IMAGE: PYROWAVE

Looking for success in chemical recycling

The success of chemical recycling projects will depend not just on technology, but also feedstock supply, purification, costs and more. Peter Mapleston reports on polystyrene and polyolefin developments

Main image: Polystyrene is the subject of a number of chemical recycling projects

The chemical recycling industry has a few pointed questions to answer: Just how effective is it at reducing post-consumer plastics waste? How good is it for the environment? Can it be done cost-effectively? The winners in this race will be, firstly, those who have technology that has been proven to work on an industrial scale with contained costs and which can clearly demonstrate the ability to help produce plastics with much lower carbon footprints; and secondly, those who source feedstocks that are consistent in quality and quantity. On top of that, players will need to convince nay-sayers – many of them in state legislatures – that chemical recycling really will help keep plastics out of our rivers and oceans, without polluting the atmosphere.

One company that appears to have a strong handle on the supply logistics situation is depolymerisation technology company **Agilyx Group**, headquartered in Portsmouth, New Hampshire, US. Agilyx claims to be the only company in the market to offer an integrated solution for chemical recycling and feedstock management.

Agilyx says it has an asset-light, technology licensing model with multiple revenue streams coming from feedstock IP (feedstock characterisations and recipes, supply chain optimisation) and depolymerisation IP (plastic-to-plastic, plastic-to-intermediaries, plastic-to-fuels).

In July, Cyclyx International, a consortium-based post-use plastic innovation company jointly owned by Agilyx (75%) and ExxonMobil, said Union Pacific Railroad, one of the largest freight railroads in North America, had joined the consortium. "Expertise in circular economy logistics and cost effective transportation solutions is critical," says Cyclyx.

In its 2021 Annual Report, Agilyx outlines future growth for Cyclyx, through expanding the consortium. At the time of publication, it said it was in ongoing membership discussions with 285 global companies.

Agilyx has developed depolymerisation technologies that can be applied to single streams, most notably polystyrene, and also mixed streams. Chemical recycling of PS is probably the furthest advanced of all plastics chemical recycling technologies. In January, Agilyx and Toyo Styrene said they were entering into the construction phase of a 10 tonnes/day chemical recycling facility in Japan, enabled by Agilyx technology.

The recycling plant will convert post-use PS into

Right: Feeding polystyrene packaging waste prior to depolymerisation

a styrene monomer that will be purified using Toyo Styrene's proprietary purification process, ready for reuse in production of more PS.

Last year, **AmSty**, the largest polystyrene producer in the Americas (a JV between Chevron Phillips and Trinseo), and Agilyx agreed to explore the development of a jointly owned chemical recycling facility. They plan initially to build a 50-100 tonnes/day plant at AmSty's Styrene production facility in St. James, Louisiana. The two companies already have a chemical recycling JV, Regenyx, at Agilyx's location in Tigard, Oregon, founded in early 2019.

Canada-based **Pyrowave** has developed modular equipment that uses microwave technology to depolymerise PS. Pyrowave is involved in a major PS chemical recycling project in a partnership with tyre maker Michelin in Europe. Michelin will operate the equipment at a location yet to be decided. It will acquire several units from Pyrowave. Michelin will use the styrene monomer to make styrene-butadiene rubber for tyres, also using bio-butadiene.

The two companies have been working together to fast-track the industrialisation of Pyrowave technology with a view to a certification and commercial roll-out in international markets. The joint development agreement will ultimately account for an investment of more than €20m. Michelin and Pyrowave are working together to develop an industrial demonstrator, funded and operated by Michelin, by 2023. Michelin is the first licensee for the Pyrowave technology.

Jocelyn Doucet, co-founder and CEO of Pyrowave, led the team that developed Catalytic Microwave Depolymerisation. The company works in tandem with major players in the polymer industry, including Total, Ineos Styrolution and AmSty.

Tyre maker Michelin took a stake in Pyrowave in 2020, with part of the investment earmarked for a demonstration plant at one of Michelin's facilities. The site has yet to be chosen, with a final investment decision due soon on what will be a 20,000 tpa plant.

IMAGE: AGILYX

Michelin will be sourcing pre-sorted material, which Doucet says will be 90-95% pure PS, having been through sorting and minimal washing and drying. It has already formed partnerships with two recycling facilities, and Doucet says 20,000 tonnes are accessible. He emphasises the need for chemical recycling plants to work with standardised input in the same way that conventional chemical plants do.

"The number one challenge we have is sourcing the feedstock," says Doucet. "You can't pipeline plastic waste. For scaling up the business of chemical recycling, regardless of the technology, there is a need for massive investment in the whole infrastructure. When we select geographies for possible operations, this is the number one thing we look at."

While Pyrowave's main focus at the moment is on the Michelin project, it is also in final negotiations on a project in Japan, where Doucet says there is a particularly strong focus on the circular economy, not least because it has few of its own natural resources and high energy costs. "It probably has the most advanced recycling infrastructure in the world," he says. He hopes to be able to make an announcement before September.

Other discussions elsewhere in the world for implementation of Pyrowave technology are "ongoing", especially in Europe. Doucet says that to a certain extent, developments depend on deployment of legislation. "Elements from a compliance perspective will force companies to move," he says. "These projects can make money, but the capital investment is substantial, so [there needs to be a strong impulse] to change the business model."

Pyrowave intends to publish a peer-reviewed

Below: Agilyx's chemical recycling technology at its Regenyx JV with AmSty

IMAGE: AGILYX


IMAGE: PYROWAVE

Distillation column at Pyrowave plant

LCA of its technology in the autumn. Doucet says: "The majority of impacts on the environment come from by-product management. Do you burn the by-products for energy recovery? Can you reintroduce them into other processes?" Working with Michelin, Pyrowave is looking at how by-products in its process can be used, possibly also in tyre production.

The second biggest impact relates to the sorting process. With PS chemical recycling, there are two levels of sorting: MRF and then PRF. Doucet says: "Both of these steps yield waste. So we are looking at how to cut the waste streams at both levels." Investment is needed in sorting technology, but rethinking in packaging design is also required – "design for recycling."

Also last year, **Styrenics Circular Solutions** (SCS), the value chain initiative to increase the circularity of styrenic polymers, unveiled the results of a comprehensive LCA for PS. "It shows excellent results for the three recycling processes – purity mechanical recycling, dissolution and depolymerisation – compared to the end-of-life option incineration and the production of virgin polystyrene," says SCS. The LCA focused on closed loop recycling routes back to food contact quality products. Dissolution and depolymerisation technologies both exhibit CO_2 emission savings of around 75%.

Jens Kathmann, Secretary-General of SCS, says: "We now have unambiguous, clear data that polystyrene is not only excellently sortable and uniquely circular, but it also comes with a significantly reduced carbon footprint for all three recycling routes we have been focusing on."

In July, styrenic thermoplastics producer **Elix Polymers** said it had completed a LCA of its more sustainable E-Loop materials. These are ABS and other materials that it has grouped together under the E-Loop brand name to denote commitment to the Circular Economy and which include polymers produced from chemically and mechanically recycled waste.

The company has completed an LCA of its production based on ISO 14040 and ISO 14044 (Cradle-to-Gate analysis), taking into account transportation to customers and including direct emissions (Scope 1) and indirect emissions (Scope 2 and Scope 3). The full LCA was validated by the Anthesis group. "The LCA shows that mechanically and chemically recycled products can considerably reduce the environmental impact of the final product and can support Elix customers in achieving their sustainability goals," said Elix.

Elix also formed a partnership in 2020 with Repsol, which has ISCC PLUS certification for all its production centres of polyolefin and other circular petrochemical products, including recycled styrene. The agreement includes the possibility of developing joint projects within the scope of the circular economy for applications in areas such as toys, small household appliances, external and internal automotive parts, and medical devices.

Styrenic plastics major **Ineos Styrolution**, together with partners including **Recycling Technologies**, is currently exploring scaling-up of PS chemical recycling technology and bringing it to commercial level, says a spokesman. Ineos Styrolution plans to build its full commercial scale recycling facility in Wingles, France, but has not given a date.

Recycling Technologies was selected by Ineos Styrolution as the technology provider for commer-

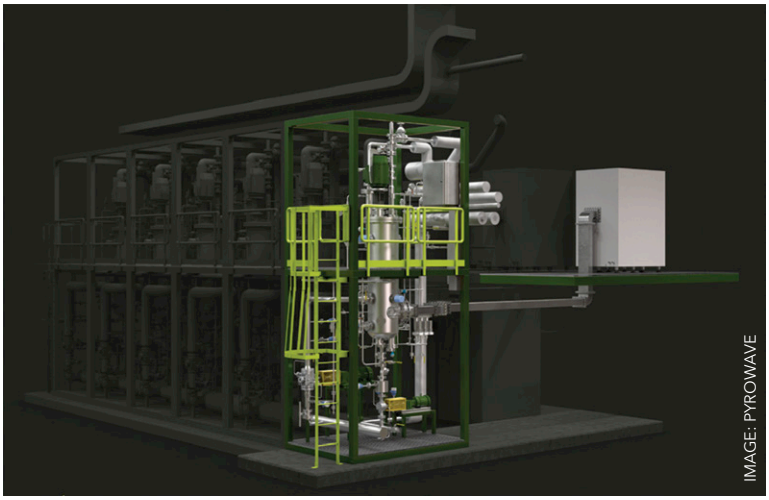
IMAGE: PYROWAVE

Below: Pyrowave depolymerisation plant for PS is modular

cial scale recycling of PS back to styrene monomer. Prior to building the commercial scale recycling plant, a PS recycling pilot plant will be built in the UK.

In June, it was announced that Indaver, a leading player in the European waste industry, and Ineos Styrolution had signed an offtake agreement today giving Ineos Styrolution access to styrene monomer produced from post-consumer waste at Indaver's planned depolymerisation plant.

The new plant will be based in Antwerp, Belgium and will start production in 2024. Indaver already manages and treats industrial and household waste in specialist facilities with plants and operations in Belgium, the Netherlands, France, Germany, Portugal, Italy, Ireland and the United Kingdom.

In September 2020, **Trinseo** and Indaver signed an offtake agreement for recycled styrene monomer. Trinseo said it would buy a minimum of 50% of the monomer produced at Indaver for a 10-year period, following start-up of the plant planned in 2023.

Indaver will collect post-consumer PS, such as yogurt pots and single-use packaging, and recycle and produce the recycled styrene through a proprietary depolymerisation technology at its Antwerp, Belgium site. The recycled styrene will then be sent to Trinseo's Tessenderlo, Belgium site nearby and will be used to manufacture recycled PS resins for dairy packaging and other applications. Both the recycled styrene and recycled PS products will be ISCC Plus mass balance certified.

Earlier this year, Trinseo announced that its plans for a world-class chemical recycling plant in Europe are progressing rapidly. The company has contracted with global technology provider Synova and global engineering services company Worley on the project and is planning to begin construction at Trinseo's Tessenderlo, Belgium location by the end of the year.

The plant will process 15,000 tpa of recycled PS flakes to enable further production of PS and/or a styrene derivative including ABS and SAN.

Trinseo has been working with CEDAP, an expert in plastic film extrusion and thermoforming, to provide food contact compliant recycled PS for the yoghurt cups of the French brand Les 300 Laitiers Bio since April 2022. Last year, Trinseo supported a similar yoghurt pot application in collaboration with sheet extruder Intrapläs and Yoplait in France. The material used for both applications is a Styron

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branded PS that combines 55% recycled styrene monomer feedstock with virgin, fossil-based content.

Controlling costs

Beyond PS, many developments are ongoing to create chemical recycling operations that can survive and prosper on a large scale. For example, **Nexus Circular** in Atlanta, Georgia, US, has developed chemical recycling technology that uses a proprietary process and pyrolysis. It says it has optimised the technology to create a highly efficient, economic, commercial and scalable system for delivering cost-effective, high quality distillate, or "circular liquid."

Nexus is currently operating with an input of around 40 tonnes/day (50 US tons), providing a yield of around 85%. Input is predominantly film, which is supplied mostly in the form of bales. The technology can handle polyolefins and PS films. President and co-founder Eric Hartz says the prices Nexus pays for its feedstock are very advantageous, partly because the company has little competition to bid against. The film is otherwise destined for landfill.

Nexus is taking post-industrial, post-commercial, post-retail, post-agricultural, and post-consumer film. Hartz reckons other recycling operations are paying as much as three to five times as much for feedstock, because it has to be pelletised or shredded, or because intermediates with their own costs are involved. He also emphasises the importance of other infrastructure elements such as site location to keep transport costs as low as possible.

Quality of output is also said to fall within very tight specification parameters. "Char is not entrenched with our liquids, so we have no post-treatment such as distillation or hydro-treating that adds a lot of complexity or cost." The process is a closed-loop system, with no air pollution issues, and which creates no wastewater, Hartz says.

He says that within five years, Nexus plans to have at least 12 large plants chemically recycling film waste coming from various sources, both post-industrial and post-consumer. Current input is over 90% post-consumer.

The original Nexus plant has been running since 2018, and while not divulging how much waste it has processed in that time, Hartz said in early July that the one hundredth truck load of output from the plant had just gone out.

In July, Nexus Circular and **Dow** announced that they have signed a detailed letter of intent (LOI) for Dow to secure the production output of a newly constructed advanced recycling facility in Dallas, Texas. The new facility will process and convert over 26,000 tpa annually of previously non-recycled plastic into feedstock that will be delivered back to Dow as a raw material to create new plastics for food-contact, health, hygiene, and fitness applications.

IMAGE: NEXUS

Above: The original Nexus plant has produced over one hundred truck loads of distillate from film waste

Nexus already has a supply agreement with **Shell**, announced in late 2020, for 60,000 tonnes over four years, of pyrolysis liquid made from plastic waste, which Shell will convert into various chemical products. Shell called the agreement "a next step towards Shell's ambition to use one million tonnes of plastic waste a year in its global chemical plants by 2025".

Early last year, Shell and **Pryme** signed pyrolysis oil supply agreements to use in Shell's chemical plants in Europe. Also last year, Shell and Environmental Solutions Asia signed a supply agreement for pyrolysis oil to use at its Energy and Chemicals Park Singapore.

"We are driving third-party volumes across the globe to help grow the market of pyrolysis oil through long term relationships with pyrolysis oil producers," says a Shell representative. "We are also collaborating with the waste management industry to develop the critical infrastructure needed to collect and sort the plastic waste that would otherwise go to landfill or incineration. Each of these elements is crucial to Shell achieving its ambition, and we are making steady progress."

The first Pryme plant in Rotterdam is under construction and scheduled to start commissioning in 2022. This will be followed by the rollout of its technology across Europe and globally in collaboration with strategic partners.

Pryme's Rotterdam plant has an initial intake capacity of 40,000 tpa of plastic waste and will

IMAGE: BASF

Above: In BASF's ChemCycling project, pyrolysis oil from plastic waste can be fed into the BASF Verbund. BASF partners include Quantafuel, which is specialised in the pyrolysis of mixed plastic waste and the integrated purification of the resulting oil. Photo shows Michael Bachtler from BASF (right) and Rasmus Kærsgaard, Plant Director at Quantafuel in Quantafuel's pyrolysis and purification plant in Skive, Denmark

produce 30,000 tpa of oil. This capacity will be increased by 50% in 2023. Boudewijn van Vliet, Executive Director at Pryme, said in mid-July that the Rotterdam plant was in the process of being brought onstream.

Pryme has also bought a site in Amsterdam where it plans to install capacity of 35,000 tpa. It is looking at various potential locations in Europe for further plants. The capacity of these plants will be based on multiples of 160,000 tpa of intake. Pryme is looking to establish partnerships with what van Vliet calls "significant" waste management partners to provide material. "We are planning partnerships all along the value chain," he says.

BASF's efforts in chemical recycling are grouped in its ChemCycling pyrolysis project, which has been running for four years in collaboration with various partners. BASF invested €20m in 2019 in **Quantafuel**, a Norwegian company specialised in the pyrolysis of mixed post-consumer plastic waste and the purification of the resulting oil. In September 2020, Quantafuel started up its first pyrolysis plant with a nameplate capacity of approximately 16,000 tpa in Skive, Denmark. It is not yet fully operational, however.

"Together, we are working on further developing and improving the process to produce pyrolysis oil from mixed plastic waste," says Christoph Gahn, Head of Chemical Recycling at BASF. Developing suitable catalysts for the new process technology is an important aspect of this. These catalysts aim to ensure that high-purity pyrolysis oil is always produced, even when the composition of the plastic waste varies.

Gahn says that "despite technical difficulties in the first months of 2022, Quantafuel's technology remains one essential building block for BASF's ChemCycling project. BASF and Quantafuel continue to jointly develop a pilot plant (design capacity: 10 tonnes/day) in Kristiansund, Norway, in which a further developed technology is tested." Test runs started in 2021.

"We can feed pyrolysis oil into our Verbund structure as an alternative to fossil raw materials and use it to make new products," says Gahn. "We use a certified mass balance approach to allocate the percentage of recycled materials to the end product." Various packaging products have already been commercialised by customers using "Ccycled" products.

The third of four production lines at Quantafuel's Skive plant in Denmark was completed on 30 June and is now in commercial production. "The onboarding of the fourth production line is targeted for early fourth quarter," says Quantafuel's CEO Lars Rosenløv.

"Our focus for the Skive plant has been on increasing production capacity and stable production. We are exposed to prevailing general market conditions with pressure on key cost drivers like natural gas, electricity, feedstock, as well as disposal costs. We are also exposed to a contractual fixed oil off-take price at the moment but are discussing this with our off-take partner."

The focus on high regularity and stable throughput at Skive continues, as well as the ability to process a variety of plastic qualities. Quantafuel processes plastic from mixed household waste, including waste contaminated with biological material. "The Skive plant continues to produce oil within product specifications, confirming Quantafuel's chemical recycling process," the company says.

In late June, Quantafuel submitted a planning application for a new plastics upcycling plant in Sunderland, UK. Quantafuel hopes to have the plant operational in 2024. The facility will be designed to process around 100,000 tonnes of low value plastic waste, such as soft food packaging and a variety of domestic and industrial plastics.

SABIC and **Plastic Energy** are over one year into the construction of the first commercial unit to significantly upscale production of SABIC's certified circular polymers derived from used plastics. The project in Geleen, Netherlands is expected to become operational in the second half of this year.

SABIC is also involved in projects for chemical recycling of so-called ocean bound plastic (OBP). It is, for example, cooperating with Portuguese film

producer Polivouga and Nueva Pescanova, a leading Spanish seafood producer, in a packaging solution using certified circular PE from such materials.

SABIC is also involved in a project that will see UPM Raflatac launch the world's first packaging label materials made from SABIC certified circular polypropylene based on chemically recycled OBP. In this case, OBP is recovered by local partners of HHI, a Malaysia based recycling company. It converts OBP into a pyrolysis oil, which SABIC uses to make PP that is processed into film by Taghleef.

In May, **TotalEnergies** and **Vanheede Environment Group** signed a long-term commercial agreement for the supply of post-consumer recycled (PCR) raw material, to be used as feedstock in the production of circular polymers for durable applications.

Under this agreement, Vanheede Polymers & Compounds will supply PCR raw material coming from its sites in France and Belgium, including Dottignies, where a new plastic waste treatment facility using innovative technology is currently under construction.

In February, **ExxonMobil** announced its first sale of certified circular polymers, to Berry Global which will use the polymers in production of food-grade packaging containers. ExxonMobil says initial quantities of the circular polymers is based on plastics waste processed at its advanced recycling facility in Baytown, Texas, US. The facility began operations in 2021 and has already processed more than 1,800 tonnes of waste.

The company says: "The operation in Baytown will be among North America's largest advanced plastic waste recycling facilities with a capacity to recycle 30,000 tpa of plastic waste when its expansion is complete later this year."

ExxonMobil also announced in February that it and **LyondellBasell** had signed a memorandum with FCC Environmental Services, which runs one of the state's largest material recovery facilities in the city of Houston, and Cyclyx. According to Dave Andrew, Vice President of New Market Development for ExxonMobil's chemical division, the idea is to improve used plastic collection rates so FCC can sort and clean it and Cyclyx can match it to both mechanical and chemical recycling efforts at ExxonMobil and LyondellBasell.

IMAGE: SABIC

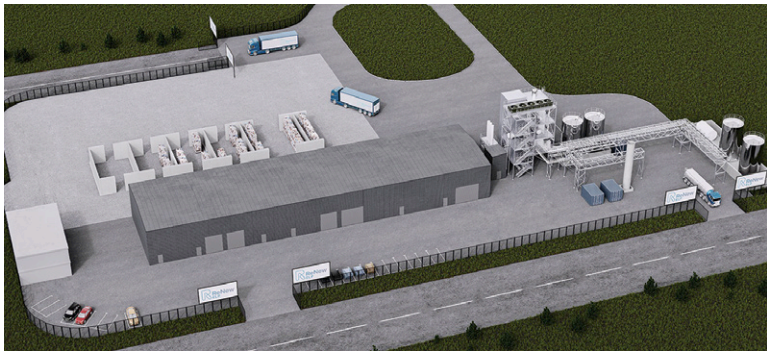
Left: SABIC chemically recycled PE is used in seafood packaging for Nueva Pescanova

Mura Technology says it is pioneering a globally scalable technology to prevent millions of tonnes of plastic and CO_2 from entering our natural environment every year and turning an $80bn lost resource of plastic waste into a valuable global commodity.

Mura's proprietary technology, HydroPRS (Hydrothermal Plastic Recycling System) uses supercritical steam to convert post-consumer household waste plastics, including flexible and multi-layered plastic packaging, into industry-ready, liquid hydrocarbon products. HydroPRS differs from pyrolysis in that heat is applied to the water and not directly to the plastic, which avoids creating 'char' and this maximises hydrocarbon product yield, whist hydrogen donation helps to reduce reactivity and excess cracking.

Mura Technology is developing a project pipeline including own-developed sites in the UK, Europe and the USA, and HydroPRS licence sales through its partner, KBR. The first site to use the

IMAGE: RENEW ELP



Above: Rendering of ReNew ELP chemical recycling site in Teesside, UK

HydroPRS process is under construction by **ReNew ELP** in Teesside, Northeast England. This 80,000 tpa capacity recycling site is located at Wilton International, an established industrial site, with readily available utilities and potential for laboratory, scale-up, and pilot facilities. ReNew ELP looks to be operational in early 2023 with the first 20,000 tonne line, with three further lines to follow by 2025.

ReNew ELP has a contract with Geminor UK to act as principal feedstock supplier to the Teesside project. The new agreement will see at least 15,000 tonnes of PE and PP rich plastic diverted away from incineration and into recycling per year, making up the majority of the feedstock supply for the first 20,000 tpa phase of the 80,000 tpa ReNew ELP project.

Dow says it will be a key off-taker of material from Mura. The two companies will also build multiple 120,000 tpa facilities in the US and Europe, adding as much as 600,000 tpa of capacity by 2030, Dow said in July.

"Using supercritical steam means the technology is also inherently scalable," says Dow. "Unlike other methods, which heat waste from the outside, the steam imparts energy from the inside, providing an efficient conversion of plastic waste; a process which can be maintained regardless of scale."

Dow says it is actively pursuing a number of commercial partnerships with customers and brand owners to scale chemical recycling technology "as quickly as possible." It has, for example, announced a strategic investment with **Plastogaz SA**, a technology start-up and proprietor of a chemical recycling technology. Dow says: "Plastogaz's proprietary catalytic hydrocracking technology solution is more efficient and less energy-intensive than some other current forms of advanced recycling."

Dow and **Fuenix Ecogy Group** are also expand-

ing upon the companies' initial agreement to scale circular plastics production through chemical recycling with the construction of a second plant in Weert, the Netherlands. The new plant will process 20,000 tonnes of waste plastic into pyrolysis oil feedstock, which will be used to produce new circular plastic at Dow's Terneuzen site in the Netherlands.

Dow has been busy signing supply deals in the recycling area, not just with Nexus Circular (see above) and Renew ELP. The group said in July it will be the main off-taker of post-consumer plastics from **Valoregen**'s project in Damazan, France, which will have capacity to process up to 70,000 tpa of plastics waste by the end of the end of Q1 2023. The project is unusual in being a hybrid recycling site combining chemical and mechanical recycling facilities in one location.

"By bringing these technologies under one roof, the plant will increase energy efficiency by enabling a yield greater than 80%, well above the average conventional mechanical recycling efficiency of approximately 60-70% – minimising waste – thanks to a smart energy management system," says Dow.

Braskem, the largest polyolefins producer in the Americas, announced in late July that it has developed a next-generation technology for addressing plastic waste. It says the process, which uses a proprietary catalyst, reduces the need for external energy sources. "This results in a significant reduction in CO2 equivalent emissions compared to the traditional advanced recycling technologies."

Jan Kalfus, Global Bioprocess Catalysis & Circularity Manager at Braskem, says the project has demonstrated high production yields for valuable intermediates, such as aromatics and monomers. "We are scaling up our reactor that will provide important data to support our future expansion. The pilot project is planned for 2025 and the technology should become available at scale by 2030."

Currently located in a lab in Sarnia, Ontario, Canada, **Aduro Clean Technologies** is expanding its R&D footprint to a much larger laboratory in London, Ontario. The purpose of the new lab is to house the bench scale process now under construction and to support optimisation of process parameters for its Hydrochemolytic technology. Aduro has also initiated the design of a pilot plant (1.5-2 tonnes/day of waste plastic feed) to be located in Ontario and expected to be completed before the end of 2023.

Aduro is also advancing its relationship with the Chemelot Campus of Brightlands in the Netherlands to build the next stage scale-up – a pre-commercial unit designed to process complex plastics that are harder to recycle and that are rejected by traditional mechanical recycling or thermal processes such as pyrolysis . Anticipation is for the process in Brightlands to be in the range of 10 to 25 tonnes/day (demonstration facility).

Aduro continues to focus on the scale up of its Hydrochemolytic process for the chemical recycling of mixed plastic waste. Ian McLennan, Senior Advisor Technology and Regulatory Affairs, says its process "involves the use of specific hydrogen donors combined with a proprietary process to specifically deconstruct various plastics (including addition polymers such as LDPE, HDPE, PP, and PS) to produce high yield, low molecular weight, saturated hydrocarbons that require minimal upgrading. Process engineering calculations have demonstrated a substantial reduction in GHGs for the Aduro process as compared to those involving thermal and hydrothermal cracking. "

The company plans to build a next-generation (so-called R3) reactor with a capacity of 2 tonnes/day, which would be scalable up to 100 tonnes/day.

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