Life cycle analysis of distributed recycling of post-consumer high density polyethylene for 3-D printing filament

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ABSTRACT

The growth of desktop 3-D printers is driving an interest in recycled 3-D printer filament to reduce costs of distributed production. Life cycle analysis studies were performed on the recycling of high density polyethylene into filament suitable for additive layer manufacturing with 3-D printers. The conventional centralized recycling system for high population density and low population density rural locations was compared to the proposed in home, distributed recycling system. This system would involve shredding and then producing filament with an open-source plastic extruder from post-consumer plastics and then printing the extruded filament into usable, value-added parts and products with 3-D printers such as the open-source self replicating rapid prototyper, or RepRap. The embodied energy and carbon dioxide emissions were calculated for high density polyethylene recycling using SimaPro 7.2 and the database EcoInvent v2.0. The results showed that distributed recycling uses less embodied energy than the best-case scenario used for centralized recycling. For centralized recycling in a low-density population case study involving substantial embodied energy use for transportation and collection these savings for distributed recycling were found to extend to over 80%. If the distributed process is applied to the U.S. high density polyethylene currently recycled, more than 100 million MJ of energy could be conserved per annum along with the concomitant significant reductions in greenhouse gas emissions. It is concluded that with the open-source 3-D printing network expanding rapidly the potential for widespread adoption of in-home recycling of post-consumer plastic represents a novel path to a future of distributed manufacturing appropriate for both the developed and developing world with lower environmental impacts than the current system.

1. Introduction

Plastic has become an integral part of society as population growth and technological development have resulted in the global production of plastic increasing by 500% over the last 30 years and it is expected to continue to grow to 850 million tons per year by 2050 (Lebreton et al., 2012; Lotfi, 2009; Shen et al., 2009). In addition to food packaging and cheap parts, plastics are now being used to replace metal, wood, paper, and glass in a variety of engineering applications (Arena et al., 2003), mulch (McCraw and Motes, 2012), sports fields, and even human body parts (Bow and Parvizi, 2011; Xue, 2011). This increase in plastic usage results in a substantial environmental burden on both land (Rees, 1980) and water pollution (Derraik, 2002) as plastics are slow to decompose naturally — taking from 10 to 450 years in a landfill (U.S. National Park Service, 2012) and toxic to burn (Lewis and Sullivan, 1992). Plastic processing, use, and disposal also comprise a significant source of energy consumption (Björklund, 2005; Rydberg, 1995; Song and Hyun, 1999). This has been largely determined from life cycle analysis studies of plastic (Arena et al., 2003; Reich, 2005) and recycling (Craighill and Powell, 1994; Perugini et al., 2005; Powell,

1996; Ross and Evans, 2003; Subramanian, 2000). First, plastics can be regarded as a form of stored potential energy as each year producing virgin plastics requires 4% of the world's oil production (Cambridge-MIT Institute, 2005) equivalent to 1.3 billion barrels a year (U.S. EIA, 2011) equivalent to the amount of oil Texas used in 2010 (U.S. EIA, 2010). As the cost of oil is expected to escalate due to rising energy prices it is likely companies will look for alternative feedstocks (Chemical Engineering Progress, 2008), thus there are both strong environmental as well as economic interests in large-scale recycling of plastics (Lotfi, 2009).

Today seven types of plastics are commonly recycled including: 1) polyethylene terephthalate (PET), 2) high-density polyethylene (HDPE), 3) polyvinyl chloride (PVC), 4) low-density polyethylene (LDPE), 5) polypropylene (PP), 6) polystyrene (PS), and 7) "other", which is primarily polycarbonate (PC) and acrylonitrile butadiene styrene (ABS). Both primary and secondary recycling schemes are well established and widely applied (Al-Salem et al., 2009). Historical trends in polymer recycling have been towards large centralized facilities to take advantage of economies of scale in producing low-value commodities (Missouri DNR, 2012; Redd, 1993). One of the primary reasons that plastic has historically been recycled at very low rates (e.g. 6.5% in 2008) in conventional centralized recycling in the U.S., is the challenge of collection and transportation for high volume, low weight polymers (Themelis et al., 2011). Thus, plastic recycling is often not economical and when it is recycled, the collection is 'subsidized' by higher value recycled content material such as aluminum (Hood, 1995).

Two recent open-source hardware technological developments, 3-D printers and RecycleBots, offer a new approach to polymer recycling encompassing the potential for distributed processing to high-value added products, which reverses the historical trend towards centralized recycling facilities. Commercial 3-D printers, which allow for accurate fabrication of products or scale models, are a useful production and design tool. 3-D printers allow for additive manufacturing, which is a process by which digital 3-D designs are used to build a component in layers by depositing material (Crane et al., 2011; Gebhardt et al., 2010; Gibson et al., 2010). This is to differentiate it from subtractive (and thus normally more wasteful methods) or conventional polymer manufacturing methods like plastic injection molding (Peças et al., 2009). The development of additive manufacturing for rapid prototyping and 3-D printing in a number of technologies has been substantial (Petrovic et al., 2010; Upcraft and Fletcher, 2003). Recently, following the open source (OS) model, the RepRap has been developed that can be built for under $500, greatly expanding the potential user base of 3-D printers. Between 2008 and 2011, it is estimated that the number of RepRaps in use had increased from 4 to 4500 (Sells et al., 2011). These machines could feasibly be used for small-scale manufacturing or as an enabling tool for green manufacturing (Kreiger and Pearce, 2013a, 2013b; Pearce et al., 2010). The primary expense of operating a 3-D printer is the filament or "3-D ink" and thus the operating costs of the RepRap can be further reduced using post-consumer plastics as feedstock.

Commercial extrusion of plastic utilizes a screw to move material through a heated barrel where it is compressed, melted, mixed and forced through a die (Rosato, 1997). One such device, which turns post-consumer plastic into a growth medium for plants (Torcellini, 2010), has been modified here to create a new, semi-automated open source "Recyclebot" to prepare RepRap feedstock from post-consumer household plastic, such as, bottles and laundry detergent containers (Baechler et al., 2013). Researchers throughout the world have attempted to adapt these principles and construct small-scale plastic extruders with varying degrees of success (Braanker et al., 2010; Kreiger et al., 2013; RecycleBot, 2010). As the RecycleBot is an open-source project

there are several other variants under development: the Lyman Filament Extruder (Lyman, 2012), the work of the Perpetual Plastic Project, the Filabot (McNaney, 2012), and the MiniRecycleBot (MiniRecyclebot, 2012), which could be utilized as post-consumer plastic RecycleBots. Bad prints, broken or worn out parts can also be recycled by this method. There is also work currently being done in the open-source community on the creation of a shredder designed to be used with the RecycleBot system. These open-source shredders are capable of shredding entire milk jugs or other recyclables. Their use, in place of a commercial paper shredder, would remove the need for cutting bottles by hand, thus reducing processing time (Thymark, 2012). The use of an open-source shredder would also increase the usable mass of post-consumer plastic containers.

Fabrication of feedstock with RecycleBots from post-consumer plastic also has the potential to reduce the environmental impact of 3-D printing, and may provide an incentive for distributed, in-house recycling of plastic (Pearce et al., 2010). Baechler et al. (2013) have demonstrated acceptable 3-D filament production from a RecycleBot using high density polyethylene (HDPE). HDPE, recycled plastic number "2", is used primarily for non-food packaging, pipes, and plastic lumber. In 2010, 984 million pounds of HDPE were recycled in the U.S. (American Chemistry Council and Association of Postconsumer Plastic Recyclers 2011), which is 27.8% of the HDPE produced (Sandhill Plastic, 2010). The total energy used annually to produce virgin HDPE is 124 billion MJ. Grant and James (2005) showed the embodied energy of recycled HDPE is 24% less than virgin plastic using their cut-off method of life cycle analysis (LCA), indicating that in there is an enormous waste of energy and material resources from not recycling HDPE.

This study explores this technical potential of using a distributed network of RecycleBots to process post-consumer goods into 3-D printing feedstock. To demonstrate the feasibility of this approach, HDPE is used as a test material. The LCA of energy consumption and carbon dioxide (CO_2) emissions is determined for this distributed approach and are compared to the standard centralized model. A sensitivity analysis is performed on two case studies comparing both the best and worst case scenarios in Michigan of geographic distribution of post-consumer plastic from a centralized facility. These results are discussed and a preliminary financial analysis is performed to draw conclusions about the viability of distributed recycling.

2. Methods

The goal of this study is to determine whether the use of a RecycleBot to create 3-D printing filament using HDPE is an environmentally feasible alternative to conventionally recycling HDPE. The cases looked at were distributed recycling using the RecycleBot and three cases for conventional recycling: highly populated area, low population area with biweekly recycling trips, and low population area with monthly trips for recycling. The other cases were then compared to the literature value of average embodied energy of virgin HDPE feedstock (Hammond and Jones, 2008). The scope of this life cycle analysis will be limited to inputs for the processing due to recycling using the RecycleBot versus conventional recycling. The functional unit is 1 kg of recycled HDPE usable for either 3-D printing or conventional manufacturing processes. The inventory data associated with these inputs will embody a "gate-to-gate" system boundary, with the gate starting at the end of first useful life of the HDPE within the consumer's home and ending immediately after production of a recycled filament or pellet. These results will be compared and used with previous LCA results on HDPE recycling from literature, to quantify the difference in energy demand and greenhouse gas emissions. SimaPro v 7.2 in
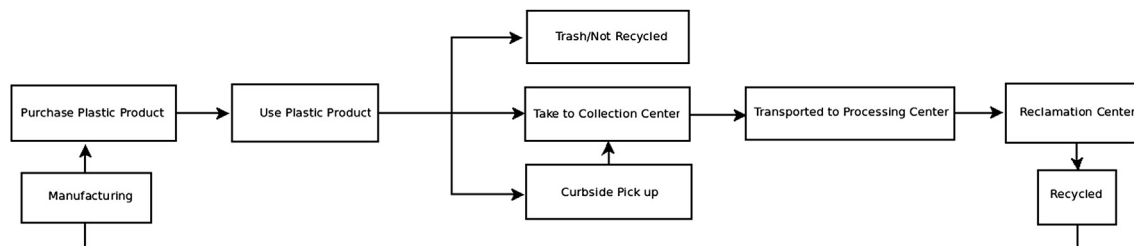
Fig. 1. Schematic of conventional HDPE recycling.

conjunction with the EcoInvent v 2.2 database of materials, was used to complete an energy and emissions LCA of a distributed recycling (RecycleBot) versus conventional recycling. Cumulative energy demand (CED) was used to analyze the overall energy costs and the model developed by Intergovernmental Panel on Climate Change in 2007 for the global warming potential over a 100-year time period, IPCC 2007 GWP 100a, was used to calculate the CO_2 equivalent emissions for the recycling comparison (Pachauri and Reisinger, 2007; Hischier et al., 2010).

The LCA began with collection and transportation of post-consumer plastic through the recycling process as indicated for the conventional recycling process shown in Fig. 1. For the distributed recycling process, the LCA was calculated for the plastics from transportation through filament drawing in the RecycleBot as seen in Fig. 2. LCAs were completed for both processes using a best and worst case scenario outlining the maximum and minimum collection distances in the U.S.

As shown in Fig. 2, for the distributed recycling case post-consumer plastic is first collected in the home and cut with scissors to be fed into a commercial paper shredder. The mass of the usable plastic was measured on a digital scale (±0.05 g). This method produces 49 g of usable mass (87% of total mass) of a milk jug, thus 20 jugs/kg. These shreds are then fed into the post-consumer plastic extruder (RecycleBot)[1], which melts them and forms a 3 mm filament that is then used in a RepRap or other 3-D printer, as detailed in Baechler et al. (2013) and Kreiger et al. (2013). The RecycleBot used in this study had improved insulation (1.5 inch high-temperature calcium silicate wrapped in kapton tape) compared to no insulation (Baechler et al., 2013) and modest insulation (Kreiger et al., 2013).

The energy consumption of the distributed recycling process was quantified experimentally using a multimeter (±0.005 kWh) that monitored an insulated RecycleBot during extrusion of 10 m and averaged. Data was recorded for each stage of filament production, including shredding (kWh/g), auger drive, heating and a filament spooler, however previous work showed that the shredding even in an uninsulated RecycleBot was negligible and was ignored here (Baechler et al., 2013). The experimental value was then put into SimaPro using the input (Electricity, Production Mix, US).

In the conventional recycling process (Fig. 1), after a plastic product is purchased and used if it is recycled it is collected at curbside and transported to a collection center. At the collection center, HDPE is sorted to produce bales. After separation the HDPE bales are sent to a reclamation facility to be purified and pelletized to be sold to manufacturers to create new goods.

An example of a "best case scenario" for conventional recycling is a city like Detroit, Michigan, where there are four collection centers in metro Detroit, as well as curbside pickup, which funnel into one processing center (Horton, 2009) for greater Detroit, as shown in Fig. 3. After separation at the processing center, the plastic bales are sent to BATA plastics in Grand Rapids, Michigan, 157 miles away, where the bales are made into quality pellets and sold to manufacturers for re-use. It is assumed that the curbside recycling trucks are never at capacity and would make the curbside pickup without the collection of post-consumer plastic and that the additional weight of the plastic would have a negligible effect on the fuel efficiency of the collection vehicles. Therefore only the embodied energy of transportation and emissions due to the transport from the collection centers to the processing center were included and normalized per unit mass.

A life-cycle inventory study of conventional recycling of HDPE was previously completed using confidential information from recycling companies to quantify the impact and energy demand (Franklin Associates, 2011) and was used as an approximation here. This literature evaluated the recycling system in California using confidential information from material recovery facilities, plastic recycling facilities, and HDPE reclaimers. Aspects not included in the literature consist of capital equipment, space conditioning, support personnel requirements, and miscellaneous materials and additives and thus will not be used in this study either. The values used for quantifying the conventional recycling were taken from the literature value for "cut-off weight based" result for the recycling of post-consumer HDPE, this method does not take the original burden of the first life of the product into account and does calculations by weight instead of volume. The value for the cumulative energy demand was 3.87 MMBtu per 1000 lbs. As this value was originally MMBtu for 1000 lbs, it was converted to kilograms then divided to represent 1 kg, and then the result was converted from MMBtu to MJ. A similar unit conversion was also done for the greenhouse gas emissions. These values are for biweekly recycling drop-offs.

For the "worst case scenario" for centralized recycling, which represents a low population density, small, geographically isolated town of Copper Harbor, Michigan was used. Located at the top of the Keweenaw Peninsula, Copper Harbor is a 48 mile drive north of the nearest recycling collection center in Houghton, Michigan and there is no curbside pickup. From Houghton, Michigan the plastics are then driven in a garbage truck to Green Bay, Wisconsin, 212 miles away, to the processing center. The average household generates 16.9 pounds of recyclables per week (U.S. EPA, 2010). The average amount of HDPE post-consumer waste, out of the total amount of recyclables, is approximately 5.2 pounds or 31% (Franklin Associates, 2011). For this case, two options are considered, recycling biweekly or monthly. The inputs used in SimaPro for conventional recycling were (Operation, passenger car, petrol, fleet average, 2010, Switzerland) for the round trip drive from Copper Harbor to Houghton, Michigan, (Operation, lorry 3.5–20 t, full, fleet average, Switzerland) for the drive from Houghton to Green Bay, Wisconsin, and a similar input for an empty truck for the return trip to Houghton. Assuming the average load for the truck was
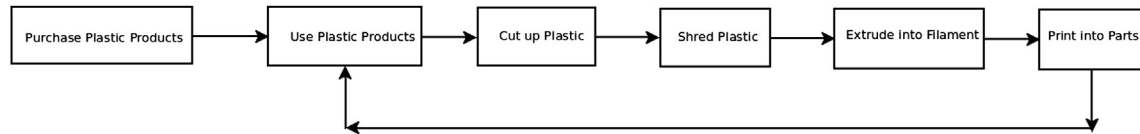

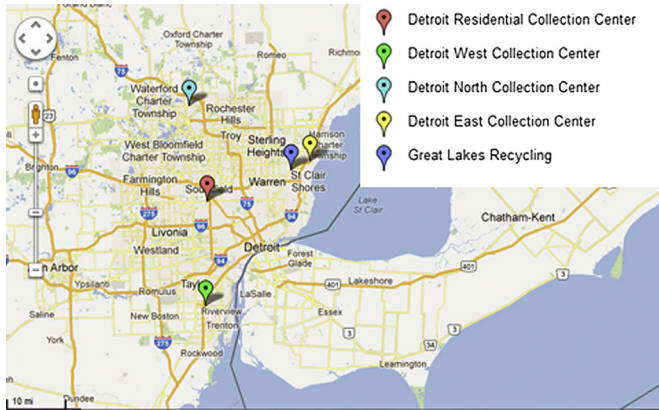Fig. 2. Schematic of distributed HDPE recycling.

Fig. 3. Map of Detroit recycling collection centers and great lakes recycling center.

38,990 lbs and a contamination amount of 8% (Franklin Associates, 2011). The energy was divided out based on the mass (kg) hauled, under the conservative assumption that hauling the recyclable materials does not change the fuel efficiency of the vehicle. The result from the person-km is multiplied by the fraction of HDPE over the total weight of recyclable materials in the trunk (16.9 lbs/wk). This result is multiplied to provide 1 kg of HDPE +8% waste so the end result is MJ/kg useable HDPE. To summarize: the "person" in the person-km is "one trunk load" and then the value adjusted to account for how much of that trunk is allocated to HDPE, and finally how many of those portions are necessary to obtain the functional unit of "1 kg of recycled HDPE". The life-cycle inventory study of conventional recycling of HDPE (Franklin Associates, 2011) was used again as an approximation here for the processing burdens. Similarly to the "best-case" conventional recycling, the values used for quantifying the "worst-case" conventional recycling were taken from the literature values for the "cut-off weight based" result for the recycling of post-consumer HDPE. The value used for this scenario was for processing only, leaving 7.51 MJ per kg HDPE recycled. From here, the collection and transportation amount calculated in this study was added onto the process amount to achieve the total amount of cumulative energy demand. This was then similarly for the greenhouse gas emissions.

3. Results

Table 1 summarizes the results of the embodied energy and greenhouse gas emissions for centralized and distributed recycling of HDPE in the high population density and low population density cases. The embodied energy values can be compared directly.

The RecycleBot required an initial heating provided by 0.06 kWh before starting any extrusion and a running requirement of 0.0036 kWh per meter of filament produced. The initial heating amount is applied to the production of 1 kg filament output and is assumed to overburden this process; this amount would realistically be allocated over the entire amount produced. As the mass per unit length of HDPE is 5.64 g/m, a kg of HDPE is 177.3 m of filament. The total energy use for filament production (including shredding,

melting and extrusion) is 0.694 kWh per kg HDPE filament, which is about 2.5 MJ/kg. In comparison, the average embodied energy of virgin HDPE feedstock is 79.67 MJ/kg (Hammond and Jones, 2008). It should be noted that this figure for conventional processing is HDPE material alone and there may be additional embodied energy for forming filament acceptable for 3-D printing. Despite this it is clear from the results that using distributed recycling reduces embodied energy of HDPE over virgin material by 89%. The RecycleBot's greenhouse gas emissions were calculated using SimaPro IPCC 2007 GWP for 100 years, with the only input being the electricity production mix of the U.S. It should be pointed out here that extreme care is necessary in comparing the greenhouse gas emissions shown in Table 1. The kg CO_2 eq per kg HDPE is heavily dependent on the emission intensity of the grid where the case is run. Previous work by Kreiger et al. showed that using low-emission intensity solar photovoltaic devices for distributed electrical generation for distributed recycling significantly reduces overall emissions for HDPE filament fabrication (2013).

There is also an apparent discrepancy between the energy demand and GHG emissions for recycled and virgin resins; as the former differ by an order of magnitude and the latter by a few percent. The reason for the difference in magnitude between the energy demand and the emissions is that the recycled HDPE does not include the energy content of the materials that end up in the product, but the energy content of any fuels or electricity inputs to the recycling process are included. Whereas, the virgin HDPE counts the energy content of the resources from nature (e.g crude oil and natural gas) that go directly into the HDPE plus the energy content of any fuels or electricity inputs used for the conversion processes. Since the natural resources used to make virgin HDPE are not used as fuel, the emissions are not released, thus the difference in magnitude.

Table 1
Energy demand & greenhouse gas emissions.

Case	Energy demand (MJ/kg HDPE)	Percent reduction (%) for distributed Recycling[c]	Greenhouse gas emissions (kg CO_2 eq per kg HDPE)
Distributed Recycling: Insulated RecycleBot	8.74	–	0.52
Virgin Resin	79.67[a]	89	1.82[b]
Centralized Recycling – High Density Population: Detroit	9[b]	3	0.63[b]
Centralized Recycling – Low Density Population: Copper Harbor (monthly)	28.4	69	2.65
Centralized Recycling – Low Density Population: Copper Harbor (bi-weekly)	48.9	82	4.04

Notes.
[a] (Hammond and Jones, 2008).
[b] Estimate based on (Franklin Associates, 2011).
[c] Percent reduction = (Central-Distributed)/Central*100.

The amount of energy for the conventional cases attributes 7.51 MJ eq from the recycling process and transport needed between each step (Franklin Associates, 2011), while the remainder is from transportation due to collection and from the collection center to the processing center. As can be seen in Table 1, when comparing the centralized recycling for low density population on either a biweekly or monthly recycling trip case, the distributed recycling can decrease the embodied energy by 69%–82%. In addition, even with varying emission intensities it is clear the distributed recycling is beneficial from an ecological standpoint. In these low population density cases the embodied energy and emissions for the personal transportation of the HDPE to a collection facility have a substantial impact on the LCA values and is added to the values for the complete process in the high-population density case. Every 2 weeks every kg of HDPE consumes 41 MJ from the round-trip drive from Copper Harbor to Houghton, Michigan. This amount of energy for simple collection dwarfs the entire embodied energy of a high population density centralized recycling or the distribute recycling cases. The use of conventional recycling in this rural case is worse for the environment in terms of energy use and emissions than creating all new products from virgin resin. For such locations, these values of transport can only be reduced by transporting more recyclable materials per trip. Thus, if one month of the total amount of post-consumer recyclables could fit in the vehicle, this results in an energy consumption of 20.5 MJ/kg HDPE for collection and thus a total embodied energy of only 28.4 MJ/kg, which is again about one third of that of virgin material.

4. Discussion

The results clearly show that distributed recycling of HDPE uses less energy than conventional recycling. If the population density is spread out these reductions can be significant ∼70% reduction, but even in the best case scenario for conventional recycling it still uses 3% more energy than distributed recycling. A 3% reduction should be looked at with caution as there is a 0.5% error in experimental measurement and a small improvement in conventional recycling can outweigh this amount for the ideal case. It should be noted that a switch to renewable energy can reduce these numbers. If the 984 million pounds of HDPE that are currently recycled in the U.S. per year in the best case for conventional recycling are instead diverted to distributed recycling, would result in the saving of 116,000,000 MJ of energy, equivalent to the energy used by more than 2800 American household's per year (U.S. EIA, 2011). However, it can be presumed that as the economic value of producing 3-D filament from household recycling became widespread the recycling rate could also be increased from the current value of less than a third. If the total HDPE supply was recycled using the distributed process, offsetting all virgin HDPE, over 100 billion MJ could be conserved per year.

This study is a conservative estimate of the benefits of distributed recycling, because the commercial pellets used for the comparison of the centralized case would then have to be further formed into filament. However, the same raw feedstock could be used directly to make filament rather than pelletizing (e.g. the same polymer melter/auger machine could be used to make filament with a spooler). The energy associated with the spooler or the pellet cutter is negligible when compared to melting the plastic (Baechler et al., 2013). It was therefore conservatively assumed the two processes are equivalent.

The distributed recycling advantage comes from both the low-overhead equipment cost of the RecycleBot and the complete elimination of embodied energy for transportation, which, as can be seen in the Copper Harbor examples, can be substantial. It is clear that recycling of HDPE should occur as close to the source of

plastic waste as possible with the largest load and lowest fuel consumption to reduce environmental impact. The results for both embodied energy and emissions show that for cases where the user is far from a recycling center, it is significantly better for the environment to do on-site recycling using a RecycleBot, than to use conventional recycling of any kind. If close to a recycling center, on-site recycling reduces energy demand and will reduce emissions as well. Not only does distributed recycling reduce energy and emissions, it will have farther reaching implications.

The amount of fossil fuels and concomitant GHG emissions required to transport billions of pounds of plastics from residences to collection centers to processing centers is considerable. If all plastics, which make of 10.5% of all recycled goods (Ohio DNR, 2012) are largely eliminated from the waste stream these trucks would not have to circulate as often. Eliminating even a fraction (e.g. 3% via elimination of the HDPE) of that through distributed recycled would be environmentally beneficial. The decrease in materials would be substantial as well. With fewer waste management trucks traveling over public roads, less damage will be done to the roads, requiring less frequent road maintenance. Similarities, when fewer plastics go through the large scale recycling system, less material is used to build and maintain the facilities.

Combining the open-source distributed recycling of the RecycleBot with the distributed production of the RepRap combination systems would be the most economically beneficial for those interested in a complete distributed manufacturing process. This could even be accomplished on a household level. The RecycleBot could be used for disposing of a single household's recycling, saving trips to return waste plastic and a stop for curbside collection. The RepRap could be used to print parts for simple household repairs and solutions, such as bike parts, knobs and handles, cooking utensils, toys, eyeglass frames, and an enormous sum of individual parts. Although these parts or products can often be purchased in most locations, they can be printed often for considerably lower costs and be made more customized or appropriate for the consumer (Wittbrodt et al., 2013). For example, at an average U.S. utility cost of $0.1153/kWh (Electric Choice, 2010), an orange juicer of volume 63.4 cm^3 of PLA uses 0.31 kWh to produce on a RepRap (Kreiger and Pearce, 2013a, 2013b). This would cost about 3.5 cents in electricity to print. If purchasing commercial filament at $36/kg of filament for a 75.47 g juicer of 3 mm PLA filament, this costs $2.72 in material, for a total cost of $2.76. Citrus juicers of lower quality and utility can be found on-line for $1 and of approximately the same quality at $7–$25, so distributed manufacturing is not necessarily economical for low-value plastic products. However, if a RecycleBot is used to make the juicer from HDPE the material costs drop to the electricity needed (0.56 cents), bringing a total manufacturing cost to a remarkably low 4 cents. Thus the RecycleBot/RepRap combination allow for two orders of magnitude price decreases even for low-value mass-produced plastic products if people are willing to invest their time to make them. As has previously been shown, such radical decreases in costs can be obtained for high-value items such as scientific equipment (Pearce, 2012, 2014; Zhang et al., 2013) using only the RepRap and would be reduced even further using recycled post-consumer plastic for filament as shown in this paper. The potential for high-value added recycling using this process is already being investigated in the developing world (Feeley et al., 2014) with the creation of the Ethical Filament Foundation to help enable waste pickers to make 3-D printer filament.[2] Future work is necessary to investigate the willingness of consumers to 1) accept 3-D printed plastic goods, 2)

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[2] http://www.ethicalfilament.org/.

recycled filament, and 3) potential of the majority of consumers to become producers.

There is a financial incentive for RecycleBot operators to produce filament even without making a finished product. The cost of commercial 3-D filament (ABS or PLA) currently ranges from $36–50/kg, while the RecycleBot iproduces 1 kg of filament from about 20 milk jugs for under 10 US cents. The RecycleBot operator could also produce pellets trading in a spooler/winder for a cutter and sell recycled HDPE on the open market for centralized manufacturers to use to make products such as wood plastic composite decking (Bolin and Smith, 2011). Although technically possible it is not economically advantageous for home recyclers to invest their time in this way as pellets cost ~$1/kg, while 3-D printer filament is currently selling at ~$35/kg and with a RepRap the recyclers can print products using the filament worth $100s–$1000 s/kg (Wittbrodt et al., 2013).

Those involved with the 'maker movement' or the more traditional informal economy would also benefit financially from this distributed manufacturing/recycling process. This sector is made up of people who are self-employed, untaxed, and unmonitored by the government, but still work within the legal limit (Sparks and Barnett, 2010). These people often run small-scale service businesses that would be well suited for a rapid prototyper. For example, someone who does computer repairs out of their home could use a RepRap printer to print any of the following: computer mouse, computer case, I/O cover plates; adapter brackets for hard drives and SSD, laptop stand, laptop privacy shields, wireless chording keyboard, docking stations, and keyboard parts.[3] Thingiverse.com, which is a repository of digital designs most of which can be printed on a RepRap, currently holds over 200,000 open-source designs and is growing exponentially (Wittbrodt et al., 2013). There is a network effect to sharing open-source hardware designs as each design added to the commons adds value to all existing 3-D printers.

The low cost and reproducibility of the RecycleBot and RepRap and their product designs make them useful in a developing world (Pearce et al., 2010). A self-replicating 3-D printer can be used to make appropriate technologies for energy generation, water distribution, utensils, shoe insoles, parts of medical equipment, parts of water filters, etc., as well as spare parts and copies of itself (Pearce et al., 2010). A major concern in the developing world is water distribution. One of the Peace Corps objectives is to install drip irrigation to places where water is limited, as drip irrigation efficiently uses water without much loss to evaporation (Peace Corps, 2011). 3-D printers can be used to make parts and fittings for drip irrigation, potentially changing the water shortage in developing countries and solving the food crisis in many areas.[4] The ability to make these useful parts or products from recycled waste using the distributed recycling paradigm discussed here, not only has the potential to radically reduce the environmental impact of HDPE-containing products, but also to substantially reduce costs for developing world communities. Lastly, it should be noted that similar potential exists for other recycled plastics such as ABS, PLA, and PET and further work is needed to perform both technical analysis and LCAs on these materials in a distributed recycling process as they provide more easily printed 3-D filament and may be more likely to be accepted by 3-D printer operators.

5. Conclusions

This study represents the first LCA on distributed recycling and provides a method to expand this class of LCAs beyond HDPE. The results of this LCA showed that distributed recycling of post-consumer HDPE for 3-D printing filament uses less embodied energy than the best-case scenario investigated for a high-population density city using centralized recycling. For centralized recycling in a low-density population case study involving substantial embodied energy use for transportation and collection these savings for distributed recycling were found to extend over 80%. These results have significant implications for policy makers interested in reducing the energy and emissions associated with plastic consumption and recycling. On the scale of U.S. yearly HDPE recycling this would amount to over 100 million MJ of energy conservation and substantial GHG emissions reductions even in the best case scenario for centralized recycling. It seems clear that policies should be enacted to create incentives for distributed recycling on environmental grounds. With the open-source 3-D printing network expanding rapidly the potential for widespread adoption of distributed recycling of HDPE represents a novel path to a future of distributed manufacturing appropriate for both the developed and developing world with lower environmental impacts than the current system.

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[3] Examples from http://www.thingiverse.com/thing:30642[#] computer mouse [1056], computer case [3944], I/O cover plates [14377]; adapter brackets for hard drives and SSD [13472], laptop stand [7346], laptop privacy shields [8412], wireless chording keyboard [6922], docking stations [16608], keyboard parts [13015].

[4] See examples http://www.thingiverse.com/jpearce/collections/open-source-appropriate-technology.

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