AMERICA'S SEED FUND SBIR·STTR

U.S. DEPARTMENT OF ENERGY | Office of SBIR/STTR Programs

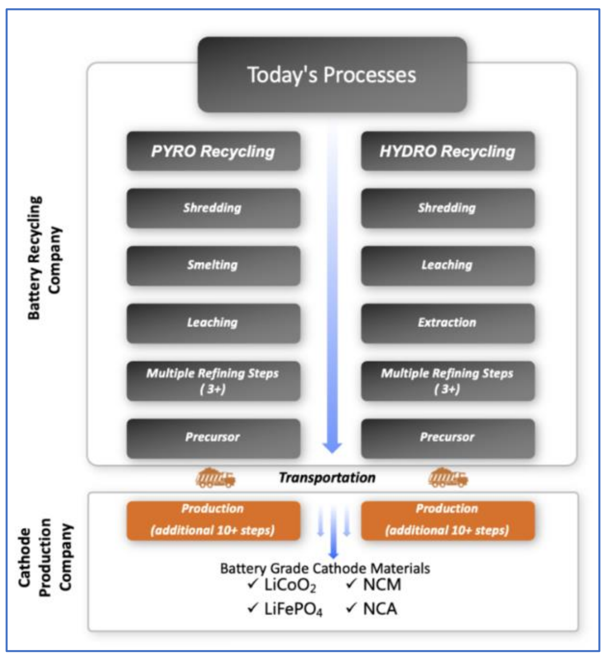
DOE SBIR-STTR SUCCESS STORY

Redefining the Battery Recycling Supply Chain

PRINCETON NUENERGY	
Founded	2019, New Jersey
Lineage	Princeton University Spin Out
Technology	Low-Temperature Plasma-Assisted Separation
SBIR Use Case	Direct Cathode Recycling
DOE SBIR Funding	$1.35mm[1]
Success Metric	$34M Private Capital Raise[2]
Employees	25+
Website	https://pnecycle.com/

Global supply chains can be inefficient and uncertain. Mining battery metals is costly and often environmentally destructive. Markets are demanding recycling. National security is on the line. What to do? Innovate – like the team at Princeton NuEnergy.

The current state of the market for lithium-ion battery recycling is based on traditional chemical processes. As shown in **Figure 1**, one method is referred to as 'pyro' or smelting. Another approach is referred to as 'hydro' or acid leaching. In both cases, the complex chemistry of the battery cathode and anode are reduced to basic metal building blocks which are then used to rebuild new batteries. This 'rebuilding' process is costly, creates significant waste, and consumes large amounts of energy.



As we examine the current battery supply chain, it consists of a global network of mining, chemical production, and manufacturing companies primarily in Asia and Europe. In addition to virgin mining, there are two sources of critical battery materials: manufacturing scrap and end-of-life batteries. During battery production, 10% to 30% of the original production materials do not become a final battery but result in manufacturing scrap. The recycling of manufacturing scrap and end-of-life batteries is increasing significantly as electric vehicle adoption

[1] Source: https://www.sbir.gov/node/1656649
[2] Source: https://pnecycle.com/news-room/

and demands for the power grid storage grow. It is anticipated that a tipping point may be reached by 2040 when as much as 50% of new batteries could be manufactured with recycled materials. This new source of battery materials is often characterized as ‘urban mining’.

Today, the majority of cathode and anode production is found in Asia – including China, Korea, Japan, and to a lesser degree, Europe – require the transshipment of materials around the globe to produce new battery feedstocks of precursors, cathode, and anode products. Because there is no guarantee that these feedstocks will return to the United States, creating a domestic U.S. supply chain to retain these critical materials and produce new product from recycled components is critical.

Driving this cycle is the fact that some of the largest U.S. manufacturers, including Apple, require that their batteries are recycled. This battery recycling process can be a money-losing proposition given materials shipping and regulatory compliance costs if not done thoughtfully and efficiently. Alternatively, virgin mining of these critical materials is not a great option. Concentrations of the essential battery materials are hard to source, expensive to mine and process, often controlled by hostile foreign governments, and the processes can be destructive to the natural environment[3].

Innovating on the current global battery materials sourcing systems, whether via recycling or virgin mining, is critical for the U.S. market and is a matter of national security.

Princeton NuEnergy (PNE) traces its beginnings back to basic research performed at Princeton University in Princeton, New Jersey in 2014-2019. PNE researchers, partnered with the university, were funded by a research grant from the U.S. Department of Energy’s (DOE’s) Small Business Technology Transfer (STTR) Program and a Seed Grant from the National Renewable Energy Laboratory (NREL) to develop basic plasma materials processing technologies, including Low-Temperature Plasma-Assisted Separation (LPAS™). Early LPAS applications focused on the use of plasma for materials processing to process hydrocarbons into useful chemicals. According to Dr. Xiaofang Yang, PNE’s Chief Technology Officer, early research provided “our fundamental understanding of plasma and its action.”

In 2019, while looking for innovative commercial applications for the LPAS™ technology, the team began considering battery recycling. Dr. Yang likens the LPAS™ technology to recycling a wooden table—with the plasma tuned to the right temperature, the old dust, dirt, and other coatings from the table without lighting the table on fire and turning it into carbon ash can be burnt off—which is effectively a *surface treatment* process to remove impurities. The basic structure of the table can be maintained without deconstructing it physically or chemically. The same could hold true for battery components, like cathodes.

Early analysis indicated that the commercialization potential of applying non-destructive LPAS™ technology to battery recycling was promising. With funding from Princeton University and the State of New Jersey, the team spun out PNE as a commercial entity. The team also won the Clean Tech Open National Grand Prize which resulted in more seed money and helped the team develop a robust network of technology and business contacts. PNE did not immediately apply for Small Business Innovation Research (SBIR) funding, however. The team felt that they were not quite ready to execute on a series of government grants to prove out the technical concepts, develop a proof of business model, and scale their technology.

[3] Source: https://www.bu.edu/articles/2016/rare-earths/

Fast forward to 2020, with a larger team in place and an initial financial footing, PNE was awarded its first and only (to date) DOE SBIR Phase I grant[4]. As the LPAS™ technology moved from basic scientific research to applied technology, DOE funding shifted as well. PNE's SBIR grant was funded by DOE's Vehicle Technology Office within the Office of Energy Efficiency and Renewable Energy (EERE).

Under EERE's topic *Electric Drive Vehicle Batteries*, the $200,000 grant titled '*Direct separation, purification and regeneration of cathode materials for aged lithium-ion battery using a novel low-temperature plasma assisted separation (LPAS™) process,'* enabled the team to prove that the LPAS™ technology could 'burn off the dust, dirt, and other coatings' from battery cathodes 'without deconstructing them physically or chemically'. The team successfully demonstrated the technical breakthrough it needed: non-destructive cathode recycling, which refers to refurbishing the cathode feedstock without breaking down and gasifying the materials.

The Phase I grant, which included the use of Technical and Business Assistance Program funds for market reports and opportunity sizing, allowed PNE to begin planning the scale up process from benchtop to prototype and prove the viability of the business. Rutgers University's EcoComplex provided a research and development facility, but PNE did not have the expertise nor financial resources to set up a pilot production facility on their own. For this proof of business model, PNE needed a partner and funding.

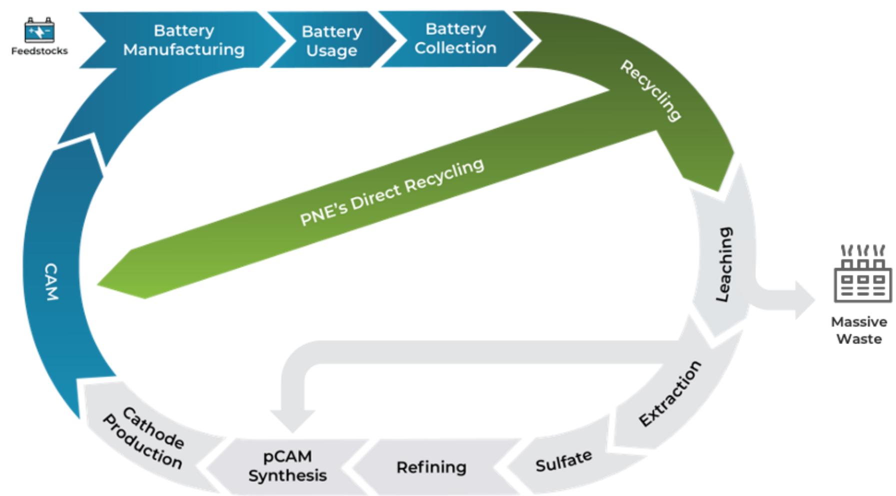
The PNE team actively worked on their professional network. Via a battery collector with whom the team had worked previously, PNE connected with Wistron Corporation, a Fortune Global 500 member and industry leader in electronics recycling services with $30 billion annual revenue and recycling operations in Texas. Wistron had expertise in industrial-scale recycling, and the employees and production lines required to disassemble and re-sort batteries from electronic devices. The Wistron relationship did not happen overnight. Wistron conducted a deep dive technical review in the market to select the best innovation partner. Backed by the Phase I grant results and Idaho National Laboratory-provided data for credibility, PNE was selected to set up a co-located direct recycling pilot line at Wistron's Texas recycling facility.

Thanks to the success of the Phase I award, the partnering relationship with Wistron, and the continued topic support from EERE, the team was awarded a $1.15 million DOE Phase II SBIR grant under the same topic and project title[5]. The goal of the Phase II grant was to develop and fully implement a pilot of the PNE-developed, 10-step plasma-assisted process required to produce regenerated cathode material. In addition to the funding PNE needed to overcome the technical challenges, the Phase II grant period helped PNE better understand the financial levers of the lithium-ion battery recycling business and hone its value proposition through the partnering relationship that it had established with Wistron.

PNE was off and running to scale the technical capabilities from bench to pilot scale and prove the early economics of the business proposition. The Phase II grant allowed PNE to develop their non-destructive cathode recovery process at pilot scale for reentry of cathodes into U.S. original equipment manufacturer processes, eliminating the need to ship materials around the world. By reducing materials

[4] https://www.sbir.gov/sbirsearch/detail/1835543
[5] https://www.sbir.gov/sbirsearch/detail/2104645

handling requirements and shipping costs, PNE developed a process with the potential to turn a profit-challenged lithium-ion battery recycling process into a highly profitable one irrespective of chemistry.



Consequently, PNE's patented LPAS™-based technology can significantly reduce the climate impacts caused by shipping hundreds of tons of metals around the world and the current conventional energy-intensive and environmentally damaging processing practices to recycle those materials as highlighted in **Figure 2.** Finally, the PNE business plan means that the critical materials remain within the United States, increasing national security of those critical cathode materials for use in industrial and military applications.

As is often the case on the heels of technological advancement, new business models begin to come to light. PNE is now exploring a business model they refer to as 'Recycling as a Service' (RaaS). In the RaaS model, the auto manufacturer collects batteries that have exceeded their useful life and pays a master recycler to recycle the components and raw materials. The manufacturer owns the components and the materials throughout the entire recycling process from collection to reentry in the supply chain, eliminating the need to sell spent batteries and then rebuy components on the open market at a later date. The RaaS model has numerous benefits including pricing stability, supply chain independence, and the associated national security implications.

Most recently, private funding markets have realized the PNE team's significant breakthroughs. In November of 2023, in exceptionally tight capital markets, PNE finished the initial close on a $16 million Series A fundraising round. This Series A has since been expanded to $30 million for a final close expected in early 2024 due to exceptionally strong investor and partner demand.

The institutional investors participating in this round included Wistron Corporation, Honda Motor Co., Ltd., GS Futures, and Traxys North America, joining previous investors Greenland Technologies, Shell Ventures, and WorldQuant Ventures, among others. This private capital is in addition to $16.4 million in follow-on EERE grants from DOE in 2022 and 2023, respectively, to support research into new chemistries and driving the efficient scaling of the technology. PNE plans to scale to multiple locations with multiple customers to concretely validate the profitable scalability of this cathode remanufacturing business. Their goal is to upend the traditional global recycling paradigm.

"PNE, like most startups, is resource limited. You need to focus on what the market needs and deliver what is needed," said Mr. Peng Zhao, PNE's Chief Operating Officer. "Scaling can be done in a very practical way: first to prove that the technology works, then prove there is a viable business model, and finally prove that you can scale the business in a profitable manner."

Dr. Xiaofang Yang also explained, "to have a successful commercialization, there's a need for good timing too. You need to know what good timing looks like and how to achieve it. First you need to achieve customer buy in, then you can advance to investor or funder buy in at a larger scale."