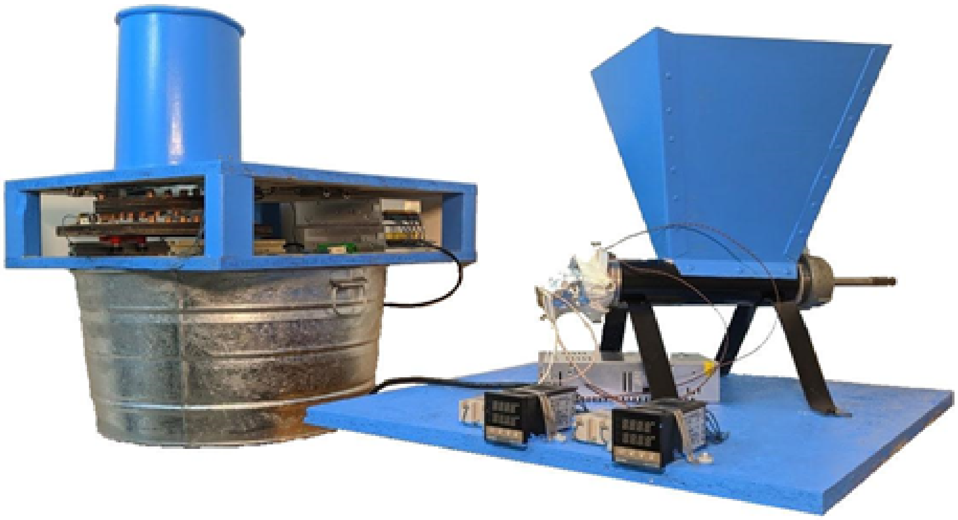
Onsite Recycling for Rural Places



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Abstract

Estimates show that the United States recycles less than 10% of plastic waste. In an effort to improve this situation, the group developed and tested a prototype to recycle expanded polystyrene, a form of plastic that has exorbitant shipping costs due to its high volume-to-weight ratio. Our prototype design reduces shipping costs by two orders of magnitude, enabling small municipalities to recycle with minimal investment. Cost estimates for a local compaction facility and transport to a state-wide recycling facility are less than the current land-fill expenses for small municipalities.

Acknowledgements

We extend our deepest gratitude to Professor Sullivan for his strong mentorship, dedication, and passion for helping students succeed. Additionally, we sincerely appreciate Professors Kmiotek and Schaufeld for their enthusiasm and open collaboration. Finally, we thank Mr. Peter Hefti for providing lab materials at a moment's notice, Mr. Ian Anderson for helping us with the CNC lathe, and Ms. Barbara Furhman for braving the Amazon.

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1. Introduction

Recycling plays an integral part in protecting the global environment. Since the industrial revolution, plastic has become a ubiquitous material in every industry, for applications in packaging, fastening, and product finishing. Plastic is constantly being generated, so it is worth taking special care to ensure it gets disposed of properly. A vast amount of consumer plastic is single-use, meaning it is intended to be used exactly once and then discarded. While recycling benefits the environment by keeping the plastic out of landfills and waterways, some plastics are not accepted in the national curbside program. This includes plastic bags but also, the focus of this report, Styrofoam or expanded polystyrene (EPS). EPS is the plastic of choice for most disposable food and drink containers, as well as packaging and shipment protection - and its inability to be recycled is disastrous for global health. Developing a system to reliably recycle EPS is an excellent mission for a student-led research project because of the potential social benefit from success, the project's small-scale attainability, and the diverse learning opportunities associated with the challenge.

Regardless of the exact design specifications, a new method for recycling Styrofoam will drastically benefit the environment and involve more citizens in the proper disposal of plastic waste. Polluted plastic is harmful to wildlife, lowers access to clean drinking water, and - over time - can raise carbon dioxide levels in the atmosphere. Even in landfills, EPS is light enough to be blown away by the wind and spread into ecosystems and waterways. The problem is that EPS is not accepted in American curbside programs, so landfills are essentially the best-case scenario for its disposal. If processing EPS in the traditional recycling pipeline were practical, then action would be taken to follow that process. Because it is not, any effort to recycle EPS involves sorting it out of trash and out of standard recycling waste. This activity will help involve citizens in recycling and create new opportunities to educate them about proper recycling etiquette. Currently, large portions of plastic in the curbside program are not cleaned well enough to be accepted, and entire shipments of post-consumer recycling gets landfilled due to contaminants. Implementing an EPS recycler will help engage people in the recycling process which in turn will be a limiting factor on pollution.

While an EPS recycler is a high-impact project, the scope is focused to make the goals attainable for student researchers. There are several plastic resins, each with different properties relevant to their recyclability. Redesigning a full-scale recycling facility would require millions of dollars in investment, but developing a recycling process around an often-ignored material significantly limits the nuances to consider. A group of students, with our education, can plausibly make strides in creating practical solutions for governments to eventually implement. Prior art exists that address the strengths and weaknesses of processing Styrofoam, and deflating EPS is not a new idea - it simply has never been economically viable. There is a wealth of literature available to help inform the prototyping decisions and, where experimentation is needed, the expertise and resources are feasible to acquire. The project can be broken down into attainable goals and still has a remarkable amount of academic depth.

Finding and implementing solutions to reliably recycle EPS requires intensive exploration across multiple disciplines. Developing and iterating upon a prototype for a recycler utilizes core design skills taught in mechanical engineering classes. Recycling requires an understanding of heat transfer and materials science while relying on fundamental principles of design. Recycling plastic is a complicated process, and engineers are trained to dissect the key elements to be simplified and improved. Some elements fall into the domain of mechanical engineering, while others diverge into aspects of chemistry. Knowledge surrounding materials safety information, breakdown properties, and chemical interaction will help identify the issues with past strategies and determine a main focus to find solutions. Though, as much as recycling EPS will require diverse engineering investigation, the problem is as monetary as it is material. Municipalities pay to recycle the waste of their residents, and at the moment, there are several plastics that are not economical to recycle. This problem will require analysis from the perspective of business interests and must consider the feasibility of nation-wide implementation. Developing the prototype in tandem with elements from a business plan will ground the project as a realistic innovation in the recycling marketplace. The diverse academic nature of this project makes it a valuable capstone to our respective educations, as well as raises the social impact generated by our efforts.

This venture is a comprehensive academic pursuit that can realistically have a dramatic positive effect on the environment. The background first identifies why decentralizing recycling centers from urban areas will increase the rate of recycling and protect our ecosystems from plastic pollution. Then, after exploring the essential elements of the recycling process, we outline a methodology for designing and building a small-scale prototype that can recycle EPS on a low budget. We analyze the value a final product could have for a rural American town and explore the options for implementation. By completing this project, the team makes vast strides in simplifying the recycling process and creates a systematic method for recycling a material that otherwise becomes pollution. Plastic waste is a real problem, and if the world is going to find a solution, a viable system to recycle EPS is essential.

2. Background

Consumerism runs on material needs, and in the modern world, those materials come wrapped in plastic. According to the EPA's most recent report on municipal solid waste, the United States population generated more than 34 million tons of plastic waste in 2015 (EPA, 2018). These immense quantities need to be disposed of sustainably, but only 9.1% of that waste was recycled. Unfortunately, current systems are not capable of controlling the generated waste. In 2010, between 5 and 14 million tons of plastic entered the world's oceans (Jambeck, 2018). The abundance of plastic, combined with the worldwide failures in its recovery, is cause for alarm.

Analyzing the systems in place surrounding plastic waste management will help to determine where there is room for improvement. This chapter explores:

- Options for waste management
- The life cycle of plastic waste
- Methods for processing post-consumer plastic waste
- Where recycled plastic goes once it is processed
- Costs associated with current waste management systems

These research topics help define the motivations behind pursuing this endeavor and also serve as the background knowledge that assist in making informed design decisions.

2.1 Waste Management

Following the consumption of consumer products, items that are no longer needed are discarded as waste. This section describes the paths taken by such waste, both recyclable and non-recyclable.

2.1.1 Waste

There is an abundance of material that cannot be recycled. When collected by municipalities, this waste is brought to state-owned landfills (EPA, 2018). Municipal Solid Waste (MSW) consists of metals, plastics, glasses, organic material (food waste, leather, yard trimmings, etc.), and other miscellaneous items. Municipalities at the city/town level are responsible for waste-related logistics - including landfilling, composting, recycling, or incineration.

2.1.2 Plastic Waste

The nomenclature of recyclable plastic is broad, denoting seven different classifications of varying chemical compositions (Bay Disposal, 2019). **#1 Polyethylene Terephthalate (PET)** composes water and soda bottles, but only 25% of the PET generated gets recycled in the United States annually. **#2 High-Density Polyethylene (HDPE)** is a more durable, thicker plastic used to make milk jugs, laundry detergent and oil bottles, toys, and plastic bags. Additionally, picnic tables, park benches, truck bed liners, and products requiring high durability and weather-resistance utilize HDPE. Of the HDPE used in the United States, approximately 30-35% is recycled each year (Cowan, 2012). **#3 Polyvinyl Chloride (PVC)** can be found in plastic food wrapping, children's and pets' toys, and inflatable pool toys. It has a high tolerance for sunlight and weather elements, making it suitable for garden hoses, trellises, and other outdoor products. PVC comprises numerous toxins, such as phthalates and vinyl chloride gases, which can leach into the environment and make PVC difficult to recycle (Bay Disposal, 2019). **#4 Low Density Polyethylene (LDPE)** is less toxic than other plastics, but not widely recycled. LDPE is most commonly used to make disposable grocery bags, as well as in various films. **#5 Polypropylene (PP)** is durable, lightweight, and possesses heat resistant qualities. It is used to make products such as plastic liners in cereal boxes, disposable diapers, plastic bottle caps, margarine and yogurt containers, straws, and chip bags. Despite its prevalence in society, only 3% of PP products are recycled in the United States (Cowan, 2012). **#6 Polystyrene (PS)**, an inexpensive and lightweight plastic, is used to produce expanded polystyrene (EPS, more commonly known as the branded Styrofoam) cups, takeout containers, packaging material, underlay for laminate flooring, and foam insulation. PS can easily separate and be dispersed into the environment due to its weak, lightweight structure and low ductility. As a result, nearly all beaches worldwide have bits of polystyrene on their shores. A surfeit amount of marine wildlife has ingested this plastic, resulting in negative consequences in their health. When heated in a microwave, PS can leach harmful carcinogens into food. EPS is extremely flammable because of its high air content and usually has to be coated to decrease fire risk. No American curbside collection services accept EPS, which is why it occupies 35% of landfills by volume (Cowan, 2012). #7 **Other, Bisphenol A, Polycarbonate, and LEXAN** encompasses all other types of plastic. Baby bottles, sippy cups, car parts, and water coolers are produced with #7 plastics. There is major concern associated with the safety of products constructed with materials found in this group, specifically polycarbonate containers have the potential for additives to leach into beverage and/or food products (Cowan, 2012).

2.2 Life Cycle of Plastic

A majority of post-consumer plastic waste comes from single-use plastic containers and packaging. All of this plastic, immediately after use, must be collected, shipped, and processed. In this section we explore the path plastic takes through the elements of that system.

2.2.1 Acquired by a Local Dump

In 2014, 33.6 million tons of plastic was used and discarded by Americans, but only 9.5% of that plastic was recycled. A further 15% was combusted for heat and electricity, but the remaining plastic waste is either thrown into landfills or littered (Columbia University, 2017). The majority of this plastic could have been recycled.

2.2.2 Shipping

Virtually no material use is self-processing. After an item is used, it must be moved to a location designed to process, reuse, or dispose of it. This is accomplished via plane, rail, ship, truck, and private car, though more than 75% of waste shipping is done by truck (Offenhuber, 2013). Alternative shipping methods are primarily for specialty waste items including batteries, printer cartridges, hazardous materials, and computer parts.

Some plastics are sent to landfills while others are sent to be recycled. Landfills are sites where municipalities and companies can contain waste long-term. In 2015, more than 137 million tons of waste were disposed of in landfills across the US (EPA, 2018). That figure equates to 52.5% of the material solid waste output of the country. In contrast, only 25.8% of material solid waste was processed in recycling facilities.

2.2.3 Materials Recovery Facilities

Alongside metals and paper, post-consumer plastic waste is most commonly processed for recycling at a materials recovery facility (MRF).

2.2.3.1 Facilities Overview

Once MRFs receive waste, they sort through it using a variety of methods. MRFs often accept mixed materials, which are then sorted. Conveyors and containers handle pre-processed recyclable material to move them through the process. Magnets help to separate materials by composition, and screens separate materials by size and eliminate dirt along with other contaminants from the stream of recycled goods.

MRFs preliminarily separate single-stream recycling material into two streams within the facility. The “green” stream comprises paper products, such as newspapers, cardboard, and office paper. The “blue” stream consists of Metals, Glass, and Plastic - known as MGP material. From there, the green and blue streams are further sorted separately.

After the MGP stream is separated, various types of densification processes reduce the size of the materials. Metal and glass waste are condensed using can and glass crushers, and many other materials are compacted into large blocks by balers. Forklifts, skid loaders, and other heavy machinery move the densified objects to pallets or bins to be shipped elsewhere (EcoMENA, 2019).

It is critical to MRFs that plastic materials are properly sorted before processing. For example, combining PVC and PET in a melt results in the formation of hydrochloric acid, which can damage the MRF, and as little as 50 ppm of PVC can contaminate a PET stream. Sorting between plastics can be done using infrared DAR (direct and route) sensors that operate on multiple wavelengths and can identify various plastics. Air ejection systems change the path of plastics by blowing them in the desired direction. In some cases, a material is sorted through a process of negative sorting. Negatively sorted items are the remains of a stream after other materials are separated out of the stream, which is a helpful strategy when the material itself is hard to identify through other means (Columbia University, 2000).

Once plastic material is sorted into streams of different types of plastic, each one goes through a similar process of being shredded, cleaned, and densified. The incoming plastics, which begin as a variety of sizes and shapes, are first reduced into small, uniform pieces by a shredder or granulator in order to make them easier to advance and clean. They are then cleaned to remove contaminants from the stream, such as food waste and dirt, often using a water-based solution. Finally, the plastics are densified using either heat or pressure.

After densification, plastics are either sold as cubes of extruded plastic, called ingots, or as small pellets which are then sold to plastic product manufacturers. The raw recycled material is extruded or melted into molds, and a new product is produced.

2.2.3.2 Environmental Impact of Waste Management Operations

Various studies have shown that recycling facilities have an adverse effect on the air quality in the area, causing pollutants to be released and affecting the health of nearby citizens (Oregon Public Broadcasting, 2011). The processes involved in recycling can give off harmful exhaust if not properly addressed. Within recycling facilities, the main concerns regarding air quality are dust particles and toxic vapors, which irritate respiratory functions (Xin et al., 2017).

To mitigate these concerns, fume and dust collectors are often used to protect workers within the recycling facilities as well as citizens in the area. Additional precautions include the donning of personal protective equipment and practicing safe material handling procedures (Health and Safety Executive, n.d.).

2.3 Post-Consumer Plastic Processing

Mixed streams of plastic need to be separated in order to properly recycle each polymer type. Following this sorting of plastics, the material is processed such that the end product is a densified repurposable material.

2.3.1 Sorting Processes

Municipal sorting is the first sorting pass in the recycling process, which occurs before waste collection. Individual households and businesses separate waste from potential recycling materials using judgement and recycling symbols to guide them. Recycling systems are totally reliant on households and businesses to sort recycling from trash and then transport it to recycling plants through curbside pick-up or direct drop-off (WIT Conferences, 2016).

Once the recycling reaches an MRF, the material goes through a single-stream sorting process. This step takes many forms, all of which use the material properties of each plastic to separate different types from one another. One such method employs infrared and x-rays to sort a single stream of mixed plastic by identifying each piece of plastic by its chemical composition (Int. Journal of Applied Sciences and Engineering Research, 2015). Another method uses density to divide a mixed stream by shredding it into small particles and pushing it vertically into the air. Selective dissolution makes use of the different solubilities of plastic in organic solvents to separate plastics from one another. This method splits individual polymers from dirt or contamination, as well as from other polymers present. Unless combined with another sorting method, the operating cost for this sorting method can be high because each polymer requires a different solvent (Int. Journal of Applied Sciences and Engineering Research, 2015). The sink-or-float sorting method makes use of buoyancy to separate plastics of differing densities. Decanter-type centrifugal separators spin plastic through fluids of varying viscosities such that sediments of different specific gravities separate more quickly than others (TOMOE Engineering Co., n.d.).

2.3.2 Shredding Processes

The shred step in the plastic recycling process can be completed in multiple ways. Shear shredders and granulators are the most commonly used devices to reduce the size of plastic waste. Shear shredders, also called industrial shredders, employ cutters along multiple parallel axes which grip the material and, using shear force, tear the material apart into smaller pieces. They operate at high torque and low speed, which is optimal for breaking down material at a low energy cost. In contrast, granulators reduce plastic into small particles by using a high speed, low torque cutting shaft which breaks pieces off of a product. The pieces then pass across a screen, which further granulates the product into miniscule particles (Jordan Reduction Solutions, 2018).

Cutting mills reduce the size of materials with spinning blades, similar to a blender or food processor (RETSCH, n.d.). Chippers operate similarly, spinning rotary knives at a high speed. Grinders chip away at material, breaking off small particles over time. These types of size reduction mechanisms are not used as frequently as shear shredders or granulators because they are not as effective at breaking material down and are difficult to clean and service (Compactor Management Company Northern California Compactors Inc, 2019).

2.3.3 Cleaning Processes

The cleaning process rids the plastic of any food waste, dirt, and other contaminants. A common, effective method used by MRFs is putting the shredded plastic into an attrition washer. This is merely a large basin with a central agitator that has propellers of opposite pitch located at both the top and bottom that produce competing counter-currents to clean plastic. Contamination prevents waste from being recycled and repurposed, so this step is crucial before the densifying process (Dart Container Corp, 2016.)

2.3.4 Densification Processes

Once the plastic is cleaned, the material is densified into small pellets, ingots, or compact bales. This can be accomplished by thermal, hydraulic, screw-drive, or hybrid densification processes (The Association of Plastic Recyclers, n.d.). Thermal densifiers melt plastic, extrude it into a rope-like shape, then feed it into a mold to form the melted plastic into an ingot, which can be easily stacked on a pallet. This type of densifier is extremely effective, but requires an extra molding step and needs proper ventilation as melted plastics generate byproducts. Hydraulic densifiers use hydraulic pressure to compact expanded plastics and foams, such as EPS, until the shape memory is gone and the plastic does not assume its former volume. These densifiers are best suited for mixed streams of plastic because they can process several types of foam, simultaneously. Screw-drive densifiers use an auger to condense plastics and shape them into a log, using varying pressures and speeds to process different densities. These densifiers process single-density streams best because if the pressure and speed settings are inaccurate, the plastic could melt inside the machine and clog it. Finally, hybrid densifiers use both hydraulic pressure and augers to compact post-consumer plastic waste, reducing the risk of unwanted melting inside of a machine.

2.4 Other Options for Processed Plastic

Once the recycled plastic has been densified and shaped, it can be repurposed at a profit to make the recycling process worthwhile. While the plastic is most commonly densified into ingots, sold, and broken down into small plastic pellets that are used to make new plastic products, EPS can also be reused in other ways.

2.4.1 Concrete

Recycled polystyrene is a useful substitution for sand in mixing concrete. Ground up polystyrene is added to regular concrete mix, giving this new polystyrene concrete distinct and favorable properties. Polystyrene concrete can weigh up to 10 times less than conventional concrete and can withstand significant tensile stress due to its elastic structure. Because of its insulative properties, polystyrene concrete can significantly reduce the need for extra insulation when building exterior walls in small-scale construction projects. This concrete is a favorable for small-scale building projects because of its unique properties and optimal for cast structures on buildings because it is lightweight (Interesting Engineering, 2016).

2.5 Cost Analysis

A method for the processing of waste plastic could be very valuable for small-town municipalities. In this section, we investigate areas in waste management that have room for improvement and explore tactics for that improvement.

2.5.1 Costs of Waste Management

Local municipalities are responsible for providing consumers with a safe and environmentally friendly way to dispose of their waste. Typically, waste falls into one of two categories: trash or recycling. The costs associated with managing each are similar. The first is collection, the process of bringing post-consumer waste to a central location. Collection tends to cost between $32 and $59 per household per year depending on the municipality's pickup schedule and their curbside program (EPA, 2016). The cost to the government can be offset by putting more of the burden on consumers, but collection must happen in every waste management system and any efficiency boosts would be slight.

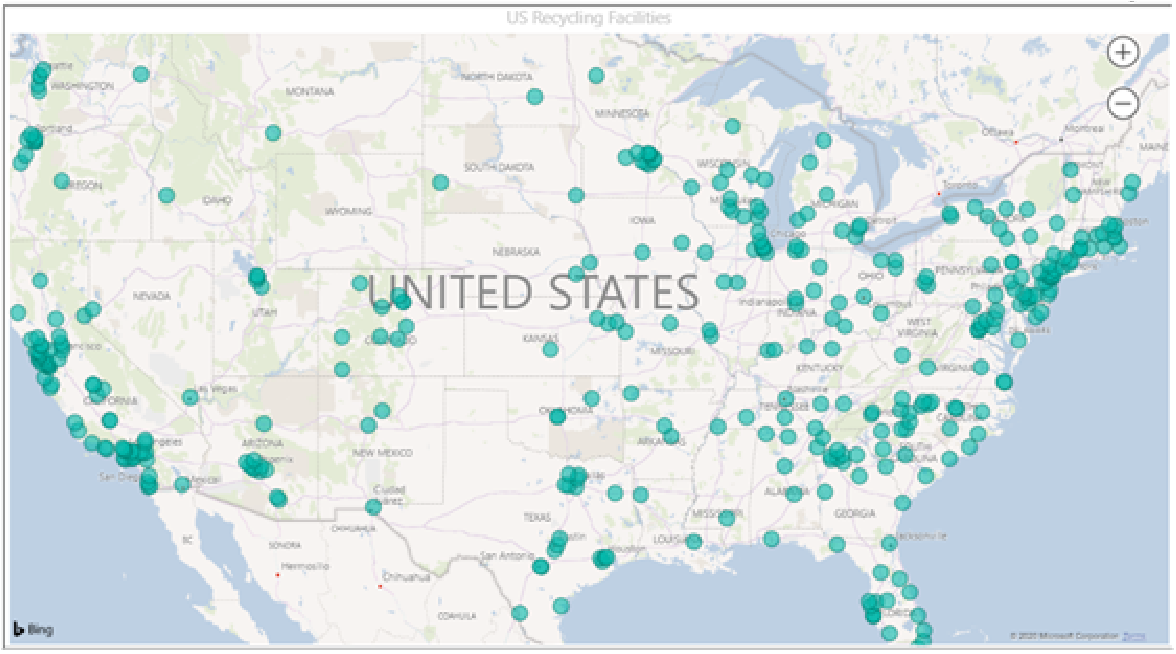


Figure A. Locations of active MRFs across the United States (Recycling Resource, 2020)

Some sources of cost are more dependent on the facilities locally available. Only about 10.4% of United States towns and cities, with more than 100 people, contain landfills (EPA, 2018), (U.S. Census Bureau, 2018) and, as indicated in Figure A, there are only 365 active MRFs (Recycling Resource, 2020). The landfills are typically state-owned and the MRFs are typically private entities, so most towns opt for transfer stations. Each transfer station has its own set of costs that towns need to consider. Temporary **storage** on location is a low expense to the town - but very difficult to avoid. **Sorting** is an optional cost for towns to take on, but opens up the possibility for processing at non-single stream facilities - and could lower costs for some towns. The transfer stations also have equipment for the **compaction** and baling of waste. This action is vital for the shipment of the material, which saves on storage needs and helps minimize load times.

One of the largest costs of in-waste management is **shipping**. Due to the poor distribution of both landfills and MRFs, rural towns have to ship materials significant distances to properly dispose of them. Not including a margin taken from trucking companies, the American Transportation Institute estimates a cost of $1.79 per mile for a loaded truck traveling across the US (American Transportation Research Institute, 2018). The trucks selected for waste management are often specially manufactured with 2-3 axles and designed for easy loading and drop-off (Federal Highway Administration, n.d.). Such trucks tend to hold 14 cubic yards and are rated to carry 30,000 lbs according to federal regulations. For most waste applications, the space on the truck is the limiting factor, so costs can be cut by opting to move high density shipments; this is typically done through compaction.

Another source of cost comes in the form of **landfill tipping fees** and **MRF gate fees** as both of these facilities charge for the material brought into them. Landfills had an average tipping fee of $51.82 per ton in 2017 (Waste360, 2017). MRFs are segmented as they charge different gate fees for municipal and private contracts. The average gate fee for municipal post-consumer waste is $38 per ton; other contracts average $48 per ton (Northeast Recycling Council, 2019). These costs go into offsetting the costs paid for by the landfills and MRFs. Both have heavy initial investment costs, and then on a continuous basis, must pay for the labor onsite, the overhead for usage and repair, as well as the depreciation of the equipment.

2.5.2 Reduction Opportunities for Shipping

There are dozens of companies across the United States that purchase scrap plastic. Densified plastic saves money on shipping costs but, if the plastic is clean and sorted, the material could also serve as a significant revenue stream. On a case-by-case basis, the seller might not be responsible for the shipment of plastic (Birch Plastics, 2019). The plastic should, however, be sorted based on resin and color - specifically between light and dark to maximize unit price. Salable plastic also must be free of contaminants, and thus must be carefully cleaned.

3. Methodology and Prototype

This section describes and elaborates the methods by which the team designed and built the prototype to recycle expanded polystyrene (EPS). In addition to explaining the rationale behind major design decisions, specifications of the final prototype are outlined.

3.1 Methodology

As previously discussed, the "shred, clean, densify" method of recycling plastics is standard among most material recovery facilities. Here, the broad concept of "shred, clean, densify" is narrowed to feasible steps for this application and then experimentally tested to determine which concepts are the most realistic.

3.1.1 Preliminary Design Philosophy and Process

Below, various concepts for each of the three steps are explored as options that a small municipality could implement, specifically tailored towards expanded polystyrene. While some of the concepts are based on prior art, others are novel inventions considered by the team.

3.1.1.1 Concepts – Shred

One method for obtaining uniformly sized and shaped pieces of EPS is using an industrial heavy-duty shredder. A shredder can intake large quantities of EPS waste and, by turning shredding teeth at a slow speed with high torque, tear the material into very small, manageable pieces. The device requires minimal power input that small towns can easily manage and is easy for operators to use. Additionally, maintenance on shredders is standard for industrial machines. What makes the device unfavorable is the EPS dust it produces as a byproduct. Microplastics enter the air, harming the environment and invading the lungs of the operators (Agency for Toxic Substances and Disease Registry, 2012).

An alternative shredding concept is using hot wire to cut the polystyrene into uniform pieces. A grid array of hot wires, such as NiCr, used in conjunction with a moving cut-off wire can cut polystyrene into cube-like pieces. This method, despite being dust-free, releases styrene gas as a result of the degrading polystyrene. Virtually all styrene gas emissions can be avoided if the nichrome wire is set to a temperature such that EPS melts, but does not vaporize (Mehta, 1995). However, maintenance on the wire arrays is far more tedious than for industrial shredders.

3.1.1.2 Concepts – Clean

Because EPS is polar, it is insoluble in and has no chemical interactions with water or common dish soap. The cleaning step is necessary in the recycling process for polystyrene because the resin end product must achieve a high level of purity for post-processing facilities to consider purchasing the material. The majority of debris on polystyrene waste is typically food residue or dirt contamination, which are easily removed by agitating the material in soap and water (Dart Container Corp, 2016.). This cleaning method is inexpensive and easy to implement, making it ideal for the stakeholders involved.

3.1.1.3 Concepts – Densify

EPS typically melts at temperatures above 300°C, at which point the bonds trapping air in the material break, producing a polystyrene resin. An option for densification of polystyrene is to simply melt the material until all air has escaped, leaving dense resin. This method can be accomplished using a heated auger screw, similar to what is used in injection molding processes (See Figure B).

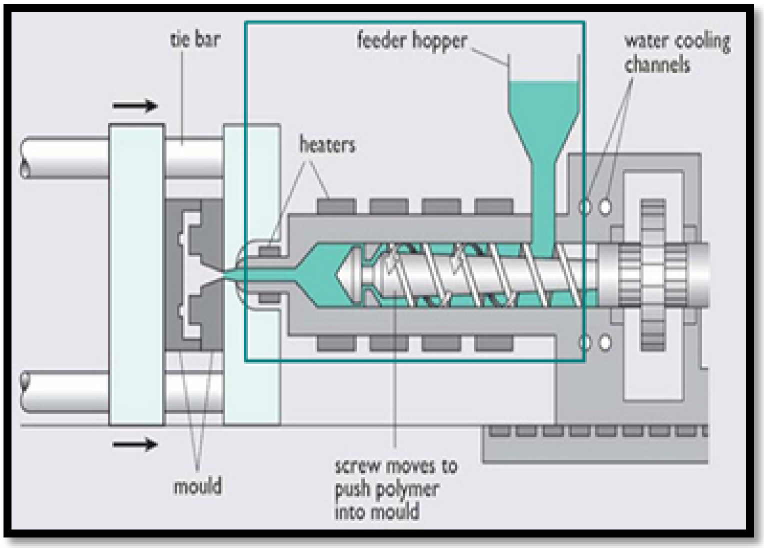


Figure B. Injection molding auger screw, modified from (Mushin, 2014)

Another alternative that leads to melted and densified polystyrene is utilizing a heated containment device. The containment device can be maintained at a high temperature so that the cut polystyrene melts into a liquified state inside the container, thus allowing it to be poured into an ingot mold.

A third method of melting EPS the team developed was utilizing an angled hot plate located at the bottom of a hopper. Shredded EPS is placed into the hopper and remains contained because an opening in the hopper along the lowest edge of the hot plate is narrow enough. Once the material has fallen onto the hot plate, it melts, and via gravity, slowly drips into a collection mold. This system allows a continuous stream of densification as opposed to producing batches like in the previous melting method. Despite this advantage, high energy input is needed to continuously heat the large surface area of the hot plate to the correct temperature.

A concept for densifying EPS without melting is using pressure to compress the material to the desired densification. A hydraulic press or other machine that can apply high pressures accomplishes this without large heat input. However, such a complex device gives rise to even greater operating costs than a melting process and requires higher initial investment to purchase the necessary components.

The last densification concept considered is using acetone to break down EPS. Polystyrene is soluble in acetone, so the bonds trapping the air in EPS break, resulting in polystyrene resin and leftover acetone. The acetone can be reused and cycled through many times. Although acetone has a very high vapor pressure compared to other solvents, the only point where it leaves the system is when it vaporizes into the atmosphere. Though possibly the easiest process to densify polystyrene, it necessitates that acetone be replenished frequently. More concerning than the replenishment cost is the danger associated with operating with copious amounts of acetone as it is highly volatile and could result in an explosion if ignited.

3.1.2 Focusing Design

This section delineates the process by which the team weighed the options for the final concept for each step of the process. Among the most important considerations when narrowing the concepts were safety, effectiveness, and cost.

For shredding, the two concepts decided upon were the use of an industrial shredder or an array of hot wire for cutting. The quality of the cut pieces, labor costs, operating costs, and the need for operators is required for both methods. The primary cost difference between the two shredding methods is maintenance. Industrial shredders are easy to clean, disassemble, and repair, but a complex and intricate wire array requires more specialty maintenance. The major drawback is that industrial shredders produce harmful polystyrene dust. The microplastics released from this harm both the environment and the operators of the system, causing lung and environmental pollution from plastic dust. This is more detrimental than the potential extra maintenance cost, and so, the hot wire method was selected.

For the cleaning stage, the only proposed method was simply using biodegradable soap with water and agitating the EPS, so the team chose this method in the final design.

The concepts determined for densifying the EPS included melting (with an auger screw, a heated reservoir, and a hot drip plate), compressing with pressure, and breaking down with acetone. All of the methods were effective for the densification step; however, the pressure concept is the least effective under reasonable budget constraints. Acetone requires no external energy to break the bonds in EPS, heat requires some external energy, and compression requires even more. This is paralleled in the cost analysis for the methods. Labor costs are likely the same for all methods, but the operating costs (primarily electricity) are higher for a method that can pressurize the polystyrene to the degree at which EPS is densified. The cost of maintenance for the methods is also relatively equal, though the acetone method requires frequent replenishment, creating an additional cost. The greatest risk relating to these methods is the extreme volatility of acetone and the danger it imposes on close human interaction with polystyrene exceeding temperatures of 300°C; the possibility of burning exists for equipment at those temperatures. The danger of the heat can be mitigated with proper training of operators, but the hazards related to acetone cannot be overlooked. That concern, along with the costs required for an effective pressure method, eliminated those two choices and left the team to consider one of the three melting procedures.

3.1.3 Testing

To even further decide which methods to use in the process, as well as confirm that our selections were effective for the prototype, the team conducted various experimental tests. Reasonable safety precautions were taken for each test conducted.

To verify that a hot wire cutting method would suffice for the shred step of the recycling process, tests were conducted with two proofs of concept. First, the team tested EPS's behavior as it made contact with the hot wire. A length of NiCr (nichrome) wire was heated to 340℃ by passing electrical current through it, and scrap pieces of EPS were pushed onto the wire. The force of gravity and heat from the nichrome wire was sufficient to immediately cut the EPS, causing it to continuously fall through. Additionally, the EPS did not adhere to itself after being cut. The 340℃ temperature was not so high that it burned the EPS, nor so cool that the EPS was difficult to cut.

Next, a potential concept for the hot wire architecture was developed - two rings of parallel hot wire lines, with one spinning. This was fabricated in a miniature prototype using 3D printed parts and fishing line. The two rings were centered on the same rotational axis, which can be seen in Figure C.

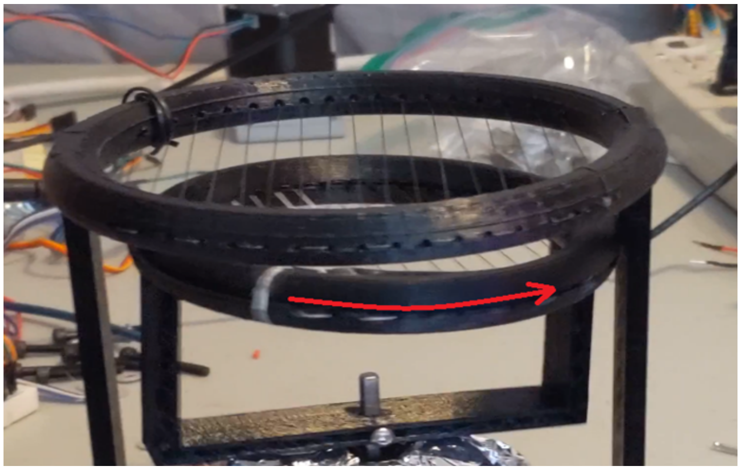


Figure C. Spinning ring cut method test

To determine whether hot wire arranged in this manner could effectively cut EPS into small, uniform, and cleanable pieces; a soft medium (stick butter) was pushed through the two rings. When placed above the center of rotation and pushed through the fishing line, the rings merely spiralized the butter without producing individual pieces. However, when offset from the center, the line cut the butter into flakes.

After deciding that a melting method of densification would most appropriately fit the prototype, the team observed EPS's behavior as it was heated in a glass beaker on a hot plate under a fume hood. During the experiment, the unmelted EPS floated on top of the melted EPS and ceased to melt further, until slight downward pressure was applied. When removed from heat, the EPS immediately began to cool and harden. The partially cooled polystyrene was extremely stringy, and the beaker was covered with a film of polystyrene at the base, once it was removed from the plate. The melted EPS was found to be extremely viscous, and essentially did not pour at all. Due to these issues, the most contained and controllable melting method, an auger-screw, was chosen over the other two methods.

3.1.4 Resulting Design

Based on the above tests, the team was able to narrow the concepts to one unified design for shredding, cleaning, and densifying. For shredding, we selected hot-wire disks with off-center axes of rotation. For cleaning, the original design of agitating EPS in soapy water was kept. For densification, the auger-screw extrusion method proved to be the best option.

3.2. Prototype

The team's end goal of the project was constructing a working prototype to recycle EPS. The sections below describe the design and development relating to the steps in the process of recycling plastic - shred, clean, and densify.

3.2.1 Design Iterations

Although the design selection process was robust, the construction of the prototype proved to have unexpected complications. Below are the various iterations for designing each portion of the prototype.

3.2.1.1 Shred Step Design

Following the initial test with the mock prototype, a design was developed for the off-centered hot wire shred disks. The top smaller, stationary disk diameter was equal to the radius of the spinning disk. The team built a geared mechanism to spin the larger disk, and the outside edge of the disk had teeth driven by an external motor with a corresponding gear, shown below in Figure D. The prototype was cut from wood to limit thermal and electrical conduction from the wires. Holes around the circumference of the disk held short pegs around which the wire was wrapped such that parallel lines of wire spanned the disk opening.

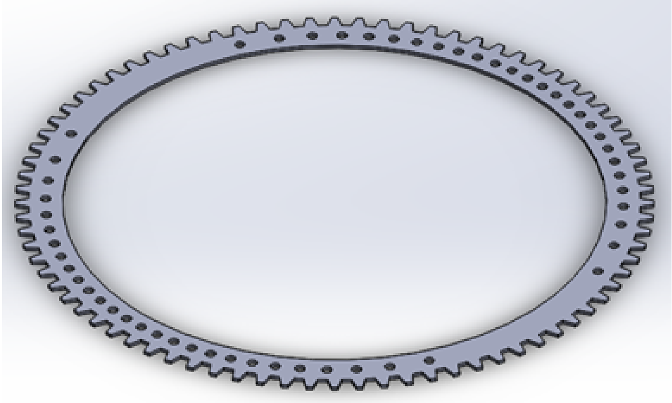


Figure D. Original large disk hot wire cutter design

Because the nichrome wire leads required a supply of power on either side of the disk, continuous rotation would have quickly shorted, entangled, or detached the wire from the power supply. To avoid this, the spinning disk turned 90° back and forth before changing direction. Ultimately, the team decided to apply a lateral cutting motion rather than using a rotating configuration, as the spinning gear would not completely cut the EPS and would result in long, irregular strips.

This change required incorporating three layers of parallel hot wire lines rather than the original two layers. The top two rings, both stationary, are oriented perpendicularly to each other to cut the EPS into columns. The moving ring rides on two parallel rails, using a crank-slider linkage to translate continuous rotation of a motor into back-and-forth linear motion. That ring of parallel hot wire lines cuts the columns into small cube-like pieces.

Because the hot wires operate at a temperature that could potentially burn the wooden pegs, an insulation method was required. Initially, high-temperature ceramic fabric sleeving was considered as an insulator between the pegs and the wires. However, due to the short length required, the small portions of ceramic sleeving were too frayed to insulate properly. The final prototype uses copper tubing, an effective insulator that adds negligible electrical resistance to the hot wire array, around each of the pegs.

3.2.1.2 Clean Step Design

Multiple options were considered for the methods to clean the EPS. The first concept was to use an attrition washer with a propeller inside a reservoir of water. The propeller would agitate the water, activating the soap and cleaning the EPS. The EPS could be kept in a mesh basket in the bucket so that the pieces would not jam the agitating propeller. To move the clean EPS to the next step, a mechanical hinge flipper would turn the basket out into a hopper for densifying.

In an effort to minimize excess power requirements, a manually powered alternative was ultimately employed for the prototype. The cut EPS falls from the shredder into a mesh basket with a handle, and the basket is manually agitated by hand in the soapy water and then transported to the hopper.

3.2.1.3 Densify Step Design

The design of the densification step remained relatively unchanged throughout the prototyping process, but certain modifications were made as the prototype was constructed. Firstly, the initial length of the pipe was too long for the auger screw that was used. The use of band heaters to heat the end of the pipe was originally preferred, but due to size constraints with the shortened pipe length, a heated cable was ultimately chosen to heat the pipe, along with a band heater that attached to the nozzle where the polystyrene was extruded.

Originally, a threaded barbed hose fitting was screwed into the end cap to function as a nozzle for extruding the densified polystyrene. However, the hex body of the fitting did not have adequate surface area contact with the band heater, so a customized nozzle was designed and machined out of brass so that the band heater fit snugly with maximum surface area contact.

3.2.2 Construction and Specifications

The team utilized facilities on the Worcester Polytechnic Institute campus including Foisie Innovation Studio Makerspace, Higgins Laboratory, and Washburn Shops to construct the machine. This section describes the final prototype constructed by the team.

3.2.2.1 Shred Step Construction and Specifications

The entire shred step of the process, displayed below in Figure E, is framed between two 24" by 24" sheets of ½" plywood, separated by 5.5" columns of 2x4 pieces in each corner. A 10" tall hopper of furnace duct surrounds an 8" diameter hole in the top sheet of plywood. On the underside of the top plywood sheet, two 1.75" standoff brackets are affixed to the plywood, one on either side of the top hole, which support the stationary hot wire disk.

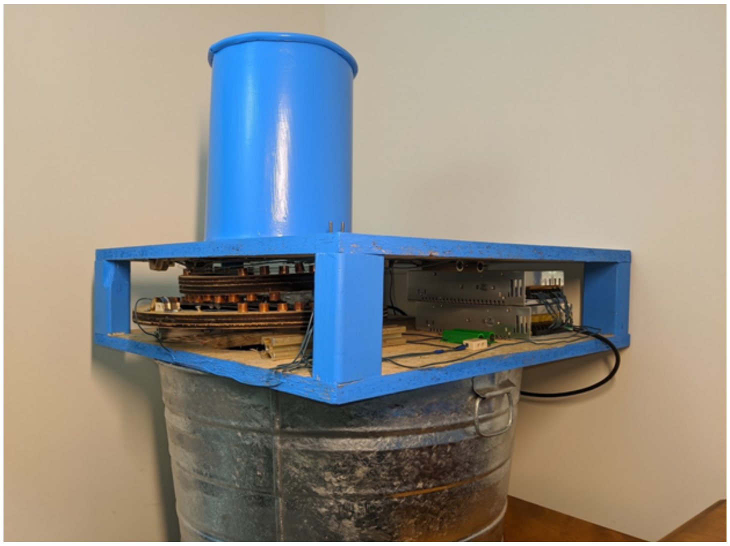


Figure E. Shred step of prototype atop basin for clean step

Each disk is laser-cut from ¼" Medium Density Fiberboard (MDF). The stationary hot wire disk has an inner diameter of 8" and an outer diameter of 10", and consists of 4 individually cut disks glued together with wood glue. The four layers have ⅜" diameter holes for pegs that hold the NiCr (nichrome) wire, evenly spaced to create a wire array. The holesets on the top two layers line up exactly, as do the sets on the bottom two layers; the top two and bottom two layers are oriented 90° to each other so that the arrays of wire are perpendicular, forming a grid.

The moving disk comprises three layers of cut MDF, with an inner diameter of 10" and an outer diameter of 14". The bottom layer does not have holes, while the top two layers have holes to hold the pegs. Oak pegs, cut from a dowel in ¾" segments, are fixed with wood glue in each of the holes in the disks. Secured around each peg is a crimped-tight portion of copper tubing to insulate the wood.

The holes for the pegs are evenly spaced so that the nichrome wires are parallel and spaced ⅜” apart when strung across the pegs for each wire layer. Short screws affixed in the disks, which add negligible resistance, act as anchor points for the nichrome wire lengths so that the wire can remain tensioned when wrapped around the pegs.

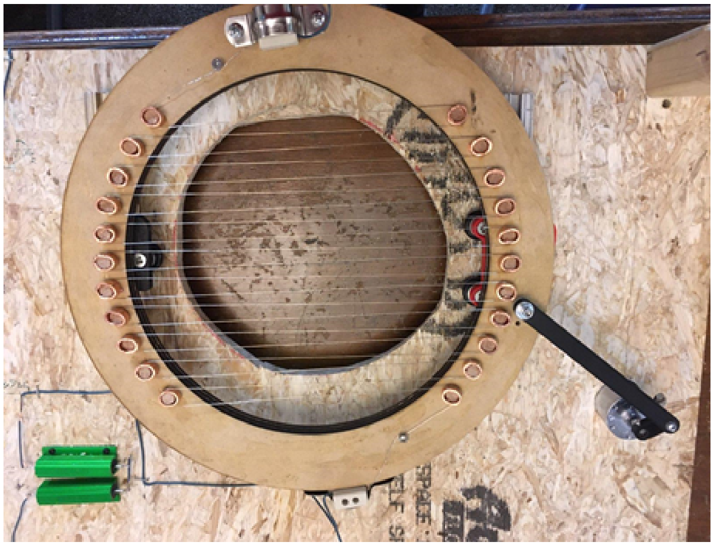


Figure F. Lateral motion cutoff disk

The bottom disk, shown in Figure F, has two carriage sliders, each fixed underneath with three bearing wheels. These sliders ride on a short segment of 8020 aluminum T-slot rail, attached to the bottom plywood sheet. A crank-slider linkage was designed such that the center of rotation is offset 4” from the center axis of the slider rail, and the distance spanned by the sliding disk is 2” in total. The two bars, 5.500” and 0.673”, are 3-D printed and held together with machine screws at the pivot points. The linkage is attached via a set screw to the shaft of a 12V 50RPM geared motor, which is powered by a 9V battery.

Separate lengths of 24-gauge nichrome wire are used for each of the three wire layers. The nichrome wires on both the top and bottom disk are attached at each end to high-temperature ceramic terminal blocks, and are wired in parallel with each other. The nichrome wire on the bottom disk has a resistance value of 38 ohms, and each of the two wires on the top disk have a resistance value of 23 ohms. The three nichrome wires are connected in parallel with each other and are attached to a 120V power supply, shown in the circuit diagram below in Figure G.

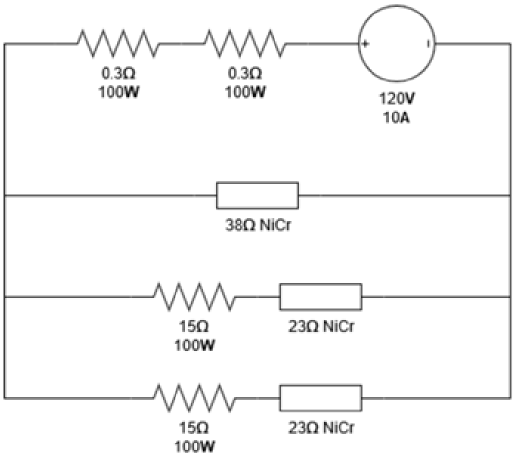


Figure G. Wiring schematic for nichrome wire

In the bottom plywood layer of the frame, an 8” diameter hole is cut such that it lines up with the upper layer’s hopper hole. When powered, the nichrome wires reach approximately 338°C, which is hot enough to easily cut EPS without releasing harmful fumes. After being sliced into columns by the top disk, the EPS is cut off into cube-like pieces, and falls through the bottom hole.

3.2.2.2 Clean Step Construction and Specifications

The cleaning step of the process takes place in a 10-gallon galvanized bucket. The bottom of the shred step’s frame is lipped so that it sits directly on top of the cleaning bucket, which can be seen in Figure XYZ. Upon being cut, the EPS pieces fall directly into a 12.75” by 6.50” mesh fry-basket. The operator manually agitates the basket of EPS in soapy water in the bucket. After satisfactorily cleaning the cut EPS, the fry basket is shaken dry, and the pieces are then turned out into the hopper of the densification step.

3.2.2.3 Densify Step Construction and Specifications

The densifying step uses a simplified extrusion auger-screw method with heating elements placed at the end to melt the EPS as it is pushed through the unit. The shredded and cleaned EPS is placed into a thin steel sheet hopper secured with pop rivets and screwed to a pipe, the interior of which is shown in Figure H.

Figure H. Densification hopper with EPS

EPS then falls into 2” outer diameter steel piping, with a slot located at the position of the hopper. Inside this pipe a 2” diameter auger screw spins, powered by a cordless drill, which moves the EPS forward through to the end of the pipe, where it is melted and pushed through a nozzle. The entire pipe is elevated by two flat steel rods, bent into the shape of feet. Two heating elements are on the outside of the pipe end-caps (made from cast iron) and the extrusion nozzle. A band heater is around the nozzle, and a cord heater is wrapped around the end-cap and partially onto the pipe. The heating elements are insulated with fiberglass. Their temperatures are dictated by thermocouples attached to proportional-integral-derivative (PID) controllers. The entire densification element is attached to another sheet of 24”x24” plywood, where circuitry is linked to the 60W 10 amp power supply with solid-core copper wire. Figure I shows the entire densification assembly with densified polystyrene extruding out.

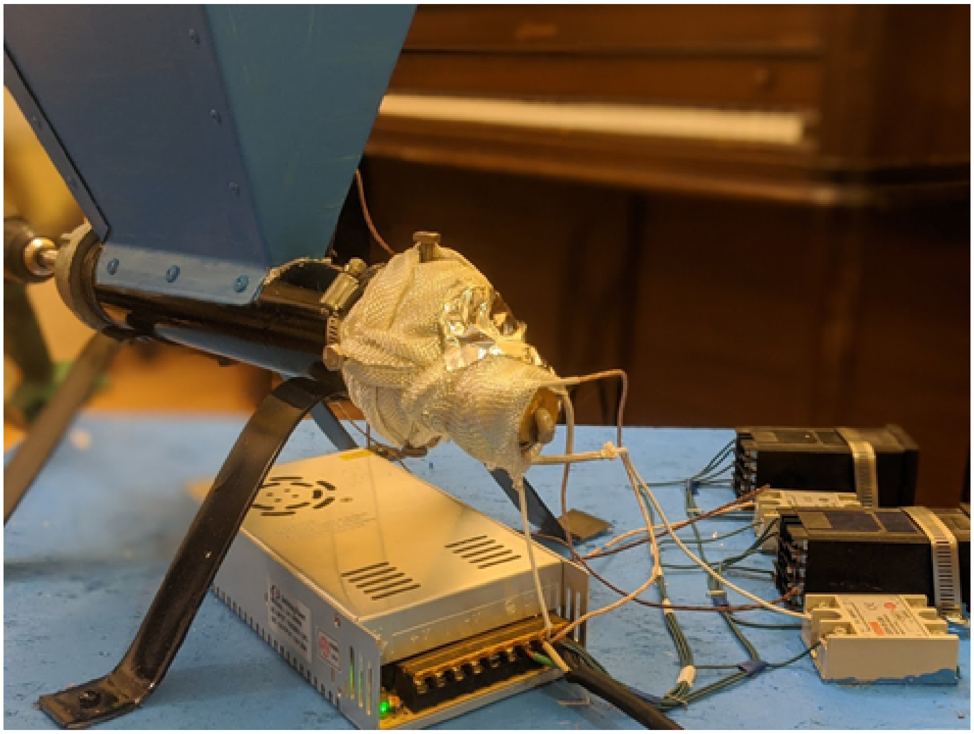


Figure I. Densification assembly extruding polystyrene

4. Results and Discussion

This section elaborates on the results from the working prototype and the cost analysis of implementing a commercial version in municipalities. Along with the feasibility and forecasted monetary benefit, certain considerations regarding safe implementation are also discussed.

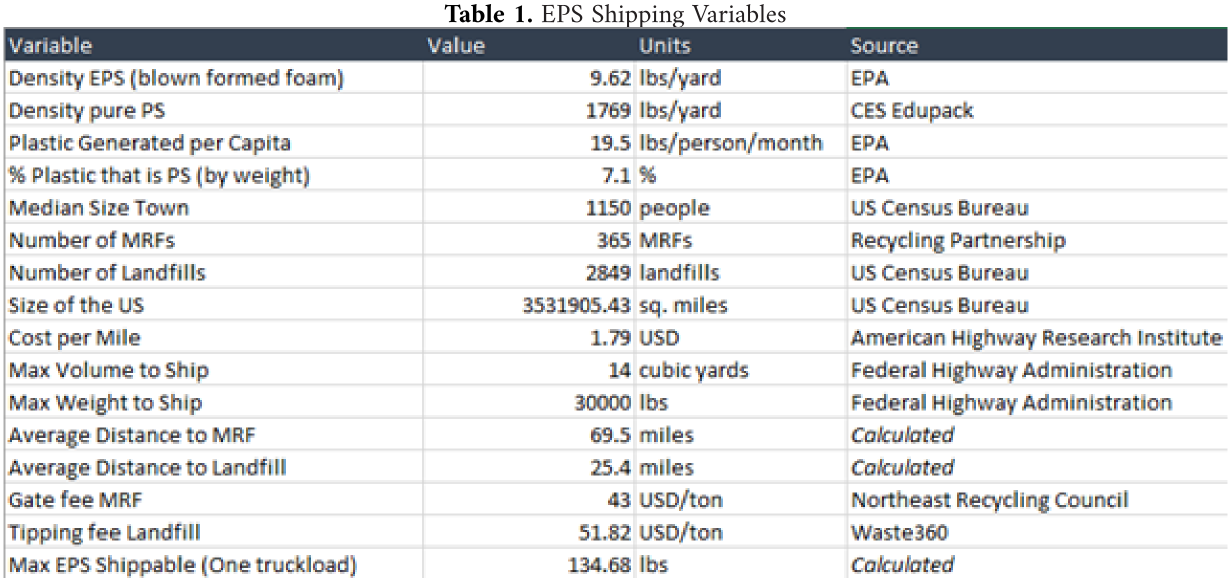
4.1 Feasibility Analysis

To determine if commercializing this prototype is viable as a venture, or at least beneficial for a town that uses it, we must consider the overall feasibility of using the design at the scale of a small town. This section includes a cost benefit analysis to consider the current costs of waste expanded polystyrene (EPS) on a town of various sizes against what the cost would be if the prototype were included. Additionally, we use a simplified Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis as a validation technique to consider the future of this idea. Finally, we explore possible sources of funding to begin the implementation of onsite recycling.

4.1.1 Cost Benefit Analysis

Several assumptions are built into the cost model, each of which either come from direct sources or are calculated from sourced information. These assumptions and their sources are displayed in Table 1.

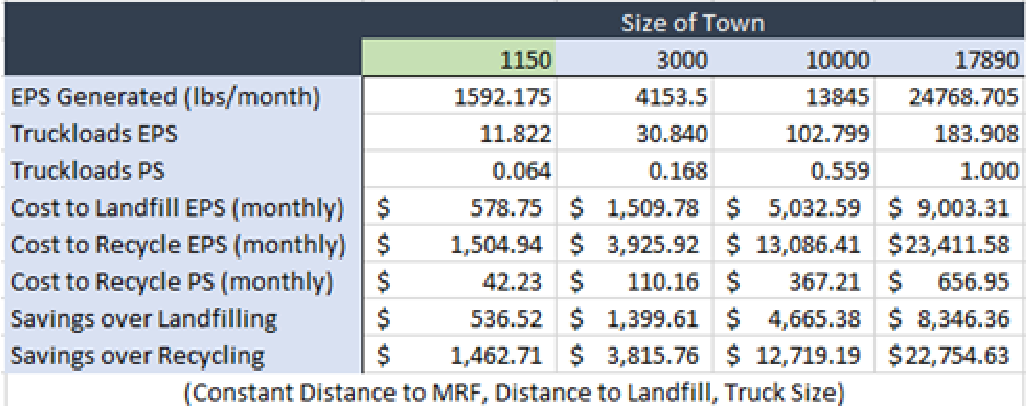
Table 1. EPS Shipping Variables



Variable	Value	Units	Source
Density EPS (blown formed foam)	9.62	lbs/yard	EPA
Density pure PS	1769	lbs/yard	CES Edupack
Plastic Generated per Capita	19.5	lbs/person/month	EPA
% Plastic that is PS (by weight)	7.1	%	EPA
Median Size Town	1150	people	US Census Bureau
Number of MRFs	365	MRFs	Recycling Partnership
Number of Landfills	2849	landfills	US Census Bureau
Size of the US	3531905.43	sq. miles	US Census Bureau
Cost per Mile	1.79	USD	American Highway Research Institute
Max Volume to Ship	14	cubic yards	Federal Highway Administration
Max Weight to Ship	30000	lbs	Federal Highway Administration
Average Distance to MRF	69.5	miles	*Calculated*
Average Distance to Landfill	25.4	miles	*Calculated*
Gate fee MRF	43	USD/ton	Northeast Recycling Council
Tipping fee Landfill	51.82	USD/ton	Waste360
Max EPS Shippable (One truckload)	134.68	lbs	*Calculated*

Many of these are kept constant in the model, as they have little effect on total costs and are based on national averages. These variables include ‘Cost per Mile’, ‘Gate fee MRF’, ‘Tipping fee Landfill’ and ‘Plastic Generated per Capita,’ each of which are reasonable estimates, and may be useful data points if the town does not have this information. Though, while the median size of a town is a value indicative of the abundance of small-town municipalities, it is not a helpful metric to determine the savings if a specific town is not median.

Table 2. Benefits of Densifying EPS for Towns of Various Sizes



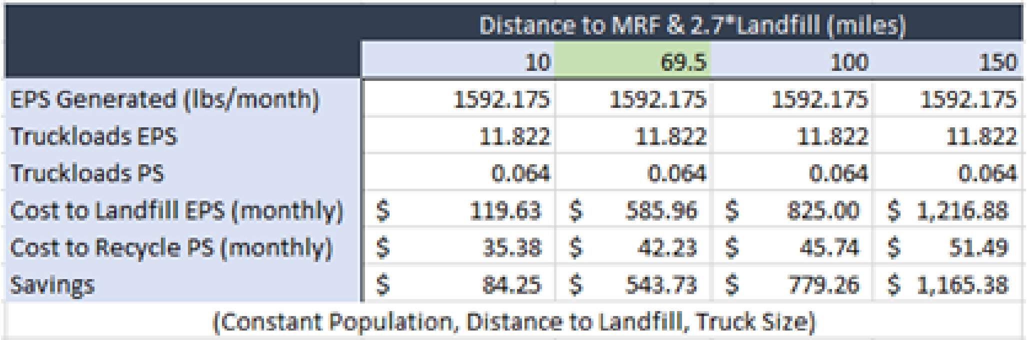
	Size of Town			
	1150	3000	10000	17890
EPS Generated (lbs/month)	1592.175	4153.5	13845	24768.705
Truckloads EPS	11.822	30.840	102.799	183.908
Truckloads PS	0.064	0.168	0.559	1.000
Cost to Landfill EPS (monthly)	$ 578.75	$ 1,509.78	$ 5,032.59	$ 9,003.31
Cost to Recycle EPS (monthly)	$ 1,504.94	$ 3,925.92	$ 13,086.41	$23,411.58
Cost to Recycle PS (monthly)	$ 42.23	$ 110.16	$ 367.21	$ 656.95
Savings over Landfilling	$ 536.52	$ 1,399.61	$ 4,665.38	$ 8,346.36
Savings over Recycling	$ 1,462.71	$ 3,815.76	$ 12,719.19	$22,754.63

(Constant Distance to MRF, Distance to Landfill, Truck Size)

Table 2 considers monthly savings generated by recycling pre-densified EPS over shipping EPS foam at its standard shipping density. There are columns for towns and cities sized at 1,150 people (median town size), 3,000 people, 10,000 people, and 17,890 people (the size of a city that generates exactly one truckload of EPS per month). The savings directly generated through limiting required truckloads by densifying the EPS follows a linear trend and always grows with the size of the town, since it is proportional with the EPS generated.

Variables with the source marked as 'Calculated' are dependent on enough elements that the values, while they are used in the model, may be inaccurate for many towns. Specifically, the variables 'Average Distance to MRF' and 'Average Distance to Landfill' are based on the square area of the United States and assume the MRFs and landfills are arranged in a grid pattern across the country. Both are certainly an underestimation since roads are not straight lines and MRFs are positioned at population centers, not evenly distributed. But a town looking to implement onsite recycling would have no trouble identifying the exact distance between where their post-consumer waste gets sorted and the locations to which it gets shipped, so for this reason, our Table 3 considers multiple distances.

Table 3. Benefits of Densifying EPS at Various MRF Distances



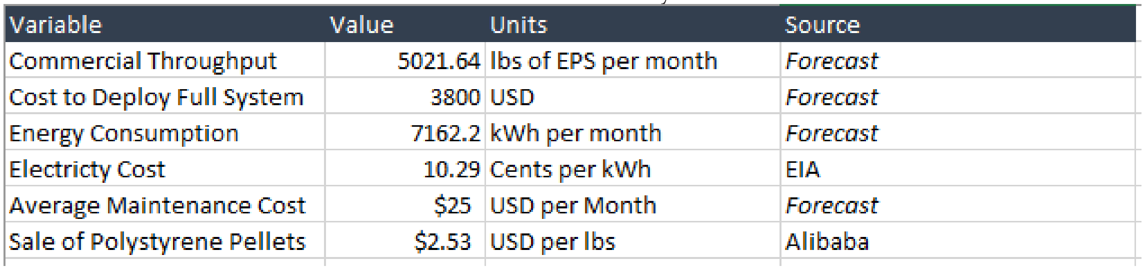
	Distance to MRF & 2.7*Landfill (miles)			
	10	69.5	100	150
EPS Generated (lbs/month)	1592.175	1592.175	1592.175	1592.175
Truckloads EPS	11.822	11.822	11.822	11.822
Truckloads PS	0.064	0.064	0.064	0.064
Cost to Landfill EPS (monthly)	$ 119.63	$ 585.96	$ 825.00	$ 1,216.88
Cost to Recycle PS (monthly)	$ 35.38	$ 42.23	$ 45.74	$ 51.49
Savings	$ 84.25	$ 543.73	$ 779.26	$ 1,165.38

(Constant Population, Distance to Landfill, Truck Size)

In an attempt to quantify how rural a town is, we considered a median town of 1,150 people that is located several distances from an MRF, where landfills are the same distance proportionally between the two averages. There are small towns in the range of 10 miles to 150 miles from an MRF all over the country, including New England (Recycling Partnership, 2020).

To identify the costs relating to a commercially viable design, we needed to make several determinations based on the team's experience.

Table 4. Commercial EPS Recycler Variables



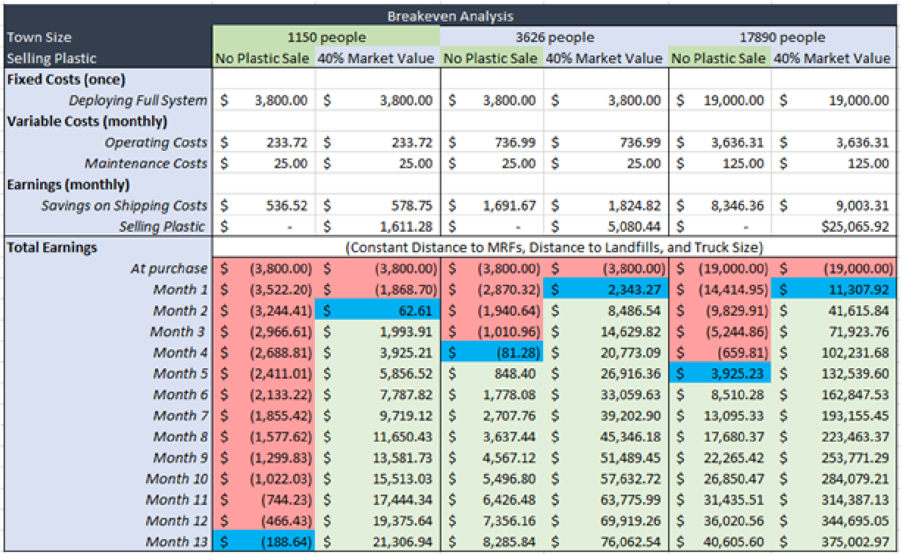
Variable	Value	Units	Source
Commercial Throughput	5021.64	lbs of EPS per month	*Forecast*
Cost to Deploy Full System	3800	USD	*Forecast*
Energy Consumption	7162.2	kWh per month	*Forecast*
Electricty Cost	10.29	Cents per kWh	EIA
Average Maintenance Cost	$25	USD per Month	*Forecast*
Sale of Polystyrene Pellets	$2.53	USD per lbs	Alibaba

The values marked as forecasts in Table 4 are estimations based on our experience with the prototype we designed. The 'Commercial Throughput' refers to how much EPS a final design might be able to process if it is designed at a price point of $3,800. The estimate is derived from processing an average of 3 cubic yards of EPS foam every hour during typical business hours throughout the year. The cost to a town, at that throughput, may be optimistic since it is based on materials, manufacturing, and delivery without regard to profit margins and operating costs for the company selling the machine.

The value for 'Energy Consumption,' however, is likely an overestimate, since it is derived from running the required power supplies at full capacity for the entire time of operation (scaled with throughput). Because the heating elements are insulated, and a commercial product would be more efficient with its power than our prototype, likely much less power would be needed. We believe the additional cost from this overestimation may still be spent in the form of related operating costs (water, cleaning, and loading and unloading the machine). In Table 5, the price generated by this calculation is simplified as 'Operating Costs.' The other variable cost is the projected 'Average Maintenance Cost' per month, which is a fairly arbitrary selection but helps ensure funds are allocated to replace nichrome wire and possible repair damages.

It is unlikely the output from the commercially viable recycling machine produces densified plastic attractive to buyers early in its implementation. However, after early adopters start using the machine and see significant results relating to quality of post-processed polystyrene, there is an existing market where towns could feasibly sell their plastic. The variable 'Sale of Polystyrene Pellets' is the minimum listed price of bulk pellets listed on a common source for plastic purchasing, Alibaba. In Table 5, we assume that - if plastic can be sold - the town would receive about 40% of that market value on post-consumer EPS that has been through our machine.

Table 5. Breakeven Analysis



Breakeven Analysis						
Town Size	1150 people		3626 people		17890 people	
Selling Plastic	No Plastic Sale	40% Market Value	No Plastic Sale	40% Market Value	No Plastic Sale	40% Market Value
Fixed Costs (once)						
Deploying Full System	$ 3,800.00	$ 3,800.00	$ 3,800.00	$ 3,800.00	$ 19,000.00	$ 19,000.00
Variable Costs (monthly)						
Operating Costs	$ 233.72	$ 233.72	$ 736.99	$ 736.99	$ 3,636.31	$ 3,636.31
Maintenance Costs	$ 25.00	$ 25.00	$ 25.00	$ 25.00	$ 125.00	$ 125.00
Earnings (monthly)						
Savings on Shipping Costs	$ 536.52	$ 578.75	$ 1,691.67	$ 1,824.82	$ 8,346.36	$ 9,003.31
Selling Plastic	$ -	$ 1,611.28	$ -	$ 5,080.44	$ -	$25,065.92
Total Earnings	(Constant Distance to MRFs, Distance to Landfills, and Truck Size)					
At purchase	$ (3,800.00)	$ (3,800.00)	$ (3,800.00)	$ (3,800.00)	$ (19,000.00)	$ (19,000.00)
Month 1	$ (3,522.20)	$ (1,868.70)	$ (2,870.32)	$ 2,343.27	$ (14,414.95)	$ 11,307.92
Month 2	$ (3,244.41)	$ 62.61	$ (1,940.64)	$ 8,486.54	$ (9,829.91)	$ 41,615.84
Month 3	$ (2,966.61)	$ 1,993.91	$ (1,010.96)	$ 14,629.82	$ (5,244.86)	$ 71,923.76
Month 4	$ (2,688.81)	$ 3,925.21	$ (81.28)	$ 20,773.09	$ (659.81)	$ 102,231.68
Month 5	$ (2,411.01)	$ 5,856.52	$ 848.40	$ 26,916.36	$ 3,925.23	$ 132,539.60
Month 6	$ (2,133.22)	$ 7,787.82	$ 1,778.08	$ 33,059.63	$ 8,510.28	$ 162,847.53
Month 7	$ (1,855.42)	$ 9,719.12	$ 2,707.76	$ 39,202.90	$ 13,095.33	$ 193,155.45
Month 8	$ (1,577.62)	$ 11,650.43	$ 3,637.44	$ 45,346.18	$ 17,680.37	$ 223,463.37
Month 9	$ (1,299.83)	$ 13,581.73	$ 4,567.12	$ 51,489.45	$ 22,265.42	$ 253,771.29
Month 10	$ (1,022.03)	$ 15,513.03	$ 5,496.80	$ 57,632.72	$ 26,850.47	$ 284,079.21
Month 11	$ (744.23)	$ 17,444.34	$ 6,426.48	$ 63,775.99	$ 31,435.51	$ 314,387.13
Month 12	$ (466.43)	$ 19,375.64	$ 7,356.16	$ 69,919.26	$ 36,020.56	$ 344,695.05
Month 13	$ (188.64)	$ 21,306.94	$ 8,285.84	$ 76,062.54	$ 40,605.60	$ 375,002.97

Based on these calculations, for towns located 69.5 miles away from an MRF and 25.4 miles away from a landfill, paying for an onsite recycling machine will produce a full return on investment within 13 months for towns as small as 1150 people. If plastic is sold to one of the dozens of companies that purchase scrap plastic, instead of shipped to a recycling center or landfill, the breakeven point occurs within 1 or 2 months for most small towns - quickly becoming a reliable source of income for the municipality.

4.1.2 SWOT Analysis

Onsite recycling and our prototype have several internal **strengths** that make it a viable investment for a town government. First, the cheap price-point makes achieving the savings in our model possible without high startup costs. Because municipalities already organize trash and recycling pickup, the transfer stations they use could perform material recovery on plastic that would otherwise be thrown out. Simply densifying before shipping provides substantial savings; even if the system is costly, it is still cheaper than shipping to the landfill.

If the prototype is ever developed commercially, there are some **weaknesses** that should be acknowledged and eventually overcome. A major challenge is the requirement for recycling to be sorted by hand. Without complex machinery, separating plastics automatically is beyond the scope of this project, so sorting is either left to the town or its citizens. Even if EPS is pre-sorted by citizens, there is still labor involved in running the machine and packaging densified EPS for shipment. While not out of the realm of work for the people already employed at transfer stations, these tasks could require hiring additional workers.

There are several **opportunities** for towns or companies that invest in onsite materials recovery. EPS which has been properly sorted, cleaned, and denisfied has potential to be a salable unit of plastic (Birch Plastics, 2019). There are dozens of companies that purchase scrap plastic, including polystyrene, and it is their general practice to pay for the plastic and entirely handle the logistics of shipping. Another opportunity involves an augmentation of the prototype's design to handle processing of additional plastic resins. Because the shredding and densification steps are both based entirely on the plastic coming in contact with heating elements, slight changes to voltage could enable the same heating elements to shred and reconstitute any form of plastic into salable ingots or pellets. This change would allow for municipalities to disassociate with traditional MRFs for all forms of plastic recovery, potentially turning large profits with scrap plastic.

The **threats** external to the design of the onsite recycling system can be encompassed in one primary challenge. Governments are slow to change. Because any venture developing a commercial small-scale recycler would end up doing business with rural governments, early adopters may be a very difficult segment. While some cities try to make a name for themselves by making bold decisions for the benefit of the environment, a small town has very little incentive to be early testers of this system.

4.2 Safety

In its raw form, polystyrene is not toxic or dangerous to humans. However, when heated, it releases irritating vapors that are harmful to human health.

4.2.1 Safety Concerns

When EPS is heated, the three main toxic products are styrene gas, benzene, and toluene. The majority of the other compounds released are carbon dioxide and water (The University of Tennessee, 2007). At high temperatures, vapors resulting from heated polystyrene cause irritation to the eyes and respiratory tract. There are no acute effects from skin contact, though at high temperatures, polystyrene can cause thermal burns. There are no known chronic health or carcinogenic effects caused by prolonged exposure to polystyrene (Videolar, 2008).

4.2.1.1 Irritating Vapors

The irritating vapors created by melting polystyrene have negative health implications with short- and long-term exposure. When inhaled, styrene gas is 1,000 times more concentrated than when found in the environment and affects the nervous system, causing visions changes, tiredness, slow reactions, less concentration, and problems balancing. The Department of Health and Human Services (DHHS), National Toxicology Program (NTP), and International Agency for Research on Cancer (IARC) all classify styrene as a likely carcinogen. Once styrene enters the environment, it is broken down by microorganisms in water or soil, or in air after 1 to 2 days (Agency for Toxic Substances and Disease Registry, 2015).

Inhaled benzene can cause tiredness, dizziness, confusion, rapid heart rate, and unconsciousness. Particularly high levels of benzene in air, between 10,000 and 20,000 parts per million (ppm), can cause death within 5 to 10 minutes. Ingesting low concentrations of benzene does not have immediate health effects, but at high concentrations, dizziness, tiredness, stomach irritation, vomiting, coma, and death are possible. Skin contact with benzene causes redness and sores. Benzene is a known carcinogen according to the DHHS, EPA, and IARC. While it degrades naturally in the environment after a few days, the preferred disposal method is combustion (Agency for Toxic Substances and Disease Registry, 2007).

Toluene affects the nervous system, with short term exposure causing dizziness, tiredness, memory loss, coordination loss, and nausea. Continued exposure can cause these symptoms to become permanent, as well as other health problems such as brain, liver, kidney, immune system, and reproductive system damage. The DHHS, EPA, and NTP do not classify toluene as a carcinogen. When toluene is released into the environment, it either evaporates rapidly in air or degrades in soil or water with the help of microorganisms. For high concentrations of the substance, the preferred method of disposal is combustion (Agency for Toxic Substances and Disease Registry, 2017).

With the quantities of EPS heated in our recycling process, only minute amounts of these chemicals will be released. At these levels, we are confident that an operator's health will not be adversely affected.

4.2.2 Air Pollution

Under extreme conditions, the release of irritating vapors during the recycling process can harm the environment by polluting the surrounding air. However, the operating conditions of this device should be controlled such that the vapors produced do not negatively impact the environment.

4.2.2.1 Volatile Organic Compounds

Most literature values for emissions from polystyrene extrusion are for the large-scale manufacturing processing of polystyrene, which can be applied to the extrusion of clean, recycled EPS. Production of volatile organic compound emissions is based on facility size, the process used, and the molecular weight of polystyrene produced. Lower molecular weight polystyrene will produce higher emission rates. Total volatile organic compounds (VOC) from polystyrene production for a plant with two batch reactors has an estimated emission range of 0.6 to 2.5g VOC/kg of product (U.S. Environmental Protection Agency, 1995). The small scale of our design and our goal of extruding dense polystyrene would produce significantly lower emissions in our commercial design. This indicates that for the extrusion process, no significant emissions will occur. No VOC control devices are typically used in batch polystyrene plants, and so our onsite recycling machine does not need one either.

4.2.2.2 Styrene Gas Emission

Styrene gas emissions contribute to air pollution because they decompose into carbon dioxide in the environment. In a typical polystyrene production plant, the emissions of styrene are 0.8-4.2 lb styrene/ton (Radian Corporation, 1993). As the machine involves a small-scale batch recycling process, the potential emissions are much lower than the rate reported above, and air pollution should not be a major concern.

5. Conclusion

Expanded polystyrene, a plastic material that *could* be recycled, is not accepted in curbside recycling programs in the United States and comprises 35% of landfills by volume. The waste management system currently in place incurs enormous shipping costs for simply transporting EPS to be processed. Neglecting to recycle material because it wastes resources and induces enormous monetary loss are no longer excuses to continue to destroy our world, and consequently, our quality of life. An innovative solution to solve the current issues with recycling waste management is crucial to countering this ever-increasing problem.

The team designed and developed a working prototype able to process EPS in order to help save our environment by reducing the 137 million tons of waste that annually flood landfills across the United States. This astronomical amount exists because humans have had the ingenuity and the audacity to produce new materials, just as nature does, but have not matched its capabilities in creating a sustainable life cycle for them.

We gave birth to the early stages of plastic's life cycle, but we abandoned the cycle before developing a post-consumer processing method. In that, we are harming the environment with our plastic waste, which snuffs out plastic's potential to aid us in our daily lives while allowing it to work towards our demise as a species.

The work we did in this academic year led to an actionable and economical solution to recycling that protects ecosystems and works toward healing the earth. By decentralizing the recycling process, we give power to citizens to ensure waste is controlled. Our prototype stands as proof that neglecting EPS in mainstream material recovery is unforgivable.

Recycling onsite, in the very same location that waste is generated, will connect us as a society to become actively engaged and invested in our environment and spur us to take responsibility for the materials we produce. This project makes great strides in simplifying the recycling process and creates a systematic method for recycling a material that otherwise becomes pollution. Plastic waste is a real problem, and this prototype not only completes the life cycle of plastic for EPS, but makes way for a final repurposing stage so that we, as a global community, may never cease to thrive.

References

Agency for Toxic Substances and Disease Registry. (2012) Public Health Statement for Styrene. Retrieved from https://www.atsdr.cdc.gov/phs/phs.asp?id=419&tid=74

Agency for Toxic Substances and Disease Registry. (2007) Toxicology Profile for Benzene. Retrieved from https://www.atsdr.cdc.gov/toxprofiles/tp3.pdf

Agency for Toxic Substances and Disease Registry. (2017) Toxicology Profile for Toluene. Retrieved from https://www.atsdr.cdc.gov/toxprofiles/tp56.pdf

Agency for Toxic Substances and Disease Registry. (2015) Public Health Statement for Carbon Monoxide. Retrieved from https://www.atsdr.cdc.gov/phs/phs.asp?id=1146&tid=253

Alibaba (2020). ROSH Injection Molding Electronic Components black high impact polystyrene hips pellets. Retrieved from https://www.alibaba.com/product-detail/ROSH-Injection-Molding-Electronic-Components-black_60087451375.html?spm=a2700.galleryofferlist.0.0.3cf7d281XnfEiD&s=p

American Transportation Research Institute. (2018). An Analysis of the Operational Costs of Trucking: 2018 Update. Retrieved September 8, 2019 from https://atri-online.org/wp-content/uploads/2018/10/ATRI-Operational-Costs-of-Trucking-2018.pdf

The Association of Plastic Recyclers. (n.d.). Foam PS Recycling Best Practices Guide [PDF file]. Retrieved September 5, 2019 from https://plasticsrecycling.org/images/pdf/Toolkits/Foam_PS/Foam_PS_Recycling_Best_Practices.pdf

Bay Disposal (2019). Recycling Responsibly: What Types of Plastic are Recyclable? Retrieved September 5, 2019, from https://www.baydisposal.com/recycling-responsibly-types-plastic-recyclable/

Columbia University. (2000). Design of a Materials Recovery Facility (MRF) For Processing the Recyclable Materials of New York City's Municipal Solid Waste. Retrieved September 8, 2019 from http://www.seas.columbia.edu/earth/dubanmrf.pdf

Compactor Management Company Northern California Compactors Inc. (2019). All About Plastic Shredders: From Applications to Advantages. Retrieved September 8, 2019 from https://www.norcalcompactors.net/all-about-plastic-shredders-from-applications-to-advantages/

Cowan, S. (2012). Plastics by the Numbers. Retrieved September 5, 2019, from https://learn.eartheasy.com/articles/plastics-by-the-numbers/

DartContainerCorp. (2016, March 25). Plastic Recycling, Inc. recycles foam #6 from a MRF [Video]. YouTube. https://www.youtube.com/watch?v=CtNk7VownCc

Earth Institute, Columbia University. (2017) What Happens to all that Plastic. Retrieved from https://blogs.ei.columbia.edu/2012/01/31/what-happens-to-all-that-plastic/

EIA (2020). Electricity Data - Electric Power Monthly. Retrieved from https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a

EPA. (2018). Advancing Sustainable Materials Management: 2015 Fact Sheet . U.S. Environmental Protection Agency. Retrieved September 6, 2019, from https://www.epa.gov/sites/production/files/2018-07/documents/2015_smm_msw_factsheet_07242018_fnl_508_002.pdf

EPA. (2016). Improving Recycling's Economic Profile | Tools for Local Government Recycling Programs. U.S. Environmental Protection Agency. Retrieved September 6, 2019, from https://archive.epa.gov/wastes/conserve/tools/localgov/web/html/collection.html

EPA (2006). Standard Volume to Weight Conversion Factors. Retrieved, from https://www.epa.gov/sites/production/files/2016-03/documents/conversions.pdf

EcoMENA (2019). Introduction to MRF. Retrieved September 5, 2019, from https://www.

ecomena.org/materials-recovery-facility/

EREF Study Reveals Increase in Average MSW Landfilling Tipping Fee. (2017, December 20). Waste360 (Online). Retrieved from http://search.proquest.com/docview/1984706052/

Federal Highway Administration. (n.d.). Comprehensive Truck Size and Weight Study. Retrieved September 9, 2019 from https://www.fhwa.dot.gov/reports/tswstudy/Vol2-Chapter3.pdf

Health and Safety Executive. (n.d.). Waste management and recycling. Retrieved from http://www.hse.gov.uk/lung-disease/waste-management-recycling.htm

Interesting Engineering. (2016) Polystyrene Concrete: A Versatile Construction Alternative. Retrieved from https://interestingengineering.com/polystyrene-concrete-construction-alternative

Jambeck, J. R. (2015). Plastic waste inputs from land into the ocean. Science Magazine, 347(6223), 768–771. Retrieved September 15, 2019 from https://science.sciencemag.org/content/sci/347/6223/768.full.pdf

Jordan Reduction Solutions. (2018). The Difference Between Shredding, Grinding and Granulating. Retrieved September 8, 2016 from https://www.jordanreductionsolutions.com/blog/the-difference-between-shredding-grinding-and-granulating/

Mehta, S., Biederman, S., & Shivkumar, S. (1995). Thermal degradation of foamed polystyrene. Journal of Materials Science, 30(11), 2944–2949. doi: 10.1007/bf00349667

National Research Council Canada. (1971) Toxic Gases and Vapours Produced at Fires. Retrieved from http://web.mit.edu/parmstr/Public/NRCan/CanBldgDigests/cbd144_e.html

Oregon Public Broadcasting. (2011). Recycling Plant Among Top Northwest Polluters. Retrieved from https://www.opb.org/news/article/northwest-air-pollution-violators-generate-fines/

Offenhuber, D., Wolf, M., & Ratti, C. (2013). Trash track – active location sensing for evaluating e-waste transportation. Waste Management & Research, 31(2), 150–159. Retrieved from https://doi.org/10.1177/0734242X12469822

Perpetual Plastic Project. (2014) Plastic Identification and Separation. Retrieved from http://www.perpetualplasticproject.com/blog/2014/3/25/plastic-identification-separation

Report on Blended Commodity Values in the Northeast. (2019). Northeast Recycling Council. Retrieved from https://nerc.org/documents/Recycling Market Development/Blended_Commodity_Values_in_the_Northeast - August_2019.pdf

Recycling Partnership. (2020). Residential MRFs. Retrieved from https://recyclingpartnership.org/residential-mrfs/

RETSCH. (n.d.). Size Reduction with Knife and Cutting Mills. Retrieved September 8, 2019 from http://www.macrolab.com.ua/pdf/brochure_cutting_mills_en.pdf

Sell Scrap Plastic, We Recycle Plastic For Cash | Birch Plastics. (2019). Birchplastics.com. Retrieved 9 October 2019, from https://www.birchplastics.com/plastic-recycling/sell-your-scrap-plastic

Techniques for Cellular Foam. Retrieved September 9, 2019 from https://trace.tennessee.edu/cgi/viewcontent.cgi?referer=https://www.google.com/&httpsredir=1&article=1353&context=utk_graddiss

TOMOE Engineering Co., Ltd. (n.d.) Mechanism of Centrifugal Separator. Retrieved from https://www.tomo-e.co.jp/machinery/english/centrifuge/separation.html.

The University of Tennessee. (2007). Degradation Mechanism of Expanded Polystyrene (EPS) Foam in Lost Foam Casting, PIPS Approach for Synthesis and Novel Expansion

U.S. Census Bureau. (2018) City and Town Population Totals: 2010-2018. Retrieved from https://www.census.gov/data/tables/time-series/demo/popest/2010s-total-cities-and-towns.html#tables

Videolar. (2008) Polystyrene (General Purpose) MSDS. Retrieved from https://www.che.iitb.ac.in/online/system/files/545/chemical_msds_entry/polystyrene+MSDS_0.pdf

WIT Conferences. (2016) Understanding Recycling Behavior: a Study of Motivational Factors Behind Waste Recycling. Retrieved from https://www.witpress.com/Secure/elibrary/papers/WM16/WM16036FU1.pdf

Xin, Z., Tsuda, T., and Doi, H. (2017). Evaluating the Effects of Air Pollution from a Plastic Recycling Facility on the Health of Nearby Residents. Acta Medica Okayama. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/28655940

Radian Corporation. "Locating and Estimating Air Emissions from Sources of Styrene." EPA.gov, United States Environmental Protection Agency, 20 Apr. 1993, https://www3.epa.gov/ttnchie1/le/styrene.pdf.

Environmental Protection Agency. "Air Emissions Factors and Quantification." United States Environmental Protection Agency, United States Environmental Protection Agency, Jan. 1995, https://www3.epa.gov/ttn/chief/ap42/ch06/index.html.