18-2124EPP, Tampa Electric Company Big Bend Unit 1 Modernization Project Power Plant Siting Application No. PA79-12-A2.

119. Declaration (March 2019) on behalf of Earthjustice in the matter of comments on the renewal of the Title V Federal Operating Permit for Valero Houston refinery.

120. Expert Report (March 2019) on behalf of Plaintiffs for Class Certification in the matter of *Resendez et al v Precision Castparts Corporation* in the Circuit Court for the State of Oregon, County of Multnomah, Case No. 16cv16164.

121. Expert Report (June 2019), Affidavit (July 2019) and Rebuttal Expert Report (September 2019) on behalf of Appellants relating to the NPDES permit for the Cheswick power plant in the matter of *Three Rivers Waterkeeper and Sierra Club (Appellants) v. State of Pennsylvania Department of Environmental Protection (Appellee) and NRG Power Midwest (Permittee)*, before the Commonwealth of Pennsylvania Environmental Hearing Board, EHB Docket No. 2018-088-R.

122. Affidavit/Expert Report (August 2019) relating to the appeal of air permits issued to PTTGCA on behalf of Appellants in the matter of *Sierra Club (Appellants) v. Craig Butler, Director, et. al., Ohio EPA (Appellees)* before the State of Ohio Environmental Review Appeals Commission (ERAC), Case Nos. ERAC-19-6988 through -6991.

123. Expert Report (October 2019) relating to the appeal of air permit (Plan Approval) on behalf of Appellants in the matter of *Clean Air Council and Environmental Integrity Project (Appellants) v. Commonwealth of Pennsylvania Department of Environmental Protection and Sunoco Partners Marketing and Terminals L.P.*, before the Commonwealth of Pennsylvania Environmental Hearing Board, EHB Docket No. 2018-057-L.

124. Expert Report (December 2019), Affidavit (March 2020), Supplemental Expert Report (July 2020), and Declaration (February 2021) on behalf of Earthjustice in the matter of *Objection to the*

Issuance of PSD/NSR and Title V permits for Riverview Energy Corporation, Dale, Indiana, before the Indiana Office of Environmental Adjudication, Cause No. 19-A-J-5073.

125. Affidavit (December 2019) on behalf of Plaintiff-Intervenor (Surfrider Foundation) in the matter of *United States and the State of Indiana (Plaintiffs), Surfrider Foundation (Plaintiff-Intervenor), and City of Chicago (Plaintiff-Intervenor) v. United States Steel Corporation (Defendant),* Civil Action No. 2:18-cv-00127 (US District Court for the Northern District of Indiana, Hammond Division).

126. Declarations (January 2020, February 2020, May 2020, July 2020, and August 2020) and Pre-filed Testimony (April 2021) in support of Petitioner's Motion for Stay of PSCAA NOC Order of Approval No. 11386 in the matter of the *Puyallup Tribe of Indians v. Puget Sound Clean Air Agency (PSCAA) and Puget Sound Energy (PSE),* before the State of Washington Pollution Control Hearings Board, PCHB No. P19-088.

127. Expert Report (April 2020) on behalf of the plaintiff in the matter of Orion Engineered Carbons, GmbH (Plaintiff) vs. Evonik Operations, GmbH (formerly Evonik Degussa GmbH) (Respondent), before the German Arbitration Institute, Case No. DIS-SV-2019-00216.

128. Expert Independent Evaluation Report (June 2020) for *PacifiCorp's Decommissioning Costs Study Reports dated January 15, 2020 and March 13, 2020 relating to the closures of the Hunter, Huntington, Dave Johnston, Jim Bridger, Naughton, Wyodak, Hayden, and Colstrip (Units 3&4) plants*, prepared for the Oregon Public Utility Commission (Oregon PUC).

129. Direct Pre-filed Testimony (July 2020) on behalf of the Sierra Club in the matter of *the Application of the Ohio State University for a certificate of Environmental Compatibility and Public Need to Construct a Combined Heat and Power Facility in Franklin County, Ohio*, before the Ohio Power Siting Board, Case No. 19-1641-EL-BGN.

130. Expert Report (August 2020) and Rebuttal Expert Report (September 2020) on behalf of WildEarth Guardians (petitioners) in the matter of *the Appeals of the Air Quality Permit No. 7482-M1 Issued to 3 Bear Delaware Operating – NM LLC (EIB No. 20-21(A) and Registrations Nos. 8729, 8730, and 8733 under General Construction Permit for Oil and Gas Facilities (EIB No. 20-33 (A)*, before the State of New Mexico, Environmental Improvement Board.

131. Expert Report (July 2020) on the *Initial Economic Impact Analysis (EIA) for A Proposal To* Regulate *NOx Emissions from Natural Gas Fired Rich-Burn Natural Gas Reciprocating Internal Combustion Engines (RICE) Greater Than 100 Horsepower* prepared on behalf of Earthjustice and the National Parks Conservation Association in the matter of Regulation Number 7, Alternate Rules before the Colorado Air Quality Control Commission.

132. Expert Report (August 2020) and Supplemental Expert Report (February 2021) on the Potential Remedies to Avoid Adverse Thermal Impacts from the Merrimack Station on behalf of Plaintiffs in the matter of *Sierra Club Inc. and the* Conservation *Law Foundation (Plaintiffs) v. Granite Shore Power, LLC et. al., (Defendants)*, Civil Action No. 19-cv-216-JL (US District Court for the District of New Hampshire.)

133. Expert Report (August 2020) and Supplemental Expert Report (December 2020) on behalf of Plaintiffs in the matter of *PennEnvironment Inc., and Clean Air Council (Plaintiffs) and Allegheny County Health Department (Plaintiff-Intervenor) v. United States Steel Corporation (Defendant)*, Civil Action No. 2-19-cv-00484-MJH (US District Court for the Western District of Pennsylvania.)

134. Pre-filed Direct Testimony (October 2020) and Sur-rebuttal Testimony (November 2020) on behalf of petitioners (Ten Persons Group, including citizens, the Town of Braintree, the Town of Hingham, and the City of Quincy) in the matter of Algonquin Gas Transmission LLC, Weymouth MA, No. X266786 Air Quality Plan Approval, before the Commonwealth of Massachusetts, Department of Environmental Protection, the Office of Appeals and Dispute Resolution, OADR Docket Nos. 2019-008, 2019-009, 2019010, 2019-011, 2019-012 and 2019-013.

135. Expert Report (November 2020) on behalf of Protect PT in the matter of *Protect PT v. Commonwealth of Pennsylvania Department of Environmental Protection and Apex Energy (PA) LLC*, before the Commonwealth of Pennsylvania Environmental Hearing Board, Docket No. 2018-080-R (consolidated with 2019-101-R)(the "Drakulic Appeal").

136. Expert Report (December 2020) on behalf of Plaintiffs in the matter of *Sierra Club Inc. (Plaintiff) v. GenOn Power Midwest LP (Defendants)*, Civil Action No. 2-19-cv-01284-WSS (US District Court for the Western District of Pennsylvania.)

137. Pre-filed Testimony (January 2021) on behalf of the Plaintiffs (Shrimpers and Fishermen of the Rio Grande Valley represented by Texas RioGrande Legal Aid, Inc.) in the matter of the Appeal of Texas Commission on Environmental Quality (TCEQ) Permit Nos. 147681, PSDTX1522, GHGPSDTX172 for the Jupiter Brownsville Heavy Condensate Upgrader Facility, Cameron County, before the Texas State Office of Administrative Hearings, SOAH Docket No. 582-21-0111, TCEQ Docket No. 2020-1080-AIR.

138. Expert Report (June 2021) and Declarations (May 2021 and June 2021) on behalf of Plaintiffs in the matter of *Sierra Club (Plaintiff) v. Woodville Pellets, LLC (Defendant)*, Civil Action No. 9:20-cv-00178-MJT (US District Court for the Eastern District of Texas, Lufkin Division.)

139. Declaration (July 2021) on behalf of Plaintiffs in the matter of *Stephanie Mackey and Nick Migliore, on behalf of themselves and all others similarly situated (Plaintiffs) v. Chemtool Inc. and Lubrizol Corporation (Defendants)*, Case No. 2021-L-0000165, State of Illinois, Circuit Court of the 17th Judicial Circuit, Winnebago County.

140. Expert Report (April 2021) and Sur-Rebuttal Report (June 2021) on behalf of the Plaintiffs in the matter of *Modern Holdings, LLC, et al. (Plaintiffs) v. Corning Inc., et al. (Defendants)*, Civil Action No. 5:13-cv-00405-GFVT, (US District Court for the Eastern District of Kentucky, Central Division at Lexington).

141. Expert Witness Disclosure (June 2021) on behalf of the Plaintiffs in the matter of *Jay Burdick, et. al., (Plaintiffs) v. Tanoga Inc. (d/b/a Taconic) (Defendant)*, Index No. 253835, (State of New York Supreme Court, County of Rensselaer).

142. Expert Report (June 2021) on behalf of Appellants in the matter of *PennEnvironment and Earthworks (Appellants) v. Commonwealth of Pennsylvania Department of Environmental Protection (Appellee) and MarkWest Liberty Midstream and resource, LLC (Permittee)*, before the Commonwealth of Pennsylvania Environmental Hearing Board, EHB Docket No. 2020-002-R.

143. Expert Reports (March 2021 and May 2021) regarding the Aries Newark LLC Sludge Processing Facility, Application No. CPB 20-74, Central Planning Board, City of Newark, New Jersey.

144. Expert Report (April 2021) for *Charles Johnson Jr. (Plaintiff) v. BP Exploration and Production Inc., et. al. (Defendant),* Civil Action No. 2:20-CV-01329. (US District Court for the Eastern District of Louisiana, New Orleans Division).

145. Expert Report (April 2021) for *Floyd Ruffin (Plaintiff), v. BP Exploration and Production Inc., et. al. (Defendant)*, Civil Action No. 2:20-cv-00334-CJB-JCW (US District Court for the Eastern District of Louisiana, New Orleans Division).

146. Expert Report (May 2021) for *Clifford Osmer (Plaintiff) v. BP Exploration and Production Inc., et. al., (Defendants)* related to No. 2:19-CV-10331 (US District Court for the Eastern District of Louisiana, New Orleans Division).

147. Expert Report (June 2021) for *Antonia Saavedra-Vargas (Plaintiff) v. BP Exploration and Production Inc., et. al. (Defendant)*, Civil Action No. 2:18-CV-11461 (US District Court for the Eastern District of Louisiana, New Orleans Division).

148. Affidavit (June 2021) for Lourdes Rubi in the matter of *Lourdes Rubi (Plaintiff) v. BP Exploration and Production Inc., et. al., (Defendants)*, related to 12-968 BELO in MDL No. 2179 (US District Court for the Eastern District of Louisiana, New Orleans Division).

149. Expert Report (May 2021) for *James Noel (Plaintiff) v. BP Exploration and Production Inc., et. al. (Defendant),* Civil Action No. 1:19-CV-00694 (US District Court for the Southern District of Alabama, Mobile Division).

150. Expert Report (June 2021) for *Wallace Smitht (Plaintiff) v. BP Exploration and Production Inc., et. al. (Defendant)*, Civil Action No. 2:19-CV-12880 (US District Court for the Eastern District of Louisiana, New Orleans Division).

C. Occasions where Dr. Sahu has provided oral testimony <u>in depositions, at trial or in similar proceedings</u> include the following:

151. Deposition on behalf of Rocky Mountain Steel Mills, Inc. located in Pueblo, Colorado – dealing with the manufacture of steel in mini-mills including methods of air pollution control and BACT in steel mini-mills and opacity issues at this steel mini-mill.

152. Trial Testimony (February 2002) on behalf of Rocky Mountain Steel Mills, Inc. in Denver District Court.

153. Trial Testimony (February 2003) on behalf of the United States in the Ohio Edison NSR Cases, *United States, et al. v. Ohio Edison Co., et al.*, C2-99-1181 (Southern District of Ohio).

154. Trial Testimony (June 2003) on behalf of the United States in the Illinois Power NSR Case, *United States v. Illinois Power Co., et al.*, 99-833-MJR (Southern District of Illinois).

155. Deposition (10/20/2005) on behalf of the United States in connection with the Cinergy NSR Case. *United States, et* al. *v. Cinergy Corp., et al.*, IP 99-1693-C-M/S (Southern District of Indiana).

156. Oral Testimony (August 2006) on behalf of the Appalachian Center for the Economy and the Environment re. the Western Greenbrier plant, WV before the West Virginia DEP.

157. Oral Testimony (May 2007) on behalf of various Montana petitioners (Citizens Awareness Network (CAN), Women's Voices for the Earth (WVE) and the Clark Fork Coalition (CFC)) re. the Thompson River Cogeneration plant before the Montana Board of Environmental Review.

158. Oral Testimony (October 2007) on behalf of the Sierra Club re. the Sevier Power Plant before the Utah Air Quality Board.

159. Oral Testimony (August 2008) on behalf of the Sierra Club and Clean Water re. Big Stone Unit II before the South Dakota Board of Minerals and the Environment.

160. Oral Testimony (February 2009) on behalf of the Sierra Club and the Southern Environmental Law Center re. Santee Cooper Pee Dee units before the South Carolina Board of Health and Environmental Control.

161. Oral Testimony (February 2009) on behalf of the Sierra Club and the Environmental Integrity Project re. NRG Limestone Unit 3 before the Texas State Office of Administrative Hearings (SOAH) Administrative Law Judges.

162. Deposition (July 2009) on behalf of MTD Products, Inc., in the matter of *Alice Holmes and Vernon Holmes v. Home Depot USA, Inc., et al*.

163. Deposition (October 2009) on behalf of Environmental Defense and others, in the matter of challenges to the proposed Coleto Creek coal fired power plant project at the Texas State Office of Administrative Hearings (SOAH).

164. Deposition (October 2009) on behalf of Environmental Defense, in the matter of permit challenges to the proposed Las Brisas coal fired power plant project at the Texas State Office of Administrative Hearings (SOAH).

165. Deposition (October 2009) on behalf of the Sierra Club, in the matter of challenges to the proposed Medicine Bow Fuel and Power IGL plant in Cheyenne, Wyoming.

166. Deposition (October 2009) on behalf of Environmental Defense and others, in the matter of challenges to the proposed Tenaska coal fired power plant project at the Texas State Office of Administrative Hearings (SOAH). (April 2010).

167. Oral Testimony (November 2009) on behalf of the Environmental Defense Fund re. the Las Brisas Energy Center before the Texas State Office of Administrative Hearings (SOAH) Administrative Law Judges.

168. Deposition (December 2009) on behalf of Environmental Defense and others, in the matter of challenges to the proposed White Stallion Energy Center coal fired power plant project at the Texas State Office of Administrative Hearings (SOAH).

169. Oral Testimony (February 2010) on behalf of the Environmental Defense Fund re. the White Stallion Energy Center before the Texas State Office of Administrative Hearings (SOAH) Administrative Law Judges.

170. Deposition (June 2010) on behalf of the United States in connection with the Alabama Power Company NSR Case. *United States v. Alabama Power Company*, CV-01-HS-152-S (Northern District of Alabama, Southern Division).

171. Trial Testimony (September 2010) on behalf of Commonwealth of Pennsylvania – Dept. of Environmental Protection, State of Connecticut, State of New York, State of Maryland, and State of New Jersey (Plaintiffs) in connection with the Allegheny Energy NSR Case in US District Court in the Western District of Pennsylvania. *Plaintiffs v. Allegheny Energy Inc., et al.,* 2:05cv0885 (Western District of Pennsylvania).

172. Oral Direct and Rebuttal Testimony (September 2010) on behalf of Fall-Line Alliance for a Clean Environment and others in the matter of the PSD Air Permit for Plant Washington issued by Georgia DNR at the Office of State Administrative Hearing, State of Georgia (OSAH-BNR-AQ-1031707-98-WALKER).

173. Oral Testimony (September 2010) on behalf of the State of New Mexico Environment Department in the matter of Proposed Regulation 20.2.350 NMAC – *Greenhouse Gas Cap and Trade Provisions,* No. EIB 10-04 (R), to the State of New Mexico, Environmental Improvement Board.

174. Oral Testimony (October 2010) on behalf of the Environmental Defense Fund re. the Las Brisas Energy Center before the Texas State Office of Administrative Hearings (SOAH) Administrative Law Judges.

175. Oral Testimony (November 2010) regarding BART for PSCo Hayden, CSU Martin Drake units before the Colorado Air Quality Commission on behalf of the Coalition of Environmental Organizations.

176. Oral Testimony (December 2010) regarding BART for TriState Craig Units, CSU Nixon Unit, and PRPA Rawhide Unit) before the Colorado Air Quality Commission on behalf of the Coalition of Environmental Organizations.

177. Deposition (December 2010) on behalf of the United States in connection with the Louisiana Generating NSR Case. *United States v. Louisiana Generating, LLC*, 09-CV100-RET-CN (Middle District of Louisiana).

178. Deposition (February 2011 and January 2012) on behalf of Wild Earth Guardians in the matter of opacity exceedances and monitor downtime at the Public Service Company of Colorado (Xcel)'s Cherokee power plant. No. 09-cv-1862 (D. Colo.).

179. Oral Testimony (February 2011) to the Georgia Office of State Administrative Hearings (OSAH) in the matter of Minor Source HAPs status for the proposed Longleaf Energy Associates power plant (OSAH-BNR-AQ-1115157-60-HOWELLS) on behalf of the Friends of the Chattahoochee and the Sierra Club).

180. Deposition (August 2011) on behalf of the United States in *United States of America v. Cemex, Inc.*, Civil Action No. 09-cv-00019-MSK-MEH (District of Colorado).

181. Deposition (July 2011) and Oral Testimony at Hearing (February 2012) on behalf of the Plaintiffs MYTAPN in the matter of Microsoft-Yes, Toxic Air Pollution-No (MYTAPN) v. State of Washington, Department of Ecology and Microsoft Corporation Columbia Data Center to the Pollution Control Hearings Board, State of Washington, Matter No. PCHB No. 10-162.

182. Oral Testimony at Hearing (March 2012) on behalf of the United States in connection with the Louisiana Generating NSR Case. *United States v. Louisiana Generating, LLC*, 09-CV100-RET-CN (Middle District of Louisiana).

183. Oral Testimony at Hearing (April 2012) on behalf of the New Hampshire Sierra Club at the State of New Hampshire Public Utilities Commission, Docket No. 10-261 – the 2010 Least Cost Integrated Resource Plan (LCIRP) submitted by the Public Service Company of New Hampshire (re. Merrimack Station Units 1 and 2).

184. Oral Testimony at Hearing (November 2012) on behalf of Clean Wisconsin in the matter of Application of Wisconsin Public Service Corporation for Authority to Construct and Place in Operation a New Multi-Pollutant Control Technology System (ReACT) for Unit 3 of the Weston Generating Station, before the Public Service Commission of Wisconsin, Docket No. 6690-CE-197.

185. Deposition (March 2013) in the matter of various Environmental Petitioners v. North Carolina DENR/DAQ and Carolinas Cement Company, before the Office of Administrative Hearings, State of North Carolina.

186. Deposition (August 2013) on behalf of the Sierra Club in connection with the Luminant Big Brown Case. *Sierra Club v. Energy Future Holdings Corporation and Luminant Generation Company LLC*, Civil Action No. 6:12-cv-00108-WSS (Western District of Texas, Waco Division).

187. Deposition (August 2013) on behalf of the Sierra Club in connection with the Luminant Martin Lake Case. *Sierra Club v. Energy Future Holdings Corporation and Luminant Generation Company LLC*, Civil Action No. 5:10-cv-0156-MHS-CMC (Eastern District of Texas, Texarkana Division).

188. Deposition (February 2014) on behalf of the United States in *United States of America v. Ameren Missouri*, Civil Action No. 4:11-cv-00077-RWS (Eastern District of Missouri, Eastern Division).

189. Trial Testimony (February 2014) in the matter of *Environment Texas Citizen Lobby, Inc and Sierra Club v. ExxonMobil Corporation et al.,* Civil Action No. 4:10-cv-4969 (Southern District of Texas, Houston Division).

190. Trial Testimony (February 2014) on behalf of the Sierra Club in connection with the Luminant Big Brown Case. *Sierra Club v. Energy Future Holdings Corporation and Luminant Generation Company LLC*, Civil Action No. 6:12-cv-00108-WSS (Western District of Texas, Waco Division).

191. Deposition (June 2014) and Trial (August 2014) on behalf of ECM Biofilms in the matter of the *US Federal Trade Commission (FTC) v. ECM Biofilms* (FTC Docket #9358).

192. Deposition (February 2015) on behalf of Plaintiffs in the matter of *Sierra Club and Montana Environmental Information Center (Plaintiffs) v. PPL Montana LLC, Avista Corporation, Puget Sound Energy, Portland General Electric Company, Northwestern Corporation, and Pacificorp (Defendants)*, Civil Action No. CV 13-32-BLG-DLC-JCL (US District Court for the District of Montana, Billings Division).

193. Oral Testimony at Hearing (April 2015) on behalf of Niagara County, the Town of Lewiston, and the Villages of Lewiston and Youngstown in the matter of CWM Chemical Services, LLC New York State Department of Environmental Conservation (NYSDEC) Permit Application Nos.: 9-2934-00022/00225, 9-2934-00022/00231, 9-2934-00022/00232, and 9-2934-00022/00249 (pending).

194. Deposition (August 2015) on behalf of Plaintiff in the matter of *Conservation Law Foundation (Plaintiff) v. Broadrock Gas Services LLC, Rhode Island LFG GENCO LLC, and Rhode Island*

Resource Recovery Corporation (Defendants), Civil Action No. 1:13-cv-00777-M-PAS (US District Court for the District of Rhode Island).

195. Testimony at Hearing (August 2015) on behalf of the Sierra Club in the matter of *Amendments to 35 Illinois Administrative Code Parts 214, 217, and 225* before the Illinois Pollution Control Board, R15-21.

196. Deposition (May 2015) on behalf of Plaintiffs in the matter of *Northwest Environmental Defense Center et. al., (Plaintiffs) v. Cascade Kelly Holdings LLC, d/b/a Columbia Pacific Bio-Refinery, and Global Partners LP (Defendants)*, Civil Action No. 3:14-cv-01059-SI (US District Court for the District of Oregon, Portland Division).

197. Trial Testimony (October 2015) on behalf of Plaintiffs in the matter of *Northwest Environmental Defense Center et. al., (Plaintiffs) v. Cascade Kelly Holdings LLC, d/b/a Columbia Pacific Bio-Refinery, and Global Partners LP (Defendants)*, Civil Action No. 3:14-cv-01059-SI (US District Court for the District of Oregon, Portland Division).

198. Deposition (April 2016) on behalf of the Plaintiffs in *UNatural Resources Defense Council, Respiratory Health Association, and Sierra Club (Plaintiffs) v. Illinois Power Resources LLC and Illinois Power Resources Generation LLC (Defendants)*, Civil Action No. 1:13-cv-01181 (Central District of Illinois, Peoria Division).

199. Trial Testimony at Hearing (July 2016) in the matter of Tesoro Savage LLC Vancouver Energy Distribution Terminal, Case No. 15-001 before the State of Washington Energy Facility Site Evaluation Council.

200. Trial Testimony (December 2016) on behalf of the challengers in the matter of the Delaware Riverkeeper Network, Clean Air Council, et. al., vs. Commonwealth of Pennsylvania Department of Environmental Protection and R. E. Gas Development LLC regarding the Geyer well site before the Pennsylvania Environmental Hearing Board.

201. Trial Testimony (July-August 2016) on behalf of the United States in *United States of America v. Ameren Missouri*, Civil Action No. 4:11-cv-00077-RWS (Eastern District of Missouri, Eastern Division).

202. Trial Testimony (January 2017) on the Environmental Impacts Analysis associated with the Huntley and Huntley Poseidon Well Pad Hearing on behalf citizens in the matter of the special exception use Zoning Hearing Board of Penn Township, Westmoreland County, Pennsylvania.

203. Trial Testimony (January 2017) on the Environmental Impacts Analysis associated with the Apex energy Backus Well Pad Hearing on behalf citizens in the matter of the special exception use Zoning Hearing Board of Penn Township, Westmoreland County, Pennsylvania.

204. Trial Testimony (January 2017) on the Environmental Impacts Analysis associated with the Apex energy Drakulic Well Pad Hearing on behalf citizens in the matter of the special exception use Zoning Hearing Board of Penn Township, Westmoreland County, Pennsylvania.

205. Trial Testimony (January 2017) on the Environmental Impacts Analysis associated with the Apex energy Deutsch Well Pad Hearing on behalf citizens in the matter of the special exception use Zoning Hearing Board of Penn Township, Westmoreland County, Pennsylvania.

206. Deposition Testimony (July 2017) on behalf of Plaintiffs in the matter of *Casey Voight and Julie Voight v Coyote Creek Mining Company LLC (Defendant)* Civil Action No. 1:15-CV-00109 (US District Court for the District of North Dakota, Western Division).

207. Deposition Testimony (November 2017) on behalf of Defendant in the matter of *Oakland Bulk and Oversized Terminal (Plaintiff) v City of Oakland (Defendant,)* Civil Action No. 3:16-cv-07014-VC (US District Court for the Northern District of California, San Francisco Division).

208. Deposition Testimony (December 2017) on behalf of Plaintiff in the matter of *Wildearth Guardians (Plaintiff) v Colorado Springs Utility Board (Defendant)* Civil Action No. 1:15-cv-00357-CMA-CBS (US District Court for the District of Colorado).

209. Deposition Testimony (January 2018) in the matter of National Parks Conservation Association (NPCA) v. State of Washington Department of Ecology and British Petroleum (BP) before the Washington Pollution Control Hearing Board, Case No. 17-055.

210. Trial Testimony (January 2018) on behalf of Defendant in the matter of *Oakland Bulk and Oversized Terminal (Plaintiff) v City of Oakland (Defendant,)* Civil Action No. 3:16-cv-07014-VC (US District Court for the Northern District of California, San Francisco Division).

211. Trial Testimony (April 2018) on behalf of the National Parks Conservation Association (NPCA) in the matter of NPCA v State of Washington, Department of Ecology and BP West Coast Products, LLC, PCHB No. 17-055 (Pollution Control Hearings Board for the State of Washington.

212. Deposition (June 2018) (harm Phase) on behalf of Plaintiffs in the matter of *Natural Resources Defense Council, Inc., Sierra Club, Inc., and Respiratory Health Association v. Illinois Power Resources LLC, and Illinois Power Resources Generating LLC (Defendants)*, Civil Action No. 1:13-cv-01181 (US District Court for the Central District of Illinois, Peoria Division).

213. Trial Testimony (July 2018) on behalf of Petitioners in the matter of *Coosa River Basin Initiative and Sierra Club (Petitioners) v State of Georgia Environmental Protection Division, Georgia Department of Natural Resources (Respondent) and Georgia Power Company (Intervenor/Respondent)*, Docket Nos: 1825406-BNR-WW-57-Howells and 1826761-BNR-WW-57-Howells, Office of State Administrative Hearings, State of Georgia.

214. Deposition (January 2019) and Trial Testimony (January 2019) on behalf of Sierra Club and Texas Campaign for the Environment (Appellants) in the contested case hearing before the Texas State Office of Administrative Hearings in Docket Nos. 582-18-4846, 582-18-4847 (Application of GCGV Asset Holding, LLC for Air Quality Permit Nos. 146425/PSDTX1518 and 146459/PSDTX1520 in San Patricio County, Texas).

215. Deposition (February 2019) and Trial Testimony (March 2019) on behalf of Sierra Club in the State of Florida, Division of Administrative Hearings, Case No. 18-2124EPP, Tampa Electric Company Big Bend Unit 1 Modernization Project Power Plant Siting Application No. PA79-12-A2.

216. Deposition (June 2019) relating to the appeal of air permits issued to PTTGCA on behalf of Appellants in the matter of *Sierra Club (Appellants) v. Craig Butler, Director, et. al., Ohio EPA (Appellees)* before the State of Ohio Environmental Review Appeals Commission (ERAC), Case Nos. ERAC-19-6988 through -6991.

217. Deposition (September 2019) on behalf of Appellants relating to the NPDES permit for the Cheswick power plant in the matter of *Three Rivers Waterkeeper and Sierra Club (Appellants) v. State of Pennsylvania Department of Environmental Protection (Appellee) and NRG Power Midwest (Permittee)*, before the Commonwealth of Pennsylvania Environmental Hearing Board, EHB Docket No. 2018-088-R.

218. Deposition (December 2019) on behalf of the Plaintiffs in the matter of David Kovac, individually and on behalf of wrongful death class of Irene Kovac v. BP Corporation North America Inc., Circuit Court of Jackson County, Missouri (Independence), Case No. 1816-CV12417.

219. Deposition (February 2020, virtual) and testimony at Hearing (August 2020, virtual) on behalf of Earthjustice in the matter of *Objection to the Issuance of PSD/NSR and Title V permits for Riverview Energy Corporation*, Dale, Indiana, before the Indiana Office of Environmental Adjudication, Cause No. 19-A-J-5073.

220. Hearing (July 14-15, 2020, virtual) on behalf of the Sierra Club in the matter of *the Application of the Ohio State University for a certificate of Environmental Compatibility and Public Need to Construct a Combined Heat and Power Facility in Franklin County, Ohio*, before the Ohio Power Siting Board, Case No. 19-1641-EL-BGN.

221. Hearing (September 2020, virtual) on behalf of WildEarth Guardians (petitioners) in the matter of *the Appeals of the Air Quality Permit No. 7482-M1 Issued to 3 Bear Delaware* Operating *– NM LLC (EIB No. 20-21(A) and Registrations Nos. 8729, 8730, and 8733 under General Construction*

Permit for Oil and Gas Facilities (EIB No. 20-33 (A), before the State of New Mexico, Environmental Improvement Board.

222. Deposition (December 2020, March 4-5, 2021, all virtual) and Hearing (April 2021, virtual) in support of Petitioner's Motion for Stay of PSCAA NOC Order of Approval No. 11386 in the matter of the *Puyallup Tribe of Indians v. Puget Sound Clean Air Agency (PSCAA) and Puget Sound Energy (PSE),* before the State of Washington Pollution Control Hearings Board, PCHB No. P19-088.

223. Hearing (September 2020, virtual) on the *Initial Economic Impact Analysis (EIA) for A Proposal To* Regulate *NOx Emissions from Natural Gas Fired Rich-Burn Natural Gas Reciprocating Internal Combustion Engines (RICE) Greater Than 100 Horsepower* prepared on behalf of Earthjustice and the National Parks Conservation Association in the matter of Regulation Number 7, Alternate Rules before the Colorado Air Quality Control Commission.

224. Deposition (December 2020, virtual and Hearing February 2021, virtual) on behalf of the Plaintiffs (Shrimpers and Fishermen of the Rio Grande Valley represented by Texas RioGrande Legal Aid, Inc.) in the matter of the Appeal of Texas Commission on Environmental Quality (TCEQ) Permit Nos. 147681, PSDTX1522, GHGPSDTX172 for the Jupiter Brownsville Heavy Condensate Upgrader Facility, Cameron County, before the Texas State Office of Administrative Hearings, SOAH Docket No. 582-21-0111, TCEQ Docket No. 2020-1080-AIR.

225. Deposition (January 2021, virtual) on behalf of Plaintiffs in the matter of *PennEnvironment Inc., and Clean Air Council (Plaintiffs) and Allegheny County Health Department (Plaintiff-Intervenor) v. United States Steel Corporation (Defendant)*, Civil Action No. 2-19-cv-00484-MJH (US District Court for the Western District of Pennsylvania.)

226. Deposition (February 2021, virtual) on behalf of Plaintiffs in the matter of *Sierra Club Inc. (Plaintiff) v. GenOn Power Midwest LP (*Defendants*)*, Civil Action No. 2-19-cv-01284-WSS (US District Court for the Western District of Pennsylvania.)

227. Deposition (April 2021, virtual) on the Potential Remedies to Avoid Adverse Thermal Impacts from the Merrimack Station on behalf of Plaintiffs in the matter of *Sierra Club Inc. and the* Conservation *Law Foundation (Plaintiffs) v. Granite Shore Power, LLC et. al., (Defendants)*, Civil Action No. 19-cv-216-JL (US District Court for the District of New Hampshire.)

228. Deposition (June 2021, virtual) on behalf of Plaintiffs in the matter of *Sierra Club (Plaintiff) v. Woodville Pellets, LLC (Defendant)*, Civil Action No. 9:20-cv-00178-MJT (US District Court for the Eastern District of Texas, Lufkin Division).

229. Deposition (June 2021, virtual) on behalf of the Plaintiffs in the matter of *Modern Holdings, LLC, et al. (Plaintiffs) v. Corning Inc., et al. (Defendants)*, Civil Action No. 5:13-cv-00405-GFVT, (US District Court for the Eastern District of Kentucky, Central Division at Lexington).

230. Testimony (June 2021, virtual) regarding the Aries Newark LLC Sludge Processing Facility, Application No. CPB 20-74, Central Planning Board, City of Newark, New Jersey.

ZERO WASTE EUROPE

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El Dorado of Chemical Recycling

State of play and policy challenges

Study

August 2019 – Zero Waste Europe

Table of Contents

Executive Summary

Over the last few years the concept of chemical recycling has been promoted by the industry as a potential solution to help curb plastic pollution and waste management as a whole. This report looks into the information available as well as the state of implementation of such technologies in the European context.

Mechanical recycling is a mature industrial process which is well established and expanding in Europe. Yet, plastics cannot be endlessly recycled mechanically without reducing their properties and quality. Besides, not all plastic types can be mechanically recycled. These limits set challenges for plastics recycling and show the need for significant improvements in the end-of-life management of plastics.

Chemical recycling today often refers to technologies that can be classed depending on the level at which they break down the plastic waste. Concretely, the technologies can be divided into 3 types:

- Solvent-based purification. Comprises technologies that go down to the polymer stage. They are capable of decontaminating the plastic but cannot address its degradation. They work only with monostreams (PVC, PS, PE, PP).

- Chemical depolymerisation. Chemical process which turns the plastics back into their monomers. Allows for decontamination but not addressing degradation. Only works with monostreams (PET, PU, PA, PLA, PC, PHA, PEF).

- Thermal depolymerisation and cracking (pyrolysis and gasification) are energy-intensive processes which turn the polymers back into simpler molecules. They are capable of decontaminating polymers and, by bringing plastic back to its original building blocks, addressing the degradation of the material. These technologies can deal with more than one monomer at a time and are also capable of producing fuels. This raises the need for strict regulatory controls to prevent plastic being turned into fuel in lieu of recycling.

Gasification and pyrolysis have been tested since decades as alternatives to waste to energy incineration with very limited results due to the energy balance and the environmental impact. In general, the information available about the environmental performance of chemical recycling technologies as a whole is still extremely limited and requires further research.

In contrast with mechanical recycling, chemical recycling is an industry in its infancy and most plants in the market are in a pilot stage. The potential roll-out of such technologies at industrial scale can only be expected from 2025-2030 and this is an important factor when planning the transition to a Circular Economy and notably the decarbonisation agenda.

For the sake of policy consistency, it is key that the right policy framework is set up in order to, on the one hand, accommodate chemical recycling as complementary to mechanical recycling and, on the other hand, ensure that the carbon stays in the plastic and is not released into the environment. Therefore, allowing plastic to fuels to be considered chemical recycling risks creating a loophole in EU Climate and Circular Economy legislation.

With all its potential, chemical recycling can have a role to play in closing the material loop and moving away from disposal and recovery operations, up the waste hierarchy. Nevertheless, the best options to curb plastic pollution from environmental and economic perspective is to invest in reduction and reuse solutions; giving excessive attention to end of pipe solutions could undermine this exercise. For the plastic waste that cannot be avoided via redesign, thermal depolymerisation of mixed plastic could undermine efforts to source separate for mechanical recycling which is more environmentally favourable. Moreover, there is a risk of putting too much expectation on a solution whose potential is yet to be proven and this could delay the necessary efforts in the field of rethinking business models and material redesign.

Chemical recycling could be a complementary solution to mechanical recycling where the latter proves to be unsuited to materially recover plastic because it is too degraded, contaminated or too complex. At the same time, increased collection of high-quality waste and design for reuse and recycling should remain the two priorities in order to increase the recycling rates for plastics and ensuring no plastic escapes the material loop via plastic to fuels. For this to happen ZWE recommends to amend current waste legislation as follows:

- Come up with a clear definition of chemical recycling that excludes any operation that does not result in the production of new plastic.
- Only processes with a lower carbon footprint than the production of plastic from virgin feedstock can be classified as chemical recycling.
- Chemical recycling should be used to deal with degraded and contaminated plastics and never with plastics coming from separate collection.
- Establish verification systems to ensure chemical recycling process outputs plastic and plastic feedstocks; facilities licensed for chemical recycling may not produce fuel for on- or off-site combustion.
- In order to avoid competition with mechanical recycling, but also to differentiate from recovery and disposal operations, a new level in the waste hierarchy should be added for those operations that recover materials from mixed waste that today would end up burned.
- For coherence with EU Climate and Circular Economy agendas EU funding should only be allowed to finance plastic to plastic chemical operations.

1. Introduction

Plastic pollution is a topic that has been gaining traction in recent years and it is already seen as a global challenge. Indeed, our civilization struggles to make an efficient and sustainable use of this material, with 335 million tonnes of plastic produced in 2016 alone which is expected to substantially increase over the next decade[1].

The current plastics system has an estimated annual material value loss of EUR 70-105 billion globally. From an environmental perspective, it is estimated that 75,000 to 300,000 tonnes of microplastics are released into EU habitats annually.

Of the 8,300 million tonnes of plastics produced by humankind since the 1950s, it is estimated that 5,800 million tonnes of plastics, representing 70% of the total amount, have become waste, of which 84% or 4,900 million tonnes, has been disposed of in landfills or in the environment[2].

In the EU, separate collection rate of plastic waste in 2014 was 37%, whilst the recycling rate after the export of 30% of the plastic waste outside EU borders was estimated to be 13% (2.15 million tonnes). The rejects of the various sorting stages amount to about 1.5 million tonnes[3].

From a systemic perspective, given the inefficient way we are managing this resource, it is clear that a big effort will be needed to rethink the way we use plastics today and many single-use applications will need to be reconsidered. Moreover, in a scenario in which two thirds of EU's plastic waste are being landfilled or burned, there is a big opportunity to increase plastic recycling.

Bearing in mind the need to reduce the use of plastic for single-use applications and the necessary diversion from landfill and incineration to mechanical recycling, there is a legitimate question about what to do with those plastics that are too degraded or too contaminated to be reintroduced in the production cycle. Currently this fraction of plastic waste is exported, downcycled or disposed of, but in recent years some technologies have been presented claiming to be able to recycle this waste stream under the name of chemical recycling. This study looks into the state of play of these technologies in the current context and explores their potential for development in the future.

[1] PlasticsEurope, 2018
[2] Geyer, Jambeck & Law, 2017
[3] Deloitte Sustainability, 2017

2. What is plastic chemical recycling?

Plastics are chains of molecules linked together. Each of these molecules is a monomer and the resulting chains are called polymers. This is why many plastics begin with "poly," such as polyethylene, polystyrene, and polypropylene. Polymers often are made of carbon and hydrogen and sometimes oxygen, nitrogen, sulfur, chlorine, fluorine, phosphorous, or silicon. The term "plastics" encompasses all these various polymers.

In order for these polymers to be of use they need to be given properties such as flexibility, fire resistance, strength, etc. and this is possible thanks to the addition of additives in the production process.

Even though plastic is used as a generic term, every polymer follows a different production process and all have different melting temperatures, which makes it impractical for different polymers to be recycled together. Therefore, quality recycling requires sorting by polymer and also differentiating between the different additives within every family of polymers. For instance, opaque PET should not be recycled with transparent PET.

Almost exclusively, today plastic recycling means sorting, washing and compounding the different polymers into secondary plastics. The process of plastic use and the mechanical recycling cause degradation in the polymer structures which limits the number of times the same polymer can be effectively recycled as the bonds become more and more degraded. Also, mechanical recycling is unable to separate the additives and the non-intentionally added substances that are present in plastic waste; this explains why contaminated plastic cannot be turned into high grade plastic which could be used for food contact applications. As long as recycled plastic use is limited to lower-quality products ("downcycling"), it cannot replace the production of virgin plastic, which is almost entirely sourced from fossil fuels, with all the attendant environmental impacts. The limitations of plastic mechanical recycling open the door to chemical recycling, for the latter can sometimes address the challenges of both polymer degradation and contamination.

The number of technologies comprised in what is commonly referred to as chemical recycling can be divided into three different categories depending on the level of decomposition that the plastic waste will be subject to (see figure 1):

- Solvent-based purification, which decomposes plastics back to the polymer stage.
- Chemical depolymerisation, which turns the plastics back into their monomers via a chemical reaction.
- Thermal depolymerisation (pyrolysis and gasification) which in some cases can be considered as chemical recycling by cracking the polymers back into monomers and further down into hydrocarbons. Thermal depolymerisation technology can also produce fuels although in that case it can no longer be considered a form of recycling.

All these outputs (except fuels) are then reprocessed to form new plastics.

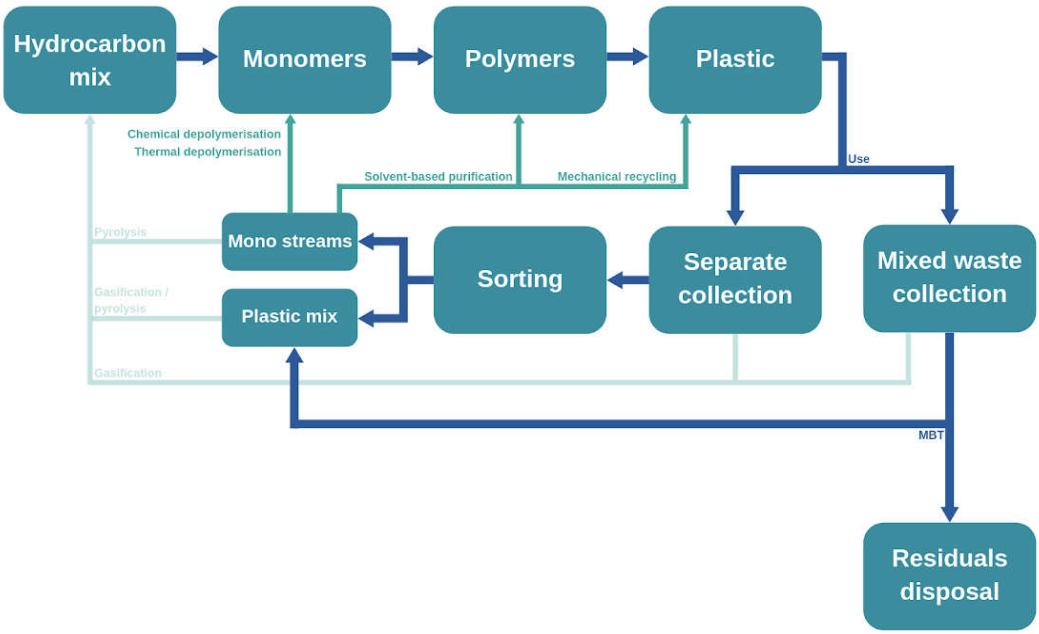

Figure 1: Diagram of different chemical recycling processes
Source: Zero Waste Europe: www.zerowasteeurope.eu

	Feedstock	Output	Decontamination	Ability to treat mixed plastic	Maturity
Mechanical recycling	PE, PET, PP, PS	Plastic (made of one or more polymers)	No	Yes*	Industrial scale
Solvent-based purification	PVC, PS, polyolefins (PE, PP)	Polymer	Yes	No	Pilot stage
Chemical depolymerisation	PET, PU, PA, PLA, PC, PHA, PEF	Monomers	Yes	No	Existing pilot plants for PET, PU, PA
Thermal depolymerisation (pyrolysis)	PMMA, PS	Monomers	Yes	No	Pilot stage
Cracking (pyrolysis and gasification)	Plastic mix	Hydrocarbon mix	Yes	Yes	Pilot stage

*Mechanically-recycled mixed plastics can be downcycled into lower-grade uses such as plastic lumber. Mechanical recycling of single resins, such as PET, can produce higher-value products.

Table 1: Technologies of different chemical recycling processes
Source: Zero Waste Europe: www.zerowasteeurope.eu

3. Solvent-based purification[4]

3.1 The technology

Solvent-based purification is a process based on the solubility of the polymer in a certain type of solvent: when immersed in this solvent, the plastic dissolves and goes back to the polymer stage. In general, the solvent is chosen so that other impurities such as additives or pigments can be removed through filtration or phase extraction. At the end of these purification steps, the polymer is recovered thanks to an anti-solvent in which the polymer is not soluble. **The solvent-based purification can only deal with homogeneous flows of plastic**. It can treat separately PVC, PS, and polyolefins such as PE and PP. The resulting output is a precipitated polymer, of sufficient purity to be reformulated into plastics in a near virgin quality since the additives, colourants and contaminants are removed at the molecular level. Their use is very diverse, from food packaging to insulating material. The composition due to mixing of different polymer grades (chain lengths or branching for example), remains more or less the same.

Nevertheless, this process raises several issues. First, the purity of the output polymer can vary according to the input and the process parameters: there is always a risk of finding residual contaminants and traces of the solvent. The treatment of the left-over solvent, which can contain plastic additives and contaminants, is not clear.

Then, even though the solvent process does not degrade the quality of the polymer, the latter needs to be processed again to form a new plastic object. As with mechanical recycling, the physical and thermal stress generated by this process decreases the average chain length of the polymer, affecting its quality. Solvent-based purification thus cannot be a perpetual recycling method for plastics.

Besides, the trend to multi-layer packaging continues: 20% of all packaging films are multi-layer[5]. This kind of packaging has some properties, such as a barrier against oxygen or water vapor, that a regular mono-layer packaging cannot have[6]. While solvent-based purification is technically able to separate complex layers of plastic, its practical feasibility remains unproven. This would indeed require additional solvation and separation steps, making the time and energy input needed for solvent removal even more important.

The economic viability of the process also needs to be evaluated. So far, this technology can only take care of homogeneous inputs of plastic. A strict upstream sorting system and the availability of sufficient amounts of plastic monostreams are therefore necessary. In general, mechanical recycling is preferable for monostreams; however, solvent-based purification is better able to process contaminated PS or PVC than mechanical recycling can. While technically feasible, this is not necessarily an economically viable process. The infrastructure and transport costs are also challenging: plastics are lightweight but production volumes need to be high. While the annual plant capacity should be above 10 or 20 kilotons to make the investment pay off, finding sufficient

[4] Crippa, M., De Wilde, B., Koopmans, R., Leyssens, J., Muncke, J., Ritschkoff A-C., Van Doorsselaer, K., Velis, C. & Wagner, M. A circular economy for plastics – Insights from research and innovation to inform policy and funding decisions, 2019 (M. De Smet & M. Linder, Eds.). European Commission, Brussels, Belgium

[5] APK, Company presentation

[6] APK, DSM and APK cooperate on recycling multilayer food packaging films, 2018, www.apk-ag.de/en/dsm-and-apk-cooperate-on-recycling-multilayer-food-packaging-films/

feedstock for a capacity above 40 or 50 kilotonnes[7] a year will probably be complicated. Striking the balance between capacity and available feedstock is therefore key.

Finally, the environmental impact of this type of processes needs to be further assessed as the energy and mass balance, emissions, solvents manufacturing, etc. are not fully analysed.

Because solvent-based purification goes down to the polymer level, some stakeholders claim that solvent-based purification is equivalent to mechanical recycling and should not be classified as chemical recycling. This lack of clarity is an argument for a clear definition for chemical recycling.

3.2 Industrial stage

As highlighted by the different points raised above, this technology still needs significant development to mature. But even though solvent-based recycling for packaging does not exist at scale, a few pilot plants are already working.

Soft Polyvinyl Chloride (PVC)

PVC is the third most produced plastic worldwide. It is used in pipes and electric cables, but also in clothing.

The VinyLoop plant was built in 2002 in Italy to treat 10,000 tonnes a year of PVC. This pilot project was founded by Solvay in order to recycle soft PVC from cables or films. It was closed in June 2018 following the new EU's REACH legislation making it clear that phthalates were hazardous. These phthalates were used in the production of PVC in the past, and it was not economically feasible to separate them through the VinyLoop process[8].

Polystyrene (PS)

The need for an alternative to mechanical recycling for PS is due to the presence of brominated flame retardant hexabromocyclododecane (HBCD) from old insulation material[9].

In 2017, PolyStyreneLoop was created with the aim of recycling PS across Europe through the CreaSolv Process. They focus on EPS (Expanded Polystyrene also known as styrofoam) containing HBCD that was used for many years in insulation and packaging. A pilot installation, with an annual capacity of 3,000 tonnes of PS foam waste, was built in Terneuzen (Netherlands). The process, developed by the German company Fraunhofer, works as follows: first the foam is dissolved with a solvent, the addition of a second solvent precipitates the polymer, while contaminants stay in the solution. The solvent is then vaporised and can be reused, as well as the polymer. HBCD remains as a sludge, which is sent to a hazardous waste incinerator with a bromine recovery unit to recover some of the bromine (which can then be used in new flame retardants).

According to Life Cycle Analyses (LCA), this process performs better than incineration regarding CO_2

[7] IFP Energies Nouvelles, www.ifpenergiesnouvelles.fr/innovation-et-industrie/nos-expertises/climat-et-environnement/recyclage-des-plastiques/nos-solutions
[8] Plastics Information Europe, *VINYLOOP Closure of operation in Italy / Phthalates issue under REACH brings down European PVC recycling project*, 2018, www.plasteurope.com/news/VINYLOOP_t240095/
[9] Crippa, M., De Wilde, B., Koopmans, R., Leyssens, J., Muncke, J., Ritschkoff A-C., Van Doorsselaer, K., Velis, C. & Wagner, M. *A circular economy for plastics – Insights from research and innovation to inform policy and funding decisions*, 2019 (M. De Smet & M. Linder, Eds.). European Commission, Brussels, Belgium

equivalent emissions and thus having less of an impact on climate change, but not as good as mechanical recycling. The Polystyrene Loop process would have an impact of about -1.5 tonnes of CO_2 eq/tonne input, while incineration of discarded plastic in a waste-to-energy plant emits 1.6 tonnes of CO_2 eq./tonne input, and mechanical recycling -2.3 tonne CO_2 eq/tonne input[10]. An ISO compliant LCA, performed by FH Münster and TÜV Rheinland, shows that the PolyStyreneLoop process performs better (roughly 50% of the impact) than incineration with energy recovery in all the impact categories for the treatment of EPS containing HBCD[11].

The current partners of this project are INEOS Styrolution, Synthos, Total, Trinseo and Versalis. It is supported by the EU through the LIFE programme and its viability without public intervention is unclear.

The use of this process can be extended to the recycling of EPS packaging, even though most of them do not contain HBCD (being mostly packaging for electrical and electronic equipment). However, from an economic and environmental point of view, it is better to mechanically recycle these EPS flows. But it offers a good alternative when the EPS is contaminated (organic waste, smell).

The Canadian company Polystyvert has also been working on PS recycling since 2011, using a patent-pending technology able to separate contaminants from PS. Agilyx opened a polystyrene recycling plant in Oregon (USA) too.

Polyolefins: Polyethylene (PE) and Polypropylene (PP)

These polymers, together representing more than 50% of the global polymer production volume, can be solvent-purified[12].

Unilever has piloted since 2017 the CreaSolv process in Indonesia to recover PE from multi-layer flexible sachets. According to the company, the plant is processing 3 tonnes of flexible plastic daily to recover the PE and use it to make new sachets[13].

In the meantime, Procter & Gamble is developing the PureCycle Technologies to purify PP - used in automobile interiors, food and beverage packaging, consumer goods packaging, electronics, construction materials, home furnishing, etc. - for use in home cleaning and hygiene product packaging in the US. This technology consists of a solvent-based purification under high temperature and pressure[14].

Finally, in Europe, APK (Germany) has worked since 2013 on the 'Newcycling technology' to recycle several polymers from multilayer packaging. With this process, they are able to produce LDPE (Low Density PE) and PA (Polyamides) in a near-virgin quality, which can be used in flexible packaging, technical injection molding, labels/stickers and films/laminates, from PE/PA multilayer film waste.

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[10] M. Broeren, E. Roos Lindgreen, G. Bergsma, *Verkenning chemische recycling - update 2019 Hoe groot zijn - en worden - de kansen voor klimaatbeleid?*, CE Delft, 2019

[11] PolystyreneLoop, www.polystyreneloop.org/

[12] Crippa, M., De Wilde, B., Koopmans, R., Leyssens, J., Muncke, J., Ritschkoff A-C., Van Doorsselaer, K., Velis, C. & Wagner, M. *A circular economy for plastics – Insights from research and innovation to inform policy and funding decisions*, 2019 (M. De Smet & M. Linder, Eds.). European Commission, Brussels, Belgium

[13] Unilever, 2017, www.unilever.com/news/news-and-features/Feature-article/2017/CreaSolv-a-breakthrough-waste-recycling-technology-that-we-want-to-share.html

[14] Newswire, 2017, *PureCycle Technologies and P&G introduce technology that enables recycled plastic to be nearly-new quality* www.prnewswire.com/news-releases/purecycle-technologies-and-pg-introduce-technology-that-enables-recycled-plastic-to-be-nearly-new-quality-300491368.html

These multilayer films are first dissolved to obtain two distinct fractions: a solid one, containing PA, and a liquid one, containing the dissolved PE. The solid fraction is washed with different solvents to remove impurities, then separated from the new liquid phase and is finally treated before being extruded or pelletised into PA. In the liquid fraction, the solvent is evaporated and can be reused after condensation, while the PE is extruded. Their plant in Merseburg (Germany) is divided into two parts: mechanical recycling and solvent-based recycling are complementing each other. The total capacity of the plant is 20,000 tonnes input per year[15].

[15] APK, www.apk-ag.de/en/about-us/history/

4. Chemical depolymerisation

4.1 The technology

Depolymerisation can be described as the exact reverse of polymerisation. It is mostly used for polymers formed through a polymerisation process called polycondensation. During this condensation, two molecules called monomers join together and lose small molecules such as water or methanol.

The activated bonds formed after polycondensation can be broken exactly where they were formed and "add back" the molecule that was lost. In some cases, it is preferable not to go back to the monomer stage again (total depolymerisation), but to divide the polymer in smaller chains (partial depolymerisation). This reaction usually happens with the help of heat and catalysers[16].

After the purification steps needed to remove colourants and contaminants, the pure monomer is obtained. In most cases, the reactant - which enables to break the bonds - for chemical depolymerisation is the solvent. Depending on the solvent used, the name of the reaction differs:

- Hydrolysis, if the solvent is water.
- Alcoholysis, if the solvent is alcohol (glycolysis for ethylene glycol and methanolysis for methanol).
- Aminolysis, if the solvent is an amine (ammoniac, ethylene diamine, etc.).

Some other techniques are being investigated - supercritical fluids, enzymes, reduction reactions or metathesis - but they are at an early research stage. In the figure below, some typical general reactions are displayed.

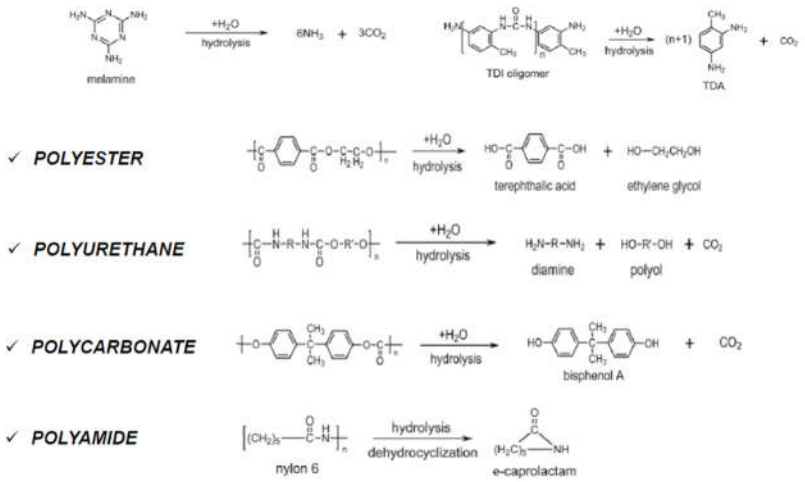

Figure 2: General reactions
Source: Enscm: www.enscm.fr/en/

The major possible feedstock for these reactions are: polyesters, polyethylene terephthalate (PET), polyamides (PA), polyurethanes (PU), polylactic acid (PLA), polyhydroxyalkanoates (PHA), polyethylene furanoate (PEF) and polycarbonates (PC). The resulting outputs are single monomer

[16] A. Parenty, C. Dadou-Willmann, 2ACR, *Recyclage chimique des déchets plastique : état des lieux et perspectives*, 2019

molecules or small polymer chains called dimers or oligomers. These must be polymerised again before the material can be converted into a new plastic product.

Since the resulting output must be polymerised again, the length of the polymer chain is not a problem as it is in mechanical recycling and the plastic can be recycled as many times as wished. The quality of the plastic is then equivalent to the quality of plastic made with virgin polymers. It also implies that the polymer is purified from all the additives that could have contaminated the plastic - from odours to flame retardants or colourants.

However, this technology needs to be performed with heat and sometimes in the presence of a catalyser. The amount of energy required by the process depends on the input material itself as well as the reaction and the separation phase. Multi-layer materials, for example, are more challenging to treat and thus require more energy.

Besides, chemical depolymerisation can be highly selective, provided that it has only one specific input. In order to be efficient, it needs a strict upstream sorting system beforehand.

Moreover, the price difference between the virgin polymer and the recycled one, can be key in the system. If virgin polymers are cheaper than recycled polymers the technology can only be viable if there is market intervention. Hence, as for solvent-based purification, finding sufficient amounts of sorted homogeneous plastic waste, infrastructure and transport are key in the economic viability of the process.

Finally, less information is available on other environmental and systemic impacts of depolymerisation such as yield, leftover by-products or chemical safety of the catalysers.

4.2 Industrial stage

Polyethylene Terephthalate PET

PET is the fourth most produced polymer worldwide. Its applications are mainly for textile (polyester) and plastic packaging, namely PET bottles. Transparent PET can be mechanically recycled, but opaque PET, which is getting more and more common in packaging, is not so easily recyclable[17].

That is why PET is the most widely researched polymer for recycling. Most of the depolymerisation projects are targeting PET flows that are not recycled today, such as packaging PET, textiles or opaque PET bottles.

PET can be depolymerised:

- Through glycolysis to produce Bis-HydroxyEthyl-Terephthalate (BHET). This method is the oldest and simplest. It involves the transesterification of PET with an excess of glycol at temperatures between 180°C and 250°C. A catalyser is usually used to accelerate the process.

[17] Crippa, M., De Wilde, B., Koopmans, R., Leyssens, J., Muncke, J., Ritschkoff A-C., Van Doorsselaer, K., Velis, C. & Wagner, M. A circular economy for plastics – Insights from research and innovation to inform policy and funding decisions, 2019 (M. De Smet & M. Linder, Eds.). European Commission, Brussels, Belgium

- Through hydrolysis, at high temperature and pressure, to produce Ethylene Glycol (EG) and Terephthalic Acid (TPA). The main drawbacks are the low purity of TPA and the relative slowness of the process.
- Through methanolysis, at relatively high temperatures (180°C-280°C) and pressure (20-40 atm) to produce Ethylene Glycol (EG) and DiMethyl Terephthalate (DMT) [18]

In the figure 3, some of the ways to depolymerise PET are described.

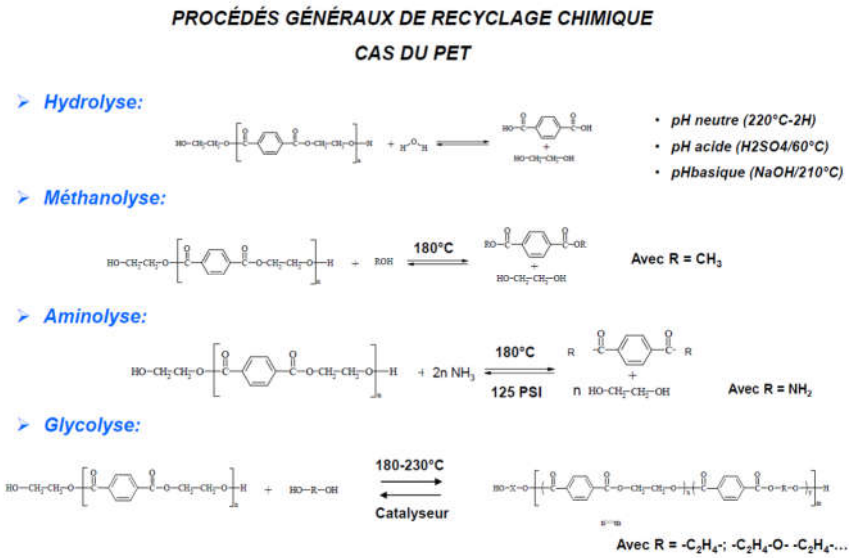

Figure 3: Depolymerisation of PET
Source: Enscm: www.enscm.fr/en/

All these molecules can be repolymerised to form PET again.

Several early stage industrial pilots to depolymerise PET both from packaging and textiles already exist. Garbo (Italy), Ioniqa (Netherlands) and Loop industries (Canada) are some of the most developed ones worldwide.

IONIQA is developing a glycolysis technology involving magnetic fluids to catalyse PET recycling into BHET, enabling it to obtain PET in a virgin quality. Even though the technique is still under development, Ioniqa has completed the funding for the next step: the construction of a production facility with a capacity of 10,000 tonnes a year, which it plans to scale up to 50,000 tonnes. The results of the first screening LCA indicate that the environmental performance of this process is not as good as the performance of mechanical recycling. However, most of the PET waste cannot be mechanically recycled and is currently stored, and could eventually be incinerated. The process developed by IONIQA performs better than incineration or storage on CO_2 equivalent emissions [19]. This process takes place at relatively low temperatures, and the catalyser can be reused many times after applying a magnetic field, keeping the operating costs low[20].

[18] Ragaert, K., et al. Mechanical and chemical recycling of solid plastic waste. Waste Management, 2017
[19] M. Broeren, E. Roos Lindgreen, G. Bergsma, Verkenning chemische recycling - update 2019 and Hoe groot zijn - en worden - de kansen voor klimaatbeleid?,CE Delft, 2019
[20] Ioniqa, www.ioniqa.com/pet-recycling/, 2013

GARBO's process, started in 2017 with EU's support, is based on a glycolysis technology with a specific purification system. They are working in collaboration with the University of Modena and Bologna to develop the so called 'ChemPET' project, which claims to be able to deal with almost all the currently non-recoverable PET waste (multi-layer thermoforming scrap and trays, multi-layer film, opaque rigid container, PET fines and dust, black PET trays, PET/PP strapping waste, non-woven fabric and polycotton). Through the reaction with ethylene glycol, PET goes back to BHET. The first plant, based in Cerano, is expected to reach 100 tonnes product per day at the end of 2019 [21].

Loop industries is using a methanolysis process and a specific catalyser to recycle waste PET of all types, including clothes, and break it down without heat or pressure into two monomers: Dimethyl Terephthalate and Mono Ethylene Glycol. Impurities and additives are removed, then repolymerised into new PET plastic, including for food packaging. Started in 2014, this company is working closely with L'Oréal, Danone, Nestlé, Coca-Cola and others. A joint facility with the plastic producing company Indorama Ventures Limited is expected to start its production in the second half of 2020. The production capacity of the plant, located in South Carolina (USA), will be 20,700 metric tonnes. They are also working on securing the feedstock needed for their commercial success[22].

The French group Soprema is currently creating a new recycling process within the Sopraloop R&D project launched in 2016. The aim is to combine mechanical recycling and depolymerisation to turn PET packaging waste into polyols used for insulating foam in the construction sector. This project is supported by Citeo (French Producer Responsibility Organisation for packaging) and the ADEME (French Environment and Energy Management Agency). A pilot unit should be created in 2019 to recycle around 5,000 tonnes of PET a year, and could double in the following years.

GR3N in Switzerland is using microwaves to catalyse the hydrolysis reaction. This patented technology called DEMETO (DEpolymerisation by MicrowavE TechnolOgy) is able to depolymerise continuously a wide range of different PET types (from colored packaging to textiles) by reducing the reaction time from 180 to 10 minutes. The pilot plant has been running since 2014 and GR3N is currently looking for more funding (€ 3.0 million) to build the first full scale pilot plant, which should produce PET equivalents suitable to all types of applications and cheaper than virgin ones[23].

IFPEN Axens (France) is developing a modular system that can be directly connected to a PET production unit. So far, their glycolysis project, that enables to produce PET monomers from opaque PET waste, is at the beginning of the pilot stage[24].
The project lead by Carbios and TechnipFMC (France) to recycle PET waste through hydrolysis with enzymatic catalysis (PETase[25]), should be taken to the industrial scale in 2021 in Lyon[26]. The first demonstrator is planned for this year.

In Japan, the company JEPLAN already owns two plants to chemically recycle PET from clothes and non-opaque PET bottles. With this technology, the BHET monomer is produced by depolymerising polyester in an ethylene glycol solvent, with a metal catalyst and heat. The product of this reaction

[21] Garbo: www.garbosrl.net/chempet-project/?lang=en and European Commission, www.cordis.europa.eu/project/rcn/210388/reporting/en, 2018
[22] Loop Industries, Securities & exchange commission Edgar Filing, www.filings.irdirect.net/data/1504678/000165495419005416/loop_10k.pdf, 2019 and Loop Industries, Supplying Demand and Transforming a Market, and Loop Industries, www.loopindustries.com/en/tech and www.loopindustries.com/assets/docs/Loop.IR%20Deck.Public.20190507.pdf, 2019
[23] GR3N, www.gr3n-recycling.com/
[24] IFP Energies Nouvelles, www.ifpenergiesnouvelles.fr/innovation-et-industrie/nos-expertises/climat-et-environnement/recyclage-des-plastiques/nos-solutions
[25] H Saporta, L'enzyme du PET nourrit le débat, Plastiques & Caoutchouc Magazine, 2018, www.plastiques-caoutchoucs.com/L-enzyme-du-PET-nourrit-le-debat.html
[26] Carbios, Carbios and TechniPFMC sign a contract on PET enzymatic biorecycling, www.carbios.fr/en/carbios-and-technipfmc-sign-a-contract-on-pet-enzymatic-biorecycling/, 2017

is then filtered with activated carbon to remove the colorants coming from the caps and the labels. Through an ion-exchange resin, impurities and the metal catalyser are removed. BHET is then crystallised at 20°C. The ethylene glycol can thus be removed, and the resulting BHET is re-polymerised into PET that can be reused in bottles or clothes[27].

PerPETual Global Technologies is based in the UK but the manufacturing and processing facilities are located in India, Turkey and South Korea. In their plant in Nashik (India), they daily convert over 2 million PET bottles into yarns through glycolysis, and are willing to increase the capacity in 2019. Their partners include big brands such as H&M, Adidas, Decathlon and Zara[28].

Finally, Eastman (USA) is currently running an engineering feasibility study for a commercial-scale methanolysis facility to recycle PET waste. The type of PET feedstock they are dealing with remains unknown. Their goal is to be operating a full-scale recycling facility by the end of 2021[29].

Polyurethanes and polyurethane resins (PU/PURs)

PU/PURs are collectively the fifth most produced plastics in the world. Chemical recycling through depolymerisation is at its early stages for these plastics. However, a few companies, including RAMPF Eco and H&S Anlagentechnik, have developed processes for recycling PU foams.

The multinational company RAMPF Eco, within their collaboration in the European project URBANREC, is producing polyols for all types of foam (shoes, cushions, insulations, mattresses, etc.) via the glycolysis of polyurethane resins from mattresses and furniture[30].

H&S Anlagentechnik has also developed a glycolysis process able to produce high-quality recovered polyols on a production scale from PU rigid foams[31].

Polyamides (PA)

The Italian company Aquafil[32] uses depolymerisation to turn used nylon in a new nylon yarn. The high energy intensity and decontamination costs are economically balanced by the high price of virgin PA, making the process cost-efficient.

[27] JEPLAN, www.jeplan.co.jp/en/
[28] PerPETual Technologies, www.perpetual-global.com/manufacturing/
[29] Eastman, www.eastman.com/
[30] RAMPF, www.rampf-group.com/en/news/newsroom/2018/chemical-recycling-expertise-for-european-project-urbanrec/
[31] H&S Anlagentechnik, www.hs-anlagentechnik.de/en/recycling-reactors-for-pu-residues.html
[32] ECONYL: "Some see trash. Others see treasure", www.econyl.com/the-process/ 2018

5. Thermal depolymerisation

Thermal depolymerisation and cracking are mainly based on pyrolysis or gasification techniques. They consist in heating up the plastics, but differ from direct combustion: the latter needs oxygen to be performed, while thermal depolymerisation and cracking work under reducing conditions (with no oxygen for pyrolysis or little oxygen for gasification).

They aim at transforming plastics and most of its additives or contaminants back into basic chemicals. Some polymers are more adapted to these techniques, namely those whose chain contains only carbon atoms: polymers synthesised via polyaddition such as polyolefins (PE or PP), PS and PMMA.

Nonetheless, it is important to distinguish between thermal depolymerisation and cracking:

- Controlled thermal depolymerisation is a selective operation which should correspond to the reverse operation of polymerisation, and produce monomers again. That is why it is also called 'plastic to monomer'.

- Cracking thermal depolymerisation consists in cutting the polymer chain in a non-selective way and produces a wide range of different molecules, leading to a product similar to petroleum fractions. Hence, it is also referred to as 'plastic-to-fuel'[33] even though it can potentially produce new plastics if the right conditions are in place.

5.1 Controlled thermal depolymerisation

Controlled thermal depolymerisation (plastic to monomer) exists for two types of plastics, PMMA and PS, because they present some activated bonds that are easier to break.

Poly (methyl methacrylate) (PMMA) is also known as plexiglass. It is a transparent plastic, often used as an alternative to glass, but also in inks or coatings. It can be pyrolysed specifically at 450°C, producing 99% liquid in which 96% is MMA, the monomer for PMMA[34]. The company Arkema, within the MMAtwo European project, is currently working on this selective depolymerisation.

For PS, the companies Agilyx (USA) and Pyrowave (Canada) are developing new processes. Pyrowave is planning to recycle PS through a catalytic microwave depolymerisation technology.

Very little information is available on these processes.

5.2 Cracking thermal depolymerisation

In general terms these technologies can in principle produce either monomers for plastic production or fuel, and whether the output will be the former or the latter depends on the inputs to the process but above all on the outputs that it aims to produce. Thermal depolymerisation aiming at producing plastic out of plastic needs to have security of supply and demand and once it is set up it is difficult

[33] A. Parenty, C. Dadou-Willmann, 2ACR, Recyclage chimique des déchets plastique : état des lieux et perspectives, 2019
[34] Dimitris S. Achilias, Chemical Recycling of Polymers. The Case of Poly(methyl methacrylate), Aristotle University of Thessaloniki, 2006

to change the output. This is why these plants tend to be built next to the facility that will be using the building blocks for new plastic, for instance Plastic Energy is building a depolymerisation plant next to SABIC which commits to buy the production. In practice this means that plastic to fuel depolymerisation is more flexible and mature than plastic to plastic depolymerisation and if left to the market alone without the right regulation it is likely that plastic to fuel depolymerisation will prevail over plastic to plastic. Because of this opportunity, some companies are deliberately conflating the two and pushing to group together plastic to plastic and plastic to fuel depolymerisation technologies.

Cracking processes are already on the market not only in the USA (Agilyx, Eastman, Plastic2oil, etc.), but also in Europe (Plastic Energy and Recycling Technologies in Great Britain, Recenso in Germany, etc.) and some other initiatives are emerging.

Pyrolysis

In the pyrolysis technique, plastics are broken down into a range of simpler hydrocarbon compounds by heating them in the absence of oxygen. Polymers tend to fragment into smaller hydrocarbon molecules which can be collected as effluents by condensing the hot gases.

Several types of pyrolysis exist:

- Conventional pyrolysis, during which the input is heated at a temperature between 400°C and 600°C.

- Integrated hydropyrolysis, during which the cracking process takes place in the presence of water at 300° C to 600°C[35].

The feedstock is supposed to be quite flexible: the technology can be applied to mixed and contaminated plastics streams. But the reality is different: some oxygenated resins such as PET are coke precursors which need to be avoided to obtain a good yield in liquid fraction, or PVC and brominated plastics, which lead to the production of acids. The formed acids, and especially HCl formed by PVC, will have to be removed (implying additional steps, even though HCl cannot be reused because it will be contaminated) and impose severe metallurgic constraints on the equipment material. Recyclers will mostly target polyolefins (PE or PP). Integrated hydropyrolysis is less sensitive to the variation in inputs, but it is still challenging to recycle PET, nylon and PVC through this technique.

The composition of the output mix can be controlled to some extent by changing the process parameters such as temperature, but the degradation is not controllable. It presents three different fractions: gas, liquid and solid residue (carbon char). Bond cleavage happens in random positions, leading to a hydrocarbon mix whose composition is similar to oil and can be used directly as fuel.

Pyrolysis enables to clean out additives and contaminants as part of the process. The output can be processed in the same way as oil, using conventional refining technologies to produce value-added chemicals, including new monomers, indistinguishable from virgin-grade ones. Hence, the additional processing infrastructure needed already exists in a mature and efficient value chain.

[35] M. Broeren, E. Roos Lindgreen, G. Bergsma, Verkenning chemische recycling - update 2019 and Hoe groot zijn - en worden - de kansen voor klimaatbeleid?, CE Delft, 2019

Plastic Energy owns two pyrolysis plants in Spain, running since 2014 and 2017, to transform LDPE, HDPE, PS and PP into hydrocarbon vapour. The resulting condensable gases are converted into raw diesel, light oil and synthetic gas components. These are then sold to the petrochemical industry to either turn them into virgin plastic, oil or transportation fuels. The other non-condensable gases produced during the process are combusted to produce the energy necessary to run the plant[36].

Nevertheless, in spite of the simplicity of this technology, pyrolysis has high energy requirements and can lead to the formation of hazardous chemicals such as Polycyclic Aromatic Hydrocarbons (PAH) or dioxins, implying the need for further purification steps. Furthermore, it is only economically viable if the volumes are large enough, and the input stable in terms of quantity, composition and quality. Pyrolysis is indeed expensive: according to the US Energy Information Administration (Department of Energy), the cost to produce 1 kilowatt of energy through pyrolysis is twice the cost of a kilowatt produced with photovoltaic solar energy[37].

Finally, considering the fact that turning the output fuel into new plastics requires other energy-consuming steps, there is a risk that the 'plastic-to-fuel' pathway will be preferred by the market. Today, the main viable market for pyrolysis output is crude diesel for power plants or ships. Besides, to optimise the conversion into plastics, increasing the naphtha fraction is necessary, which is challenging. **Encouraging pyrolysis would consequently create a 'linear lock-in' for plastics**.

Policy intervention is therefore mandatory to ensure this technology is indeed used to close the plastic-to-plastic loop and help decarbonize the economy instead of contributing to it by turning plastic into fuel.

Gasification

The gasification technique consists in heating mixed after-use materials (plastics and possibly biomass), in the presence of limited oxygen. It is able to treat almost every feed composed of organic material. There are several types of gasification, in which the temperature and other parameters can vary. Medium temperature gasification is less sensitive to fluctuations in composition and moisture than low temperature gasification.

The Texaco gasification process (figure 4) is the most common and well-known technology. The plastic waste is first cracked into synthetic heavy oil and some condensable and non-condensable gas fractions. The non-condensable gases are reused in the liquefaction as fuel (together with natural gas). The oil and condensed gas produced are injected into the entrained gasifier. The gasification is carried out with oxygen and steam at a temperature of 1,200°C – 1,500°C. Finally, a number of cleaning processes are performed (amongst others HCl and HF removal)[38].

The gasification output is a mix of predominantly hydrogen and carbon monoxide, smaller quantities of methane and carbon dioxide called syngas. It can be used to produce a variety of chemicals and plastics. It also contains impurities: NH_3, H_2S, NOx, alkali metals and tars. The purification step is the major contributor to the costs of producing the syngas.

[36] Plastic energy www.plasticenergy.com
[37] M Wilson, C. Arkin, In our opinion: Fueling a fantasy, 2018, www.resource-recycling.com/recycling/2018/04/02/in-our-opinion-fueling-a-fantasy/
[38] Ragaert, K., et al. Mechanical and chemical recycling of solid plastic waste. Waste Management, 2017

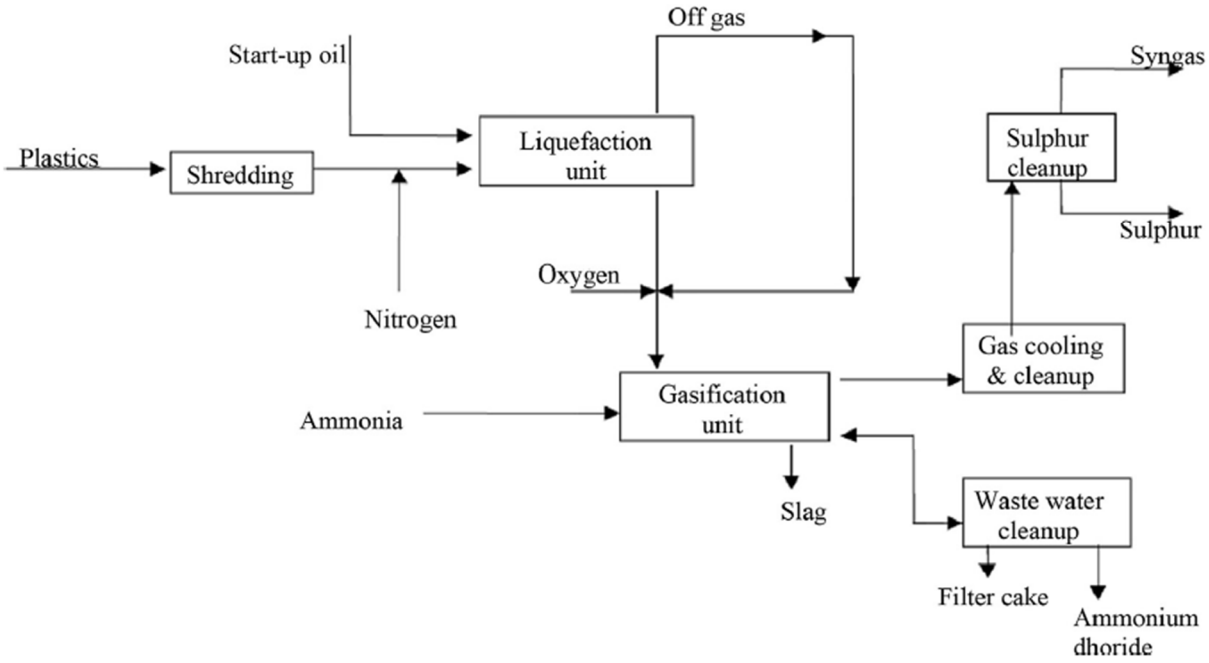

Figure 4: The Texaco gasification process schematic diagram
Source: Brems et al., 2015 Gasification Of Plastic Waste AsWaste- To- Energy Or Waste- To- Syngas Recovery Route, Solid Waste as a Renewable Resource. Apple Academic Press, pp. 241–263.

However, for low temperature gasification (700°C - 900°C), the syngas is only suitable for energy applications. For medium temperature gasification (900°C - 1,650°C), the syngas is suitable for plastic-to-plastic applications, but only after an additional step to increase the quality of syngas, which is measured by the ratio H_2/CO. There is thus a strong focus on energy production.

Enerkem in Canada is using a medium temperature gasification with a fluidised bed technology to produce fuel (ethanol) and methanol from sorted municipal solid waste (after recycling and composting). A similar project is being developed in Rotterdam (Netherlands): a consortium gathering Air Liquide, Enerkem, Nouryon, the Port of Rotterdam and Shell was created to build the first 'waste-to-chemicals' plant in Europe. It should be able to process 360,000 tonnes of waste into 220,000 tonnes of methanol. The conversion from syngas to methanol is usually performed at high temperature and pressure. This methanol can then be converted into chemicals such as acetic acid (for fibres and adhesives), thickening agents and dimethyl ether, which are currently produced almost entirely from fossil fuels[39].

Gasification presents more or less the same risks and challenges as pyrolysis. The technology is also energy-intensive and requires large volumes of stable waste in terms of composition and moisture. A pre-treatment is necessary to remove moisture and increase the calorific value of the input, resulting in higher costs. The output chemicals can produce fuels and fertiliser, but they will most likely be used as fuel, as it is the case today.

As with pyrolysis, policy intervention is needed to ensure plastic gasification stays in the plastic-to-plastic loop instead of being diverted to fuel.

[39] Ragaert, K., et al. Mechanical and chemical recycling of solid plastic waste. Waste Management, 2017

5.3 Environmental impact assessment of chemical recycling

The chemical recycling processes studied in this report are still very new and so far, most of the existing analysis were performed or led by the industries themselves. Therefore, further analysis on the environmental impact –notably analysing plants at scale and not at pilot stages- needs to be performed before a conclusive statement can be made or operating permits given.

The same is true for the energy and mass balance of the technologies analysed. Information available is, at best, insufficient, and at worst discouraging for technologies such as pyrolysis[40]. The health impacts from the emissions of such plants are also unknown.

An ISO compliant LCA, considering the whole plastic product life cycle, in which a realistic energy mix provenance is considered, is a good method to evaluate the consistency of such techniques from an environmental perspective. These calculations should take into account all the necessary purification steps. The results of these analyses should be compared with other existing and mature end of life treatments - mechanical recycling, mechanical and biological treatment (MBT), landfilling and energy recovery incineration.

It is important that the environmental impact assessments look not only at the climate impacts of today but also at the impacts that these technologies will have in the future, in the context of a decarbonising economy.

[40] Rollinson, A., & Oladejo, J. (2018). 'Patented blunderings', efficiency awareness, and self-sustainability claims in the pyrolysis energy from waste sector

6. Plastic to fuel in the XXI century

This study presents how some of the technologies used to produce plastic from plastic waste via chemical recycling, namely pyrolysis and gasification, can be used to produce fuel. Although these operations use the same core technology as other chemical recycling operations, their outputs, and therefore their impacts on the environment and the plastic economy, are quite different. Therefore from a political and economic perspective it is paramount to differentiate them. There are several reasons for doing so:

1. They risk undermining the Circular Economy agenda[41]. Turning plastic into fuel does not reduce the demand for virgin plastic, meaning that new plastic needs to be produced out of fossil sources. These techniques are undermining plastic reduction, the development of sustainable alternatives or innovations, and the incentives to phase out non-recyclable plastics. It prevents the EU from achieving its ambitious goals under the Circular Economy Strategy, including having all plastic packaging placed in the market be reusable or easily recyclable by 2030. As China's ban on recyclable imports is giving an opportunity for real change, plastic-to-fuel is encouraging to stay in this system by convincing consumers and cities that this waste can be "recycled" when the plan is to burn it.

2. It undermines the EU decarbonisation agenda[42] and the Paris agreement. Since plastic is made overwhelmingly from fossil fuels, plastic-derived fuels are a form of fossil fuel. The EU is currently set in the path to move away from fossil-fuel based sources of energy and plastic-to-fuel opens new doors to continue emitting CO_2 when we should be closing them. Turning plastic waste into fuel doesn't help to close the loop as it is still an energy intensive process that requires new virgin plastic to be produced. As such, plastic-to-fuel could be used to justify an increased virgin plastic production, creating this linear lock-in for plastics. Building new plastic-to-fuel facilities risks lock-ins at both the upstream and downstream ends of the plastic lifecycle: new PTF facilities will require a steady stream of fossil-based plastics produced.

Consequently, in order to avoid creating a legislative loophole in both the Circular Economy and the Climate agendas, it is key that the EU sets the right policies to direct plastic waste to plastic recycling operations, be it plastic to plastic mechanical or chemical recycling.

6.1 The right legal framework for chemical recycling

A clear definition

According to the current EU waste legislation:
Art 3.17 (WFD, 2008/98/EC): "*"recycling" means any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations".*

Therefore, the Waste Framework Directive's definition of recycling already comprises plastic-to-plastic recovery operations whether the process is mechanical or chemical. However, this poses the

[41] www.ec.europa.eu/environment/circular-economy/index_en.htm
[42] www.ec.europa.eu/clima/policies/strategies/2050_en

problem of blurring the preference that mechanical recycling should have over chemical recycling and it is important to make explicit that **chemical recycling is only suitable for those cases in which plastic waste is too degraded, too complex or too contaminated to be mechanically recycled**.

A definition is also important to differentiate plastic-to-plastic chemical recycling from plastic-to-fuels, given the growing confusion of both terms promoted outside EU borders. For instance, the Chemical Recycling Alliance created by the American Chemistry Council, considers chemical recycling as *those technologies that convert post-use plastics into chemicals, fuels and other products*[43]. Such consideration is at odds with the European waste legislation and it is yet another reason to provide legal certainty to these operations.

A potential definition for chemical recycling that excludes both mechanical recycling and plastic to fuels could be:

"Chemical recycling means any recovery operation by which waste materials that are unfit to be mechanically recycled are reprocessed into building blocks of a material of higher quality than the waste input."

A new level in the waste hierarchy

Besides a clear definition for chemical recycling, it is recommended to amend the EU waste hierarchy (Art 4) in order to create a new level to accommodate material recovery operations that are not mechanical recycling but whose output allows closure of the material loop. The rationale for this is based on the current available evidence on the environmental impacts of the different operations but also on the understanding of the economic and logistical aspects of current waste management processes. In this respect the waste hierarchy sets the following operations from lowest to highest environmental impact: prevention operations, mechanical recycling, chemical recycling and energy recovery.

Indeed, the process of mechanical recycling has the limitation that it is not possible to mechanically recycle every type of plastics (e.g. opaque PET), plastics which contain toxics (e.g. brominated flame retardants) or plastics that are too degraded. Mechanical recycling also usually entails downgrading the plastic quality, a process known as "downcycling". Mechanical recycling is consequently not a perpetual recycling method for plastics. This is why chemical recycling could play a role in the Zero Waste Hierarchy, as described in figure 5.

The nature of the plastic waste that is to be chemically recycled is equivalent to what today would be considered to be residual waste, since properly sorted plastic waste would be mechanically recycled. This is another argument for creating a dedicated level in the waste hierarchy to deal with residual waste in a way that allows for avoiding new virgin materials to be used.

This is what in the Zero Waste Hierarchy (see figure 5[44]) belongs to the 5th level: "Material and chemical recovery" namely dealing with the discards of sorting processes or with mixed waste with Mechanical Recovery and Biological Treatment operations that recover materials and stabilise organic waste, or with chemical recycling whose output are new building blocks for new plastic applications.

[43] www.plastics.americanchemistry.com/Chemical-Recycling-Alliance.html
[44] Zero Waste Europe, A Zero Waste hierarchy for Europe, 2019, www.zerowasteeurope.eu/2019/05/a-zero-waste-hierarchy-for-europe/

In contrast, the technologies that turn plastic to fuel don't allow for plastic waste to achieve its highest and best use and hence in the Zero Waste Hierarchy belong to the 7th level classed as "unacceptable".

Figure 5: A Zero Waste Hierarchy for Europe
Source: www.zerowasteeurope.eu/2019/05/a-zero-waste-hierarchy-for-europe/

7. Recommendations & conclusion

Today Chemical Recycling offers a range of potential solutions to the limitations of plastic as a circular material. Indeed, the capacity to upcycle degraded or contaminated plastics is an opportunity to close the loop and detoxify the Circular Economy which should be explored.

However, these technologies are still mostly in a pilot stage and they will not be able to operate at scale until the second half of next decade at the earliest. Considering the speed of change in the way we are using plastic today, it is uncertain how the plastic waste market will look 10 years down the line. Chemical recycling is currently uncompetitive with virgin plastic production and will require large-scale shifts in market conditions to establish itself. On the other hand, the lack of a clear legal definition for chemical recycling - in particular, one that excludes plastic-to-fuel - invites confusion and risks undermining both the Circular Economy and climate goals.
If plastic is to become a circular material and the toxics are to be phased out, maybe there will be no need for chemical recycling to deal with contaminated plastics in a world in which plastics should be designed to be less and less toxic. On the other hand, we know that plastics cannot be infinitely recycled and hence a solution for degraded plastics that does not involve downcycling or incineration is worth considering.

Moreover, it is important not to lose sight of the scale of the challenge and the solutions at hand. Whilst chemical recycling can be a tool in the waste management toolbox, one should not forget that **the solution to the plastic challenge is not to be found in how we manage the waste we create, but rather in how to prevent this waste from arising and preserve the value of materials in the economy**.

Indeed, the chemical recycling hype should not divert the attention from the real solution to plastic pollution which is replacing single-use plastics, detoxifying and simplifying new plastics, and designing business models to make efficient use of plastics.

This is especially relevant when it comes to potential EU funding to be made available in the coming years for the transition to a Circular Economy. The EU should avoid repeating past mistakes in waste policy such as the financing of waste-to-energy technologies instead of the higher levels of the waste hierarchy. EU funding should be directed to prevention, reuse operations, and any business model that prevents waste from being created. Too much focus on the residual waste treatment operations will not deliver a real Circular Economy.

With this in mind, a number of question marks are to be addressed in the roll out of the chemical recycling technologies. What are the scale of the plants that will make chemical recycling economically viable considering the costs of collection of such a low-weight material? Can chemical recycling be cost-competitive with virgin plastic in a world in which plastic from fracked gas makes recycling less and less competitive? What is the demand for the chemical recycling outputs of the different recycling processes? What are the real environmental and health impacts of the different chemical recycling processes when operating at scale?

The success of chemical recycling lies in the ability to be complementary to the other waste management processes whilst contributing to move towards a low carbon Circular Economy. At present the level of legal and economic uncertainty is high as is the lack of independent information available. It is key that the EU takes the initiative to regulate and provide the legal certainty that the market needs.

Glossary

atm	atmosphere (pressure unit)
BHET	Bis(2-Hydroxyethyl) terephthalate
DMT	Dimethyl Terephthalate
EG	Ethylene Glycol
EPS	Expanded PolyStyrene
HBCD	HexaBromoCycloDodecane (brominated flame retardant)
HCl	Chlorhydric Acid
HF	Fluorhydric acid
H_2S	Hydrogen Sulfide
LCA	Life Cycle Analysis
LDPE	Low Density Polyethylene
NH_3	Ammonia
NOx	Nitrogen oxides
PA	Polyamides
PAH	Polycyclic Aromatic Hydrocarbons
PC	Polycarbonate
PE	Polyethylene
PEF	Polyethylene Furanoate
PET	Polyethylene Terephthalate
PHA	Polyhydroxyalkanoates
PLA	Polylactic Acid
PMMA	Poly(methyl methacrylate)
PP	Polypropylene
PS	Polystyrene
PU	Polyurethane
PVC	Polyvinyl Chloride
TPA	Terephthalic Acid

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Zero Waste Europe is the European network of communities, local leaders, businesses, experts, and change agents working towards the same vision: phasing out waste from our society. We empower communities to redesign their relationship with resources, to adopt smarter lifestyles and sustainable consumption patterns, and to think circular.
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