2012

THE USE OF LIFE-CYCLE ANALYSIS TO REDUCE THE ENVIRONMENTAL IMPACT OF MATERIALS IN MANUFACTURING

Megan A. Kreiger
Michigan Technological University

Recommended Citation

Kreiger, Megan A., "THE USE OF LIFE-CYCLE ANALYSIS TO REDUCE THE ENVIRONMENTAL IMPACT OF MATERIALS IN MANUFACTURING", Master's Thesis, Michigan Technological University, 2012.
https://digitalcommons.mtu.edu/etds/885

Follow this and additional works at: https://digitalcommons.mtu.edu/etds

Part of the Materials Science and Engineering Commons, and the Sustainability Commons

THE USE OF LIFE-CYCLE ANALYSIS TO REDUCE THE ENVIRONMENTAL IMPACT OF MATERIALS IN MANUFACTURING

By

Megan A. Kreiger

A THESIS

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Materials Science and Engineering

MICHIGAN TECHNOLOGICAL UNIVERSITY

2012

This thesis has been approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE in Materials Science and Engineering.

Department of Materials Science and Engineering

Thesis Advisor:	*Joshua Pearce*
Committee Member:	*Stephen Hackney*
Committee Member:	*David Shonnard*
Department Chair:	*Stephen Kampe*

Table of Contents

Preface

This thesis is composed of three published (or submitted for publishing) papers. The author's contributions are described hereafter.

Chapter 2 is "Life cycle analysis of silane recycling in amorphous silicon-based solar photovoltaic manufacturing" published in the journal *Resources, Conservation, and Recycling* (http://dx.doi.org/10.1016/j.resconrec.2012.10.002). This article was written by M. Kreiger, D. Shonnard, and J. Pearce. M. Kreiger's contribution to this paper was the literature review, entire life-cycle analysis, remaining analysis, results, figures, writing, and multiple revisions. D. Shonnard's contribution was advice on life-cycle analysis and editing. J. Pearce's contribution was writing, editing, and consultation.

Chapter 3 is "Life cycle analysis of distributed 3-D printing and conventional manufacturing of polymer products" which is planned for submission to the *Environmental Science and Technology*. This paper was written by M. Kreiger and J. Pearce. M. Kreiger's contribution to this paper was the literature review, experimental data, entire life-cycle analysis, figures, tables, results, writing, and multiple revisions. J. Pearce's contribution was writing, editing, and consultation.

Chapter 4 is "Life cycle analysis of distributed recycling of post-consumer high density polyethylene for 3-D printing filament" which has been submitted to the journal *Resources, Conservation, and Recycling*. This paper was written by M. Kreiger, M. Mulder, A. Glover, and J. Pearce. M. Kreiger's contribution to this paper was the methods, help building the filament spooler, contacting the recycling companies and life cycle analysis company to determine locations and values, entire life-cycle analysis, table, remaining analysis, experimental values using the RepRap, writing, and multiple revisions. M. Mulder's contribution was preliminary work and literature review. A. Glover's contribution was the development of the filament spooler and energy readings. J. Pearce's contribution was the RecycleBot, the idea, writing, editing, and consultation.

Acknowledgements

The researcher would like thank the Sustainable Futures Institute at Michigan Tech for providing use of the life-cycle analysis software used in this thesis. I would like to acknowledge my advisor Dr. Joshua Pearce and committee members Dr. Stephen Hackney and Dr. David Shonnard for all of their help and advice. Thank you to Gerald Anzalone, Meredith Mulder, Alexandra Glover, my fellow graduate students, and the MOST research group for their assistance and the sharing of ideas.

A special thank you to my family, whose patience and dedication made this possible.

Abstract

This thesis is composed of three life-cycle analysis (LCA) studies of manufacturing to determine cumulative energy demand (CED) and greenhouse gas emissions (GHG). The methods proposed could reduce the environmental impact by reducing the CED in three manufacturing processes.

First, industrial symbiosis is proposed and a LCA is performed on both conventional 1 GW-scaled hydrogenated amorphous silicon (a-Si:H)-based single junction and a-Si:H/microcrystalline-Si:H tandem cell solar PV manufacturing plants and such plants coupled to silane recycling plants. Using a recycling process that results in a silane loss of only 17 versus 85 percent, this results in a CED savings of 81,700 GJ and 290,000 GJ per year for single and tandem junction plants, respectively. This recycling process reduces the cost of raw silane by 68 percent, or approximately \$22.6 and \$79 million per year for a single and tandem 1 GW PV production facility, respectively. The results show environmental benefits of silane recycling centered around a-Si:H-based PV manufacturing plants.

Second, an open-source self-replicating rapid prototype or 3-D printer, the RepRap, has the potential to reduce the environmental impact of manufacturing of polymer-based products, using distributed manufacturing paradigm, which is further minimized by the use of PV and improvements in PV manufacturing. Using 3-D printers for manufacturing provides the ability to ultra-customize products and to change fill composition, which increases material efficiency. An LCA was performed on three polymer-based products to determine the CED and GHG from conventional large-scale production and are compared to experimental measurements on a RepRap producing identical products with ABS and PLA. The results of this LCA study indicate that the CED of manufacturing polymer products can possibly be reduced using distributed manufacturing with existing 3-D printers under 89% fill and reduced even further with a solar photovoltaic system. The results indicate that the ability of RepRaps to vary fill has the potential to diminish environmental impact on many products.

Third, one additional way to improve the environmental performance of this distributed manufacturing system is to create the polymer filament feedstock for 3-D printers using post-consumer plastic bottles. An LCA was performed on the recycling of high density polyethylene (HDPE) using the RecycleBot. The results of the LCA showed that distributed recycling has a lower CED than the best-case scenario used for centralized recycling. If this process is applied to the HDPE currently recycled in the U.S., more than 100 million MJ of energy could be conserved per annum along with significant reductions in GHG. This presents a novel path to a future of distributed manufacturing suited for both the developed and developing world with reduced environmental impact.

From improving manufacturing in the photovoltaic industry with the use of recycling to recycling and manufacturing plastic products within our own homes, each step reduces the impact on the environment. The three coupled projects presented here show a clear potential to reduce the environmental impact of manufacturing and other processes by implementing complimenting systems, which have environmental benefits of their own in order to achieve a compounding effect of reduced CED and GHG.

1. Introduction

1.1 Motivation

The objective of this research was to study various methods to which the environmental impact and energy use could be reduced in manufacturing. It is proposed that process gas recycling in photovoltaic manufacturing with 3-D printers powered with solar, and distributed recycling of polymers provide gateways to a new manufacturing paradigm that radically reduces the impact of manufacturing on the environment.

1.2 Thesis Outline

This thesis will begin in chapter 2 by introducing the reader to a case study published by the author where the energy and environmental impact for an existing process can be improved (recycling of silane in amorphous silicon solar photovoltaic manufacturing). Chapter 3 will discuss how the manufacturing process of polymer products and components can be revolutionized using distributed manufacturing, while reducing the environmental impact of production. In addition, the use of distributed generation of electricity from solar cells is quantified to drive this process. In chapter 4, this distributed manufacturing process can be further improved with the introduction of distributed recycling of post-consumer goods. Chapter 5 will discuss how all of these processes can be used in conjunction to reduce the environmental impact of manufacturing.

2. Life-cycle analysis of silane recycling in amorphous silicon-based solar photovoltaic manufacturing[1]

Abstract

Amorphous silicon (a-Si:H)-based solar cells have the lowest ecological impact of photovoltaic (PV) materials. In order to continue to improve the environmental performance of PV manufacturing using proposed industrial symbiosis techniques, this paper performs a life cycle analysis (LCA) on both conventional 1 GW-scaled a-Si:H-based single junction and a-Si:H/microcrystalline-Si:H tandem cell solar PV manufacturing plants and such plants coupled to silane recycling plants. Both the energy consumed and greenhouse gas emissions are tracked in the LCA, then silane gas is reused in the manufacturing process rather than standard waste combustion. Using a recycling process that results in a silane loss of only 17 percent instead of conventional processing that loses 85 percent silane, results in an energy savings of 81,700 GJ and prevents 4,400 tons of CO_2 from being released into the atmosphere per year for the single junction plant. Due to the increased use of silane for the relatively thick microcrystalline-Si:H layers in the tandem junction plants, the savings are even more substantial - 290,000 GJ of energy savings and 15.6 million kg of CO_2 eq emission reductions per year. This recycling process reduces the cost of raw silane by 68 percent, or approximately $22.6 million per year for a 1 GW a-Si:H-based PV production facility and over $79 million per year for tandem manufacturing. The results are discussed and conclusions are drawn about the technical feasibility and environmental benefits of silane recycling in an eco-industrial park centered around a-Si:H-based PV manufacturing plants.

Keywords: amorphous silicon; cryogenic separation; life cycle analysis; photovoltaic manufacturing; silane; recycling

---

[1] "The material contained in this chapter was previously published in *Resources, Recycling, and Conservation*."

2.1 Introduction

The world requires inexpensive, reliable, and sustainable energy sources. As world population and affluence increase, it is projected that between 2 to 10 times the energy currently produced will be required over the next 50 years (Lewis and Nocera, 2006; Allen and Shonnard, 2012). In order to provide future generations with sufficient energy, environmental impacts per unit of energy produced will have to be reduced significantly. Solar photovoltaic (PV) technology, which converts sunlight directly into electricity, offers a globally-scalable technically-sustainable solution to the projected enormous future energy demands (Dincer, 2000; Pearce, 2002; Fthenakis, et al., 2009). The potential for PV to be a sustainable technology has been reinforced by numerous life cycle analysis (LCA) studies considering both embodied energy and emissions (Alsema 2000; Alsema and de Wild-Scholten, 2005; Alsema and Nieuwlaar, 2000; Alsema, et al., 2006; Fthenakis and Alsema, 2006; Fthenakis and Kim, 2007; Fthenakis, et al., 2008; Mason, et al., 2006; Palz and Zibetta, 1991; Pearce and Lau, 2002). However, in order to compete economically with fossil fuels in all markets in the current subsidy landscape, further decreases in the levelized cost of electricity from solar are needed (Branker, Pathak & Pearce, 2011). If this were to occur the potential market would be substantial and begin to rival the traditional fossil-fuel-based energy market in size. For example, consider recent work by Keiser that showed that at US$3 per watt for complete PV systems – and some commercial projects are at this level now – addressable electricity consumption rises to 440 billion kWh, equivalent to over 300GW of capacity in the U.S. alone (Keiser, 2011). To meet the cost goals for solar electricity to compete economically with fossil fuel-fired electricity, work has started exploring the use of industrial symbiosis to obtain economies of scale and increased manufacturing efficiencies for solar PV cells (Andrews and Pearce, 2011; Nosrat et al., 2009; Pearce, 2008a). Of the PV materials, hydrogenated amorphous silicon (a-Si:H)-based PV, a second generation thin film technology, offers the best ecological balance sheet (Alsema, 2000; García-Valverde, Cherni, and Urbina, 2010; Jungbluth, 2009; Palz and Zibetta, 1991; Pearce and Lau, 2002; Wronski, et al., 2002.). This type of PV has an energy payback time around 1 year and can produce up to 31 times the amount of energy its initial consumption within a 30-

year lifetime (Pearce and Lau, 2002). In addition, increased stabilized efficiencies (> 10%) have been demonstrated with dual junction a-Si:H / microcrystalline (μc-Si:H) tandem solar cells, which further improve ecological performance of Si:H-based PV.

Unfortunately, there is a significant amount of waste in the Si:H material deposition process as only approximately 15 percent of the silane (SiH_4) is used (Briend, 2011). Embodied energy and greenhouse gas emissions of silane are very large, 1,146 MJ / kg silane and 61.3 kg CO_2 equivalents (eq.) / kg silane respectively (Ecoinvent, 2012), suggesting recycling as a promising approach to reduce impacts of a-Si:H manufacturing despite the small quantity of active semiconductor in the entire module. In order to continue to improve the environmental impact of PV manufacturing, this paper investigates this opportunity by performing an LCA on four scenarios: (1) conventional 1GW-scaled a-Si:H-based single junction plant, (2) a conventional 1GW a-Si:H/μc-Si:H tandem cell solar PV manufacturing plant, (3) a 1GW-scaled a-Si:H-based single junction plant coupled to silane recycling plant, and (4) a 1GW a-Si:H/μc-Si:H tandem cell solar PV manufacturing plant coupled to silane recycling plant . Both the energy consumed and carbon dioxide (CO_2) equivalent emissions (all important greenhouse gases included) from the processing of silane are tracked in the LCA and the silane gas is reused in the manufacturing process rather than standard combustion. The results are discussed and conclusions are drawn about the technical feasibility and environmental benefits of silane recycling in an eco-industrial park centered around an a-Si:H-based PV manufacturing plant.

2.2 Background

2.2.1 A-Si:H-based PV Manufacturing

The current manufacturing process for Si:H-based PV cells varies between different substrates, methods, and manufacturers, but the actual deposition of a-Si:H and μc-Si:H layers are formed by running the substrate through a set of chambers and exposing it to a mixture of hydrogen and silane using plasma-enhanced chemical vapor deposition

(PECVD) (Street, 2000; Wronski and Carlson, 2001). The layers of a-Si:H PV are constructed in a p-i-n or n-i-p device structure. The p-layer is usually a boron-doped a-Si:H or a-SiC:H , followed by an i-layer of either undoped a-Si:H or amorphous silicon germanium a-SiGe:H and an n-layer of phosphorous doped a-Si:H (Izu and Ellison, 2003; Street, 2000; Wronski and Carlson, 2001; Wronski et al., 2002).

For the tandem cell structures, μc-Si:H has been shown to be able to act as an active layer in p-i-n solar cells (Meier, et al., 1998; Keppner, et al., 1999; Meier, et al., 2006;). Compared to the bandgap of a-Si:H (1.8eV), μc-Si:H was found to have a significantly lower energy bandgap of around 1 eV and thus the combination of both materials (two absorbers with different gap energies) leads to a tandem cell structure, referred to as the "micromorph" cell, with superior performance to both single and double junction a-Si:H-based cells because of increased use of the solar spectrum (Meier, et al., 2006).

Silane is the primary source gas for both amorphous and microcrystalline Si:H-based PV manufacturing. When silane is deposited, only approximately 15% of the gas gets used, while the remaining 85% goes unused and is treated as waste (Briend, 2011). The typical method of disposing of unused silane, which is a pyrophoric gas that undergoes spontaneous combustion in air, is to utilize combustion.

2.2.2 LCA of Si:H PV Manufacturing

Hydrogenated amorphous silicon PV has one of the lowest total embodied energy demands for PV modules of 1200 MJ eq. per meter squared (Alsema, 2000) and energy payback times between 1-3 years (García-Valverde, Cherni, and Urbina, 2010; Pearce and Lau, 2002). This is in part due to the minimal amount of silicon needed to produce a-Si:H modules, utilizing only a fraction of what is found in conventional crystalline silicon-based cells and the ability for a-Si:H to utilize roll-to-roll production (Izu and Ellison, 2003), which reduces both production time and transportation costs with the production of these modules (Jungbluth, 2009). The performance of tandem Si:H-based cells is expected to be even better because of the increased cell performance with only an increased energy expense due to the increased thickness of 2.5 microns, of the μc-Si:H absorber layer.

Although this ecological performance is excellent particularly when compared to fossil-fuel based energy sources that it replaces, the emissions due to Si:H-based PV manufacturing can cause a carbon emissions / energy cannibalization effect that limits the carbon neutral growth rate of the technology (Kenny, et al., 2010). Energy cannibalism refers to an effect where rapid growth of an entire energy producing industry creates a need for energy that uses (or cannibalizes) the energy of existing power plants (Pearce, 2008b). Thus, as PV is experiencing rapid growth the industry as a whole could produce no net energy because new energy is used to fuel the embodied energy of future power plants. A similar analysis is made for greenhouse gas (GHG) emissions and thus it is important to reduce the embodied energy and emissions of PV as much as possible to allow for accelerated growth rates of the industry (Kenny, et al., 2010). With global PV production having proved it is capable of >100% growth per annum, reducing the energy payback time is necessary to stay ahead of the carbon neutral growth rate.

2.3 LCA Methods

2.3.1 Goal, Scope, and Functional Unit

The goal of this study is to determine if in-situ silane recycling is environmentally feasible during PECVD manufacturing of Si:H-based PV (both single junction a-Si:H and tandem a-Si:H/ μc-Si:H) . The scope of this life cycle analysis will be limited to differences in inputs for processing ("cut-off method") of silane for recycling versus not-recycling. The functional unit is 1 kg of silane used in PV production. However, the inventory data associated with these inputs will embody a "cradle-to-gate" system boundary. These results will be compared with previous LCA results from the literature to quantify the variance in embodied energy and greenhouse gas emissions.

2.3.2 LCA Software, Inventory, and Impact Assessment Methods

SimaPro v. 7.3 (Pré, 2012) was used to complete an energy and emissions LCA of a Si:H based PV manufacturing and silane recycling plants. SimaPro is a life cycle analysis tool that gives a quantitative measure of the impact of a product or service. In this analysis, the Ecoinvent v. 2.2 database of materials was used, which is based directly off of data from industry, evaluated by professionals, and is well known as a reliable database (Jungbluth, Tuchschmid, Wild – Scholten, 2008). Cumulative energy demand 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 (Pachauri, 2007; Solomon 2007), was used to calculate the CO_2 equivalent emissions for the recycling comparison.

2.3.3 Silane Recycling

The silane recycling protocol studied here was proposed by Briend (2011) and is outlined in Figure 2.1. Figure 2.1 shows the relationship between the 1 GW Si:H-based PV manufacturing plant (4) and the semiconductor recycling plant (5) in an eco-industrial park proposed by Pearce (2008a). This production plant size is evaluated because of the previously discussed benefit of scale (Pearce, 2008a). It should be noted that the use of silane recycling is considered an in-process form of recycling, although the context of the study is in an 8 plant eco-industrial park. The waste silane mixture from the reaction chamber in the PV plant can be recycled by first pumping the waste silane from the reaction chamber at near atmospheric pressure and mixing it with nitrogen to avoid ignition. The diluted silane/nitrogen mixture can be processed using a filter (centrifugal separator, scrubber, etc.). If the mixture is free of corrosive compounds, a compressor can then be used to bring the pressure to 2-35 bars (Briend, 2011). Otherwise, additional filters must be placed before the compressor to reduce corrosion. After obtaining the proper pressure, a cryogenic separator is used to condense/solidify the silane and remove the hydrogen/nitrogen mixture. This point allows another potential recycling opportunity, the nitrogen and hydrogen can also be purified and reused, but will be left for future work. From this point, the silane needs to be distilled to achieve the proper purity level for the reaction chamber and the recycled silane can then be put into storage bottles/tanks or pumped through a system of parallel buffers and run through the deposition process directly again.

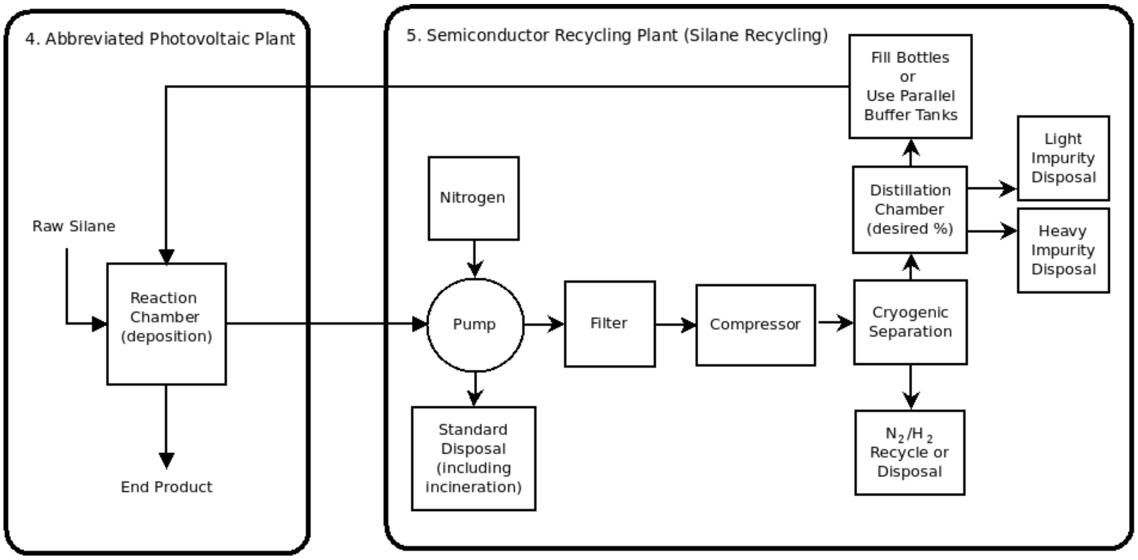

Figure 2.1: Schematic of LCA of silane recycling in an industrial symbiotic system manufacturing Si:H-based PV.

Currently, only 15% of the silane is used in the standard deposition process (Briend, 2011) and the remaining 85% is wasted. The percentages of potential silane wasted using the process outlined by Briend were calculated using:

$$a_r\ (\%) = 1 - a_d(\%) - a_w(\%) \times a_v \qquad (2.1)$$

where a_r is the total percent of waste that can be recycled, a_d is the total percent of silane deposited, a_w is the percent of silane originally wasted, a_v is the fraction due to the efficiency of recoverable silane by use of recycling. From this 85 percent waste, the recycling process outlined by Briend (2011) is able to save up to 80 percent, thus saving up to 68 percent of the original amount injected into the PEVCD. This leaves a waste of 17 percent using silane recycling versus the original 85 percent waste.

The inputs for the energy and nitrogen required to create 1 kg of raw silane and 1 kg recycled silane mixture for both single junction a-Si:H PV and tandem a-Si:H/ μc-Si:H

PV production are shown in Table 2.1. Inputs for components outlined by Briend (2011) were estimated from manufacturer specifications and calculations for the application of recycling silane (Edwards Limited, 2012; Hijet Engineering Ltd, 2012; Kaeser Compressors Inc, 2012; Praxair Inc, 2003). Electrical use was calculated using the power rating for one hour, divided by the amount of silane recycled from one hour of continuous production from a 1 GW-scaled manufacturer. This results in an overestimate of the amount of electricity used to produce 1 kg of recycled silane. A facility at this scale would present a need for 8.61 kg of usable recycled silane to be produced every hour from an a-Si:H facility and 30.14 kg of usable recycled silane every hour from a tandem a-Si:H/ μc-Si:H. The inputs differ for a-Si:H and tandem a-Si:H/ μc-Si:H PV due to a difference in the volume of silane moving through the recycling system, when there is more volume at the same theoretical energy usage, the energy per unit volume is decreased. Inputs for the United States (US) were used when possible, otherwise European (RER) inputs were used. The SimaPro LCA input for 1 part was 1 kg of raw silane (silicon tetrahydride, at plant/RER U) used 100% raw materials. The terms S and U behind their country designation, refers to “system process” and “unit process”. The system process includes all processes of the system as a whole, whereas the unit process shows references to previous processes.

After designing an input for the recycled silane component, the LCA can be conducted for the actual deposition using recycled silane by considering Equation 2.1, which will be referred to as the recycled silane mixture. Using equation 2.1, it is found that 32% raw silane will be needed for the deposition process in conjunction with 68% recycled silane, due to the 32% loss during the initial deposition process and the recycling process.

Table 2.1

LCA inputs for 1 kg of Recycled Silane Mix for both a-Si and tandem PV production: using 32% of 1 kg input of Raw Silane and 68% of the Recycle Process Silane Inputs for 1 kg output using the process as outlined by Briend (2011) (Figure 1). Ecoinvent ecoprofiles are listed for each input. Acronyms US/US refer to United States (US) made inputs used within the US, and RER refers to European (RER) inputs. The S at the end of the input name means that all processes to create the input are considered as a whole.

Recycle Process Silane Inputs	a-Si:H	Tandem	Unit	Details
Nitrogen, liquid, at plant/RER S	1.875	1.875	kg	Pump: Edwards – iH80 Dry Pump 460V
Electricity, production mix US/US S	0.313	0.090	kWh	
Electricity, production mix US/US S	0.910	0.910	kWh	Filter/Compressor: Centrifugal Separator w/ Kaeser compressor
Electricity, production mix US/US S	0.605	0.605	kWh	Basic Cryogenic Air Separator
Electricity, production mix US/US S	1.742	0.498	kWh	Distillation Column: Vacuum distillation unit

These inputs were determined using a 1GW-scaled PV manufacturing plant, running continuously, with 70 W/m^2 for the single junction a-Si:H PV and 100W/m^2 for the tandem a-Si:H/μc-Si:H PV produced. It should be pointed out here that the fundamental differences in the inputs between a-Si:H/μc-Si:H and single-junction a-Si:H PV is the thickness of the absorber layers. The absorption coefficient of the i-layer of the μc-Si:H cells are relatively low and necessitate a factor of five increase in thickness. For this analysis, the gas plant was assumed to be located next to the manufacturing plant due to the scale of the PV plant, so transportation of silane and nitrogen to the PV plant was assumed to be negligible to minimize cost and downtime due to transportation time. A sensitivity analysis was done and showed that a transportation distance of 1000 miles had less than 0.1% effect on the results. No other inputs besides those necessary for recycling were included for comparison between the life cycles of raw and recycled silane.

2.4 Results

The analysis of the cumulative energy demand results in the recycled silane mixture for an a-Si:H PV facility and a tandem a-Si:H/μc-Si:H PV facility having an impact of 409 and 397 MJ per kg of usable silane, respectively. For entire production process of raw silane, 1,146 MJ are used to create one kilogram. This means that the amount of energy to recycle silane in an a-Si:H PV plant is only 35.7% and in a tandem a-Si:H/μc-Si:H PV plant is even less at 34.6% of what it takes to create raw silane, as shown in Figure 2.2.

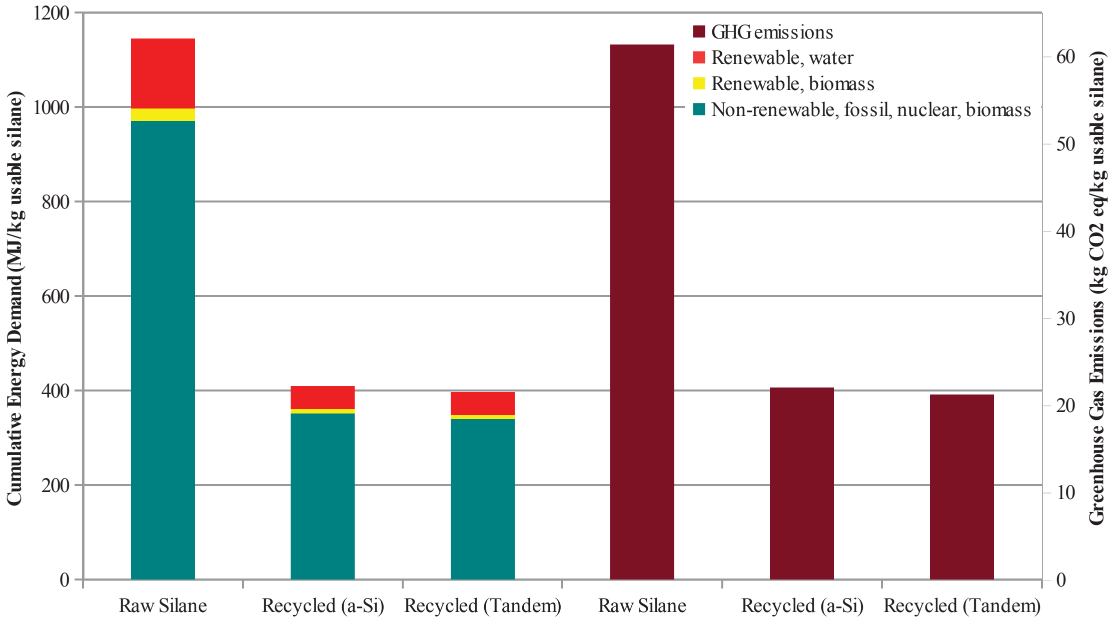

Figure 2.2: Cumulative energy demand and CO_2 emissions for raw and recycled silane for 1kg of silane, scaled for a 1 GW a-Si:H and tandem a-Si:H/μc-Si:H factory.

Using the IPCC 2007 GWP 100a v 1.02 method to determine greenhouse gas emissions in carbon dioxide equivalents for raw and recycled silane, the total emissions are 22 kg CO_2 per kg recycled silane mixture at an a-Si:H plant, 21.2 kg CO_2 per kg recycled silane mixture at a tandem a-Si:H/μc-Si:H plant, and 61.3 kg CO_2 per kg raw silane. The amount of greenhouse gas emissions related with the recycled silane mixture is 35.8% for a-Si:H and 34.8% for tandem a-Si:H/μc-Si:H PV of that of raw silane as seen in Figure 2.2.

The amount of CO_2 emitted differs from the amount of energy use by a small amount due to the various inputs required for silane to be produced. Various steps in the production of silane use different forms of energy, and some processes produce a greater amount of emissions for the same amount of energy used.

2.5 Discussion

As the results in Figure 2.2 show, recycling silane in Si:H-based PV manufacturing consumes less energy and emits less greenhouse gas emissions compared to silane produced from new resources. This is due to the high level of processing and transportation required in making PV-grade silane from new resources. The difference in total energy demand is 736 MJ per kg between the recycled silane mixture and the raw silane for a-Si:H single junction PV manufacturing. For comparison, 1 kg of silane can produce approximately 129 m^2 of a-Si:H PV material with 15 percent deposition efficiency. This means that for every meter squared produced, a total savings of 5.7 MJ can be realized. To put this figure into context, for a 1 MW scaled factory, 1 m^2 of frameless PV material, consumes approximately 1,200 MJ of energy (Alsema, 2000). If it is assumed that the difference in recycling for such a smaller plant will be approximately the same due to the store of the waste gas, reducing the size of the recycling process, and/or limiting the running time for the process, then recycling has the potential to save up to 5.7 MJ of the total manufacturing energy demand for each meter squared created at the MW scale. It should be pointed here that the embodied energy due to the buildings and equipment were not included in the study as it was found to be negligible (<2% of total energy demand in photovoltaic systems – ecoinvent database (SCLCI, 2012).

If a tandem module of a-Si:H/μc-Si:H is compared to a single-junction a-Si:H module, the effect of recycling is increased, as shown in Figure 2.3. Assuming all inputs and methods are approximately the same except for a total i-layer absorber silicon thickness of 2.5 microns, 1 m^2 of tandem PV material would have a cumulative energy demand of 1235.6 MJ using raw silane. By recycling silane, this type of PV material has the potential to save 29.1 MJ for every meter squared produced, resulting in a cumulative energy savings of 2.4%.

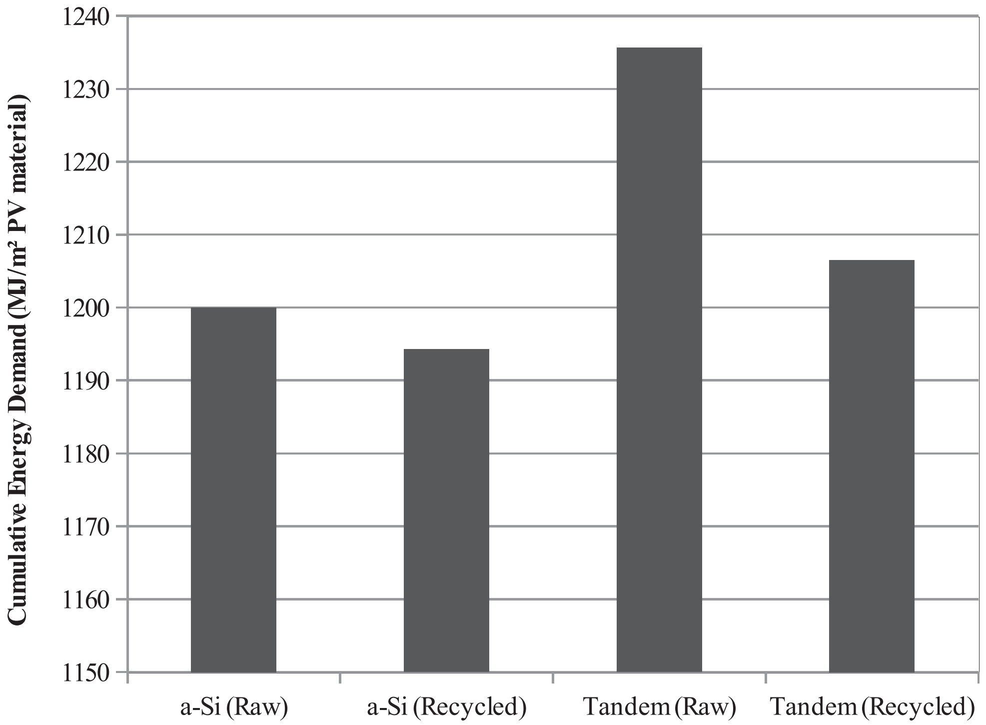

Figure 2.3: Cumulative energy demand comparison between raw and recycled silane for 1 meter squared of a-Si:H and tandem a-Si:H/µc-Si:H photovoltaic material

A 1 GW single-junction a-Si:H manufacturer running continuously will use 111,000 kg of silane per year of which 94,300 kg of silane will go through the deposition chamber and be wasted. By recycling, there is a potential to save 55,400 kg for reuse in the deposition chamber, with an end result of only 18,900 kg being disposed. When the difference in the amount of energy and CO_2 associated with 1 kg of silane is considered and multiplied by the amount of silane used per year, the end result of recycling silane is approximately 81,700 GJ of energy savings and 4.4 million kg of CO_2 eq per year.

These are substantial energy and emission savings. To put this into perspective, these values can be compared to other methods previously discussed in the literature in relation an industrial symbiosis centered on a 1 GW a-Si:H manufacturing plant. For, example Nosrat et al. investigated the glass used for the front and back substrate of a-Si:H at this scale (2009). The energy that could be saved by maximizing recycling of glass in a-Si:H-based PV in a similarly scaled plant is 220,000 GJ (Nosrat, et al., 2009). Thus, the embodied energy conserved by recycling silane is about one third that of potential savings from using recycled glass in the back glass layer.

Raw silane has a cost associated with its purchase approximated by Sematech at US$0.30/g for bulk production (Visokey, et al., 1995), although it should be noted that costs are highly variable. Thus, the process outlined here for recycling reduces this cost by 68 percent, or approximately $22.6 million/year for a 1 GW a-Si:H-based PV production facility. These cost savings thus help provide a cushion for thin film PV manufacturers from volatile silane cost fluctuations. However, these economic savings also may provide a direct competitive advantage for a-Si:H fabs that recycle silane by potentially reducing overall production costs and presumably market prices. However, it should be noted that the capital and operating costs need to be determined for the recycling process in future work. As previously noted, reduction in the installed cost of PV can have dramatic effects on consumer acceptance and market size (Keiser, 2011).

The impacts of recycling silane in a 1 GW tandem a-Si:H/μc-Si:H manufacturing plant under the same recycling assumptions is even more substantial. The tandem fab will use 388,000 kg of silane per year and could save 264,000 kg of silane by recycling. This is equivalent to 290,000 GJ of energy savings and 15.6 million kg of CO_2 eq per year. This represents a larger potential embodied energy savings than integrating recycled glass in the back glass encapsulation layer (Nosrat, et al., 2009). Most strikingly, silane recycling results in a reduction of raw silane purchase costs of approximately $79.2 million/year for a 1GW-scaled tandem a-Si:H/μc-Si:H manufacturing plant. At a thin film PV module cost of $0.70/Wp a 1GW-scaled plant generates $700 million in revenue/year, so the potential cost savings from silane recycling are approximately 11% of revenue. The percentage of potential savings from recycling would increase, as cost declines are made possible by improved efficiency and increased market competition reduces margins.

Future work is needed to do a full life-cycle economic analysis of this process that would compare the economic benefit from recycling silane with the increased costs of capital equipment and operating energy costs needed to recycle the silane outlined in Table 2.1. In addition, Briend et al. (2011) outlined methods to recover both nitrogen and hydrogen, which could also be considered for future work to continue to depress the already small embodied energy, energy payback time, and ecological footprint while increasing the already substantial energy returned on energy invested (EROI) of Si:H-based PV manufacturing. Finally, a full LCA including all impact categories of the environmental analysis should be investigated as energy and silane are not the only contributers in the process to environmental impact.

2.6 Conclusions

This is the first LCA study of silane recycling in GW-scaled Si:H-based PV manufacturing plants. From the results found in this study, it is clear that not only would silane recycling allow Si:H-based PV manufacturers to become less dependent on silane cost volatility, but that silane recycling reduces energy consumption and emissions in Si:H-based PV production. In the case of a 1 GW a-Si:H plant this amounts to savings of approximately 81,700 GJ and over 4,000 metric tons of CO_2e per year. For the more material intensive 1 GW-scaled tandem a-Si:H/μc-Si:H PV manufacturing plant the savings are even more substantial: 290,000 GJ of energy savings and 15.6 million kg of CO_2 eq per year. It can be concluded that instead of buying all new silane only to discard 85%, it is more environmentally-responsible for thin film Si:H-based PV manufacturers to begin recycling silane and only supplementing the recycled supply with raw silane. The recycling process outlined here reduces the cost of raw silane by 68 percent, or over $22 million/year for a 1 GW single-junction a-Si:H-based PV production facility and over $79 million/year for a tandem a-Si:H/μc-Si:H PV manufacturing plant. These savings represent a significant fraction of revenue and thus silane recycling offers the potential to reduce the LCOE of

Si:H-based PV, which could in turn make it more competitive in the PV market and increase PV penetration in the overall grid.

Acknowledgements

The authors would like to thank the Sustainable Futures Institute of Michigan Tech for support.

References

Allen DT, Shonnard DR. Sustainability in Chemical Engineering Education: Identifying a Core Body of Knowledge. AIChE Journal 2012, 58(8):2296-302.

Alsema EA. Energy pay-back time and CO_2 emissions of PV systems. Progress in Photovoltaics: Research and Applications 2000;8:17–25.

Alsema EA, Nieuwlaar E. Energy viability of photovoltaic systems. Energy Policy 2000;28(14):999-1010.

Alsema EA, de Wild-Scholten M. Environmental impact of crystalline silicon photovoltaic module production. In: Material Research Society Fall Meeting, Symposium G: Life Cycle Analysis Tools for "Green" Materials and Process Selection. Boston, MA. 2005.

Alsema EA, de Wild-Scholten MJ, Fthenakis VM. Environmental impacts of PV electricity generation – a critical comparison of energy supply options. In: 21st European Photovoltaic Solar Energy Conference. Dresden, Germany. 2006.

Andrews R, Pearce JM. Environmental and Economic Assessment of a Greenhouse Waste Heat Exchange. Journal of Cleaner Production 2011;19:1446-54.

Branker K, Pathak MJM, Pearce JM. A Review of Solar Photovoltaic Levelized Cost of Electricity. Renewable & Sustainable Energy Reviews 2011;15:4470-82.

Briend P, Alban B, Chevrel H, Jahan D. American Air, Liquide Inc. Method for Recycling Silane (SiH4). United States Patent US 20110011129. 2011 Jan 20.

Dincer, I. Renewable energy and sustainable development: a crucial review. Renewable and Sustainable Energy Reviews 2000;4(2):157-75.

Ecoinvent, Version 2.2, Swiss Centre for Life Cycle Inventories, 2012. [cited 2012 Jun 8] Available from: http://www.ecoinvent.ch/

Edwards Limited, 2012. iH80 Dry Pump. [cited 2012 Apr 15] Available from: http://www.edwardsvacuum.com/Products/View.aspx?sku=A59000908

Fthenakis V, Alsema E. Photovoltaics energy payback times, greenhouse gas emissions and external costs: 2004–early 2005 status. Progress in Photovoltaics: Research and Applications 2006;14:275–80.

Fthenakis VM, Kim HC. Greenhouse-gas emissions from solar electric- and nuclear power: a life-cycle study. Energy Policy 2007;35:2549–57.

Fthenakis VM, Kim HC, Alsema EA. Emissions from photovoltaic life cycles. Environmental Science & Technology 2008;42:2168–74.

Fthenakis VM, Mason JE, Zweibel K. The technical, geographical, and economic feasibility for solar energy to supply the energy needs of the US. Energy Policy 2009;37(2):387–99.

Hijet Engineering Ltd. Case study 6: Vacuum Distillation Unit at API Ancona Refinery, Italy. 2010. [cited 2012 Apr 15] Available from: http://www.hijet.com/?mode=vacuum_api&xy=46

Izu M, Ellison T. Roll-to-roll manufacturing of amorphous silicon alloy solar cells with in situ cell performance diagnostics. Solar Energy Materials and Solar Cells 2003;78(1–4):613-26.

Jungbluth N, Stucki M, Frischknecht R. Part XII Photovoltaics. Swiss Centre for Life Cycle Inventories. 2009.

Jungbluth N, Tuchschmid M, Wild – Scholten MJ. Life Cycle Assessment of Photovoltaics: update of ecoinvent data V2.0 . ECN Solar Energy. 2008.

Kaeser Compressors Inc. 2012. [cited 2012 Apr 15] Available from: http://www.kaeser.com/images/p-725-ed-tcm8-6771.pdf

Keiser R. PV Tech. 2011. [cited 2012 Jun 1] Available from: http://www.pv-tech.org/guest_blog/100gw_of_demand_and_the_coming_inflection_point_in_the_us_solar_market

Kenny R, Law C, Pearce JM. Towards Real Energy Economics: Energy Policy Driven by Life-Cycle Carbon Emission. Energy Policy 2010;38:1969–78.

Keppner H, Meier J, Torres P, Fischer D, Shah A. Microcrystalline silicon and micromorph tandem solar cells. Applied Physics A: Materials Science & Processing 1999;69:169–77.

García Valverde R, Cherni JA, Urbina A. Life Cycle Analysis of Organic Photovoltaic Technologies. Progress in Photovoltaics: Research and Applications 2010;18(7):535-58.

Lewis NS, Nocera DG. Powering the planet: Chemical challenges in solar energy utilization.

PNAS 2006;103(43): 15729-35.

Mason JE, Fthenakis VM, Hansen T, Kim HC. Energy payback and life-cycle CO_2 emissions of the BOS in an optimized 3.5 MW PV installation. Progress in Photovoltaics: Research and Applications 2006;14:179–90.

Meier J, Torres P, Platz R, Dubail S, Kroll U, Selvan JAA, et al. On the Way Towards High Efficiency Thin Film Silicon Solar Cells by the “Micromorph” Concept. MRS Proceedings 1996; 420; 3.

Meier J, Dubail S, Cuperus J, Kroll U, Platz R, Torres P, et al. Recent progress in micromorph solar cells. Journal of Non-Crystalline Solids 1998; 227–230(2):1250–6.

Nosrat AH, Jeswiet J, Pearce JM. Cleaner Production via Industrial Symbiosis in Glass and Large-Scale Solar Photovoltaic Manufacturing. Proceedings IEEE Toronto International Conference – Science and Technology for Humanity (TIC-STH) 2009;967-70.

Palz W, Zibetta H. Energy pay-back time of photovoltaic modules. International Journal of Solar Energy 1991;10:211–6.

Pachauri RK, Reisinger A. Climate change 2007: Synthesis report. Contribution of Working Groups I, II and III to the Fourth assessment report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change, 2007. Geneva, Switzerland.

Pearce JM. Photovoltaics – A Path to Sustainable Futures. Futures 2002. 34:663-74.

Pearce JM. Industrial Symbiosis for Very Large Scale Photovoltaic Manufacturing, Renewable Energy 2008a;33:1101-8.

Pearce JM. Thermodynamic limitations to nuclear energy deployment as a greenhouse gas mitigation technology, International Journal of Nuclear Governance, Economy and Ecology 2008b;2(1):113–30.

Pearce JM, Lau A. Net Energy Analysis For Sustainable Energy Production From Silicon Based Solar Cells. Proceedings of American Society of Mechanical Engineers Solar 2002: Sunrise on the Reliable Energy Economy. R. Cambell-Howe; 2002.

Praxair Inc. Better way to produce cold stuff. R&D. 2003. [cited 2012 Apr 15] Available from: http://www.rdmag.com/Awards/RD-100-Awards/2003/09/Better-Way-To-Produce-Cold-Stuff/

Pré, 2012, Product Ecology Consultants, SimaPro LCA Software, Amersfoort, The Netherlands.[cited 2012 Jun 8] Available from: http://www.pre-sustainability.com/content/simapro-lca-software/

SCLCI, Swiss Center for Life Cycle Inventories, EMPA – Swiss Federal Laboratory for Materials Science, Lerchenfeldstrasse 5, 9014 St-Gallen, Switzerland.

Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, et al. Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY: Cambridge University Press.

Street RA. Technology and Applications of Hydrogenated Amorphous Silicon. Berlin, Germany. Springer; 2000.

Visokey M, Meissner K, Beasley J, Viera M, Chowdhury N. Comparative Analysis of a Silane Cylinder Delivery System and a Bulk Silane Installation (ESH B001). SEMATECH: Technology Transfer 95092976A-ENG. [cited 2012 Jun 1] Available from: http://www.sematech.org/docubase/document/2976aeng.pdf

Wronski CR, Carlson, DE. Amorphous Silicon Solar Cells. In Archer MD, Hill R. Clean Electricity From Photovoltaics. Imperial College Press, London, UK, 2001.

Wronski CR, Pearce JM, Koval RJ, Ferlauto AS, Collins RW. Progress in Amorphous Silicon Based Solar Cell Technology. Proceedings of Rio 2002: World Climate and Energy Event, 2002;67-72.

3. Life Cycle Analysis of Distributed 3-D Printing and Conventional Manufacturing of Polymer Products[2]

Abstract

With the recent development of the RepRap, an open source self-replicating rapid prototyper, distributed low-cost 3-D printing is now a technically viable form of distributed manufacturing of polymer-based products. Using 3-D printers for distributed manufacturing provides the ability to ultra-customize products and to change fill composition, which increases material efficiency. This property combined with the reduction in embodied energy of transportation made available by home manufacturing allow for the possibility that it could be less energy and greenhouse gas emission intensive than conventional manufacturing. However, the aggregate environmental benefits of distributed manufacturing are not clear due the potential for increases in the overall embodied energy of the manufacturing due to reduction in scale (e.g. thermodynamic limitations to working with smaller volumes). To quantify the environmental impact of distributed manufacturing using 3-D printers, a life cycle analysis (LCA) was performed on three plastic products. The embodied energy and emissions from conventional large-scale production in low-labor cost countries and shipping are compared to experimental measurements on a RepRap producing identical products with acrylonitrile butadiene styrene (ABS) and poly-lactic acid (PLA). The results of this LCA study indicate that the cumulative energy demand of manufacturing polymer products can be reduced by 25 to 64% using distributed manufacturing with existing low-cost open-source 3-D printers when using PLA under 25% fill. These savings are increased to 45-74% with the use of solar photovoltaics, along with a dramatic decrease in emissions. These positive environmental results for distributed manufacturing are expanded to ABS, which demands hotter bed and extruder temperatures when low emission intensity sources of power are utilized such as solar photovoltaic technology, with a savings of 34-53% under 25% fill. The results indicate

---

[2] "The material contained in this chapter is planned for submission to the *Environmental Science and Technology*"

that the ability of RepRaps and similar 3-D printers to vary fill percentage has the potential to significantly diminish environmental impact on many products. It can be concluded from the results of this study that open-source additive layer distributed manufacturing is both viable and beneficial from an ecological perspective.

3.1 Introduction

The benefits of large-scale manufacturing are well established and include reduction in costs due to the economies of scale from: i) purchasing (bulk buying of materials, supplies, and components through long-term contracts), ii) increased specialization of employees and managers, iii) favorable financing in terms of interest, access to capital and variety of financial instruments, iv) marketing and v) purely technological advantage of returns to scale in the production function.[1-3] The last advantage is in part due to lower embodied energy during manufacturing of a given product because of scale. These advantages have created a general trend towards large-scale manufacturing in low-labor cost countries, especially for inexpensive plastic products.[4,5] The environmental burden that plastics consumption has on the environment is well established due to their slow decomposition rate and pollution of land, water and air.[6-8] With annual global production of 245 million tons increasing by approximately 6% per year, there is a clear need to reduce the environmental impact on global plastic consumption.[9]

One new potential method of reducing the environmental impact of plastic products is to use distributed manufacturing with low-cost open-source 3-D printers[10-13] as the nature of 3-D printing allows for the minimization of production waste while maximizing material utilization.[16] The technological development of 3-D printers has been substantial[14,15], which has benefited many industries; however, the costs of 3-D printers have historically been too expensive to be feasible for distributed or home-based manufacturing.[16] Recently, several open-source (OS) models of commercial rapid prototypers have been developed,[16] which offer an alternative model of low-cost production. The most successful of these is the self-replicating rapid prototyper (Rep Rap), which can be built from printed parts, open-source electronics, and common hardware for under $500.[17,18] The RepRap, has opened the door of additive layer manufacturing to a wide range of potential users due to cost and simplicity while making distributed small-scale production technically feasible.[10,19] The ability to change fill composition allows more complicated shapes to be produced with structural integrity while minimizing material use. This property combined with the reduction in embodied energy of transportation made available by distributed manufacturing allow for the possibility that it could be less energy and emission intensive than conventional manufacturing. However, the aggregate environmental benefits of distributed manufacturing are not clear due the potential for increases in the overall embodied energy from reduction in scale (e.g. thermodynamic limitations to working with smaller volumes).

This study evaluates the technical potential of using a distributed network of 3-D printers to produce several types of plastic components and products. A life cycle analysis (LCA) of energy consumption and greenhouse gas (GHG) emissions is performed for distributed manufacturing using low-cost open-source 3-D printers and compared to conventional manufacturing overseas with shipping. To further evaluate the distributed manufacturing system, a distributed electricity generation system using solar photovoltaic (PV) technology was quantified, as the embodied emissions are highly dependent on the grid emission intensity.[20] These results are evaluated and discussed to draw conclusions about the viability and environmental performance of distributed manufacturing.

3.2 Methods

3.2.1 Production methods

The RepRap (Prusa Mendell variant) with a 200 mm x 200 mm x 140mm (height) build envelope was used to print all product/product components using the thermoplastics: acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA).[21] PLA is made from organic material and has a low environmental impact, making it a good alternative plastic.[22] The ABS extruder temperature was 230°C and bed temperature was 110°C. PLA was printed using an extruder temperature of 185°C, with a first layer bed temperature of 63°C to ensure adhesion, followed by print bed temperature of 60°C. Energy measurements were taken using a multimeter (±0.005 kWh) during initial heating and while printing each individual object.

Three products were 3-D printed with 45 degree fill using a rectilinear pattern in ABS and PLA: a “block”, a “water spout”, and a “juicer” (Fig. 3.1).

The Naef building block is a simple, but expensive toy that is typically handcrafted in Switzerland from hardwood. The fill percentage was varied to include 0, 5, 10, 25, and 100% fill, as seen in Fig.3.2, within the PLA block in order to determine the relationship between fill percentage and environmental impact. The ABS blocks were printed only at 25% fill.

The water spout attaches to a post-consumer 2-Liter bottle and can be used to water plants replacing a typical watering can. PLA and ABS were printed at 100% fill to ensure leak protection.

The citrus juicer is used to produce juice from oranges, grapefruits, lemons, limes and other citrus fruit. It is fixed upon a post-consumer glass jar for collection. A 15% fill was used in order to reduce the amount of plastic used to produce it, while maintaining the necessary functional mechanical strength.

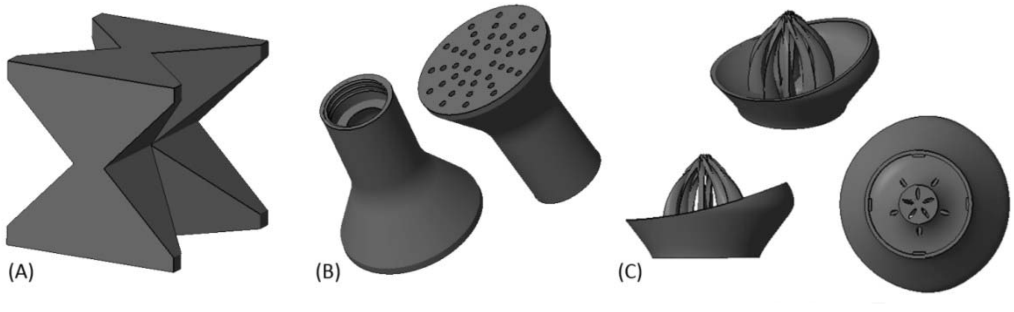

Fig. 3.1: Naef building block[23] (A), water spout[24] (B) and juicer[25] (C)

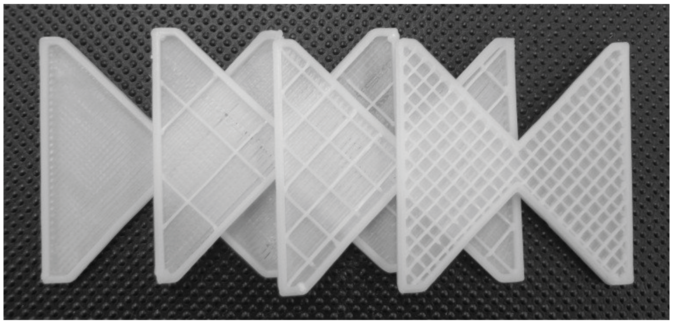

Fig. 3.2: Fill percentages for blocks 0, 5, 10, and 25% (left to right).

3.2.2 Life-cycle analysis methods

Life-cycle assessment is a growing topic of study[26] and was used here to quantify the difference in environmental impact between distributed and conventional manufacturing. Similar studies compare and improve the environmental impact of various goods, production methods, fuel sources, etc., such as lubricants[27] and cement.[28] SimaPro 7.2 was used to get the cumulative energy demand (CED 1.07) and global warming potential over 100 years (IPCC GWP 2007 100a) as kg CO_2 equivalent emissions for each product using the database EcoInvent v2.0. A "cradle-to-gate" analysis was done (from raw material extraction from nature to the product exiting the factory gate), with the gate located in the United States.

3.2.2.1 Distributed manufacturing methods

Distributed manufacturing was quantified using the electricity consumption of the RepRap and the material inputs by weight for ABS or PLA, where inventory data was obtained from these ecoprofiles: (Electricity, Production Mix, US) or (Electricity, PV, at 3kWp, a-Si panel, Switzerland) was used as an input, in addition to (Polylactide, NatureWorks Nebraska, US) and (Acrylonitrile-butadiene-styrene copolymer, Switzerland). Plastic production was assumed to be in the United States for the distributed case. United States eco-profiles were used when available, otherwise European eco-profiles were used.

3.2.2.2 Conventional manufacturing methods

Conventional manufacturing was input into SimaPro assuming a 100% fill and was input based on the weight from experimental results. The inputs used for conventional were material inputs PLA or ABS, as done for distributed assuming production of plastics in China, in addition to injection molding (Injection molding, Switzerland) and shipping 9,213 km using (Transoceanic freight ship, international) from Shanghai, China to Seattle, WA.[29] The injection molding was done with the European eco-profile due to limitations on Chinese inputs, this is presumed to underestimate the energy use and emissions due to higher regulations in Europe and the large dependence of China on coal-fired electricity. The injection molding input states that the finished product is 99.3% of its input, this was considered in the analysis for both the material input and the injection mold.

One additional version of the conventional manufacturing was done for the case of the “block” to consider wood using inputs (Sawn timber, hardwood, kiln dried U=10%, Switzerland) using a wooden cube with 2” sides and shipping 6,275 km using (Transoceanic freight ship, international) using the approximate distance from Bern, Switzerland to New York, NY.[29] Additional processing is unknown for the case of the wood block and is assumed to be underestimated in this study.

3.2.2.3 Additional assumptions and study limitations

Processing for each of these cases should be assumed to underestimate total cumulative energy demand and emissions, as additional processing may be required for consumer use (i.e. sanding, finishing, etc). Overseas shipping distance is an underestimate due to taking a straight-line trip across the ocean. Shipping over land, infrastructure, molds, packaging and waste were not included in this analysis thus underestimating the embodied energy of traditional manufacturing and are left for future work. The materials PLA and ABS were used as an example for each product, but may not be the ideal materials for these products or may require additional coatings to make them food-grade or child-safe. Limitations on input locations exist in this study, as noted above.

3.3 Results and Discussion

Measured experimental values from the RepRap are shown in column “Measured Energy” in Table 3.1 and were input into SimaPro and compared to conventional methods as described for cumulative energy demand (CED) and greenhouse gas emissions in global warming potential over 100 years (GWP) (Table 3.1).

Table 3.1.
Experimental values (measured energy), conventional (conv.) and distributed (distr.) manufacturing total cumulative energy demand values using SimaPro (CED) and emission values in global warming potential (GWP) and for distributed manufacturing with and without the use of solar PV to provide low emission intensity electricity.

Prod.	Method	Fill	Plastic	Measured Energy	CED	Δ from Conv.	CED w/PV	Δ from Conv.	GWP	Δ from Conv.	GWP w/PV	Δ from Conv.
		%	PLA or ABS	kWh	MJ eq	%	MJ eq	%	kg CO_2 eq	%	kg CO_2 eq	%
Block	Conv.	100	PLA	~	7.09	~	~	~	0.26	~	~	~
	Distr.	0	PLA	0.09	2.52	-64.5	1.84	-74.0	0.11	-57.7	0.05	-80.8
	Distr.	5	PLA	0.1	2.77	-60.9	2.02	-71.5	0.12	-53.8	0.06	-76.9
	Distr.	10	PLA	0.11	3.21	-54.7	2.38	-66.4	0.14	-46.2	0.07	-73.1
	Distr.	25	PLA	0.14	4.22	-40.5	3.16	-55.4	0.19	-26.9	0.09	-65.4
	Distr.	100	PLA	0.24	8.23	16.1	6.42	-9.4	0.35	34.6	0.19	-26.9
	Conv.	100	ABS	~	9.76	~	~	~	0.44	~	~	~
	Distr.	25	ABS	0.26	6.58	-32.6	4.62	-52.7	0.34	-22.7	0.17	-61.4
Spout	Conv.	100	PLA	~	1.93	~	~	~	0.07	~	~	~
	Distr.	100	PLA	0.1	2.55	32.1	1.80	-6.7	0.12	71.4	0.05	-28.6
	Conv.	100	ABS	~	2.38	~	~	~	0.11	~	~	~
	Distr.	100	ABS	0.19	4.20	76.5	2.77	16.4	0.22	100	0.09	-18.2
Juicer	Conv.	100	PLA	~	11.58	~	~	~	0.43	~	~	~
	Distr.	15	PLA	0.31	8.66	-25.2	6.32	-45.4	0.39	-9.3	0.18	-58.1
	Conv.	100	ABS	~	13.71	~	~	~	0.62	~	~	~
	Distr.	15	ABS	0.52	12.96	-5.5	9.03	-34.1	0.68	9.7	0.32	-48.4

The environmental impacts of the distributed manufacturing cases were minimized using a solar PV array to provide electricity following recommendations by Pearce et al. that would allow for 3-D printing fabrication in most locations in the world.[19] It has been well established that PV technology is a sustainable source of energy that significantly reduces environmental impact of electricity use and is amenable to distributed generation[30,31] and the embodied energy of PV decreases as advancements are made.[32] PV technology has the potential to prevent a significant amount of emissions[33] with at least 89% of air emissions produced by conventional electricity.[31] Although there are no commercial PV-powered RepRap 3-D printers, proof of concepts already exist and the open-source development community that supports the RepRap has been experimenting with variants.[34] These variants would enable distributed manufacturing even in remote communities without access to the conventional electric grid.

3.3.1 Naef building block

The results for the block prints had the CED and emissions compared to conventional and wood synthesis (Table 3.1 and Figs. 3.3-3.5). In the Figures, the CED is split into two categories: renewable and non-renewable energy sources involved to display the level of sustainable energy for each case. Renewable consists of renewable bio-mass, wind, solar, and water energy sources that are part of the conventional energy mix and does not directly relate to the PV-powered systems. Non-renewable consists of non-renewable energy sources fossil fuels, nuclear, and bio-mass. The CED for the blocks can be found in Table 3.1 and Figure 3.3. The CED for wood block is 2.16 MJ with emissions of 0.02 kg CO_2 eq. The CED for the conventional method for PLA and ABS at 100% fill was found to be 7.09 MJ and 9.76 MJ, respectively, which is a factor of roughly four times the embodied energy of the wood case. The CED for the distributed 25% ABS block was 6.58 MJ and with a PV system 4.61 MJ, representing 33-53% decrease over conventional production. As expected, Figure 3.4 shows a linear trend between fill ratio and energy use for blocks printed in PLA with and without PV. The addition of a PV system results in a saving of emissions from the traditional energy source between 22-27%. The CED values under the PV distributed system were less than the conventional manufacturing values for all fill percentages, while the traditional energy source distributed system is less than the conventional below 79% fill. The typical print is done at 25% fill or less, depending on the structural integrity needed, with the majority of prints being 15% or less. Producing goods with less than a 79% fill is easily achieved by the average 3-D printer for this reason, implying that distributed manufacturing will have less of an environmental impact than conventional for almost all print jobs.

The emissions for the blocks are shown in Table 3.1 and Figure 3.5. The emissions for the conventional ABS block is 0.44 kg CO_2 eq, while the distributed case without and with PV had 23 and 61% savings in emissions respectively at 25% fill. The emissions for the conventional PLA block was 0.26 kg CO_2 eq, while the distributed system PLA blocks were between 0.11-0.35 kg CO_2 eq and between 0.05-0.19 kg CO_2 eq for the distributed + PV system. The distributed manufacturing cases have the lowest emission values compared to traditional manufacturing for all cases, except for distributed without PV for 100%. Again, it is clear for this particular product 100% fill is unnecessary. This implies that without PV, distributed manufacturing should be done at the smallest percent fill acceptable for an application in order to reduce energy consumption and concomitant GHG emissions. With the use of PV, distributed manufacturing minimizes the emissions for manufacturing compared to the conventional methods. The wood block has the lowest emissions out of all cases due to being handmade and made from potentially renewable resources, but if this product was to switch to plastic, distributed PLA + PV at 0 or 5% fill should be considered as the CED is even slightly lower than the wood value for these cases. Since PLA is made from organic materials, bio-degradable, and has a high green design ranking among plastics, it would make a good alternative to wood.[22] Similar products with the same potential would be other toys or household goods in addition to other products that could be made lightweight by replacing the inside with a hatch fill to provide structural integrity.

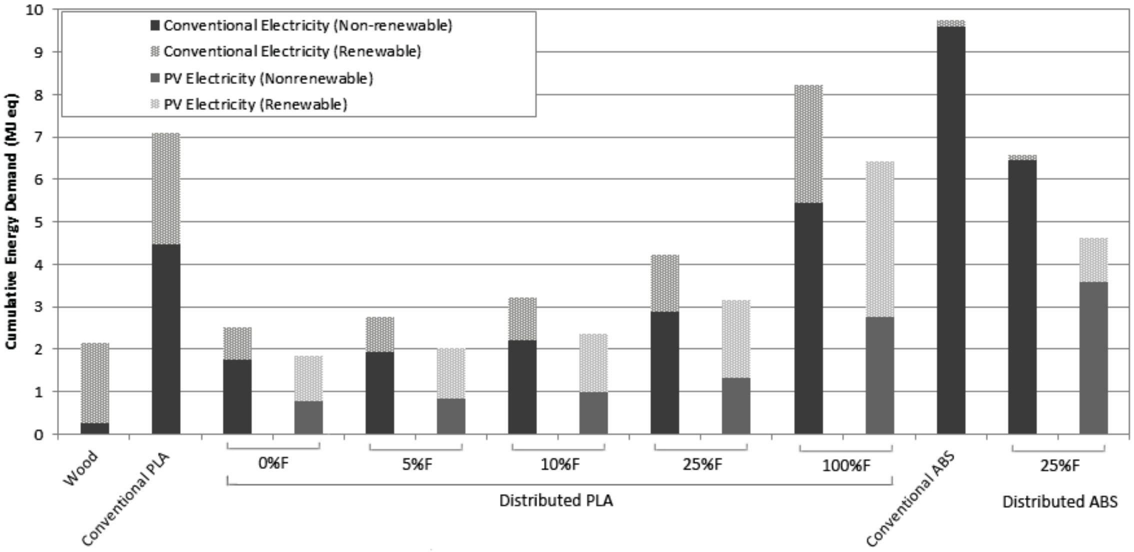

Fig. 3.3: CED of the blocks showing wood, conventional PLA and ABS at 100% fill, distributed PLA from 0-100% fill, distributed ABS 25% fill, along with the effect of PV electricity.

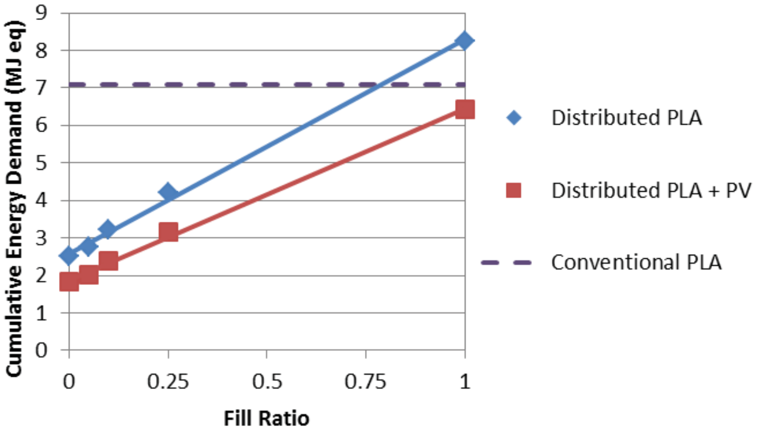

Fig. 3.4: Blocks - Fill ratio vs. energy demand. The conventional value is put here for comparison purposes, but is at 100%. If other fill percentages were possible for the conventional method, this value would change based upon fill.

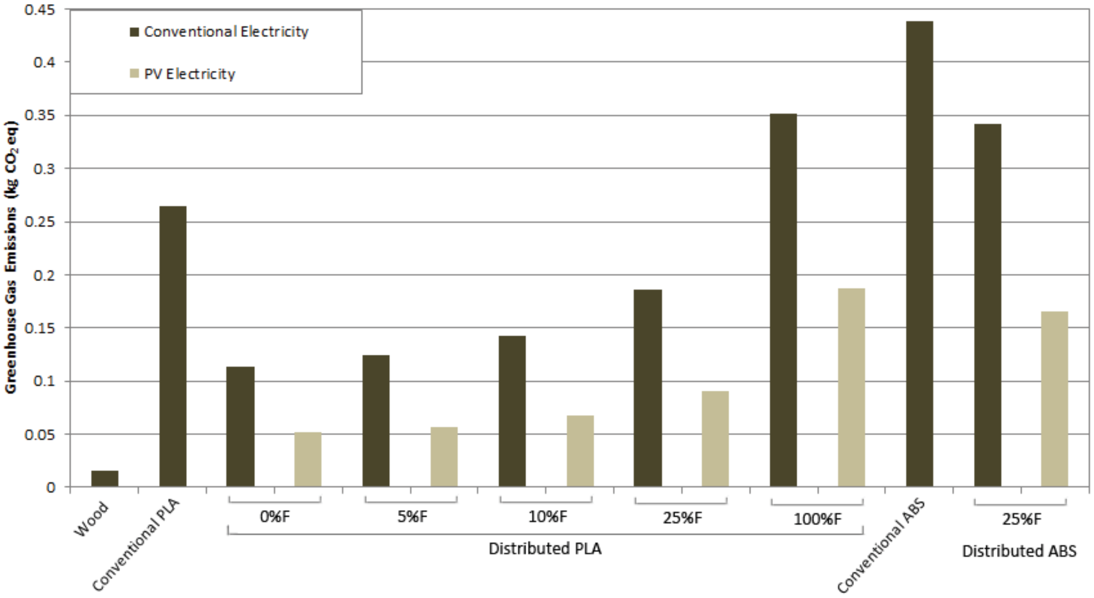

Fig. 3.5: Greenhouse gas emissions in kg CO_2 eq (GWP 100a) for the block for wood, conventional PLA and ABS 100% fill, distributed PLA from 0-100% fill, distributed ABS 25% fill, along with the effect of PV electricity.

3.3.2 Water spout

The distributed manufactured water spout not only replaces a centralized manufactured one, but also provides the interesting complexity of allowing for the re-use of a 2L bottle, while replacing a conventional watering can. The comparison was done between the distributed case and the conventional case (Figs. 3.6, 3.7). It is important to stress that this analysis was done for a spout using both distributed and conventional manufacturing, when in reality the spout created would actually be replacing a full watering can that would use more material and energy to create than shown here. For example, a 210g 2L watering can[35] made in China using injection molding in PLA or ABS would require a cumulative energy demand of 19.8 MJ or 27.4MJ and emissions of 0.738 or 1.23 kg CO_2 eq, respectively.

The CED and emissions for conventional manufacturing at 100% fill using PLA and ABS were found to be 1.93 and 2.38 MJ, and 0.07 and 0.11 kg CO_2 eq, respectively. The distributed case using 100% fill without PV yielded slightly higher values for PLA and ABS of 2.55 and 4.2 MJ, and 0.12 and 0.22 kg CO_2 eq for CED and emissions, respectively. While these values are higher than the conventional method listed, a full watering can under conventional methods would require 6.5 times more energy than distributed for ABS and 7.5 times more for PLA, due to the amount of plastic and processing required to make the entire can. The distributed values were minimized for PLA and ABS using PV to get 1.8 and 2.77 MJ, and 0.05 and 0.09 kg CO_2 eq, respectively. PLA with PV resulted in a 6.7% cumulative energy savings over the conventional spout production, while ABS with PV was 16.4% larger than the cumulative energy for conventional. Using the same fill percentage (100%) for distributed and conventional manufacturing resulted in conventional having lower CED values for all cases except distributed PLA + PV. The emissions were reduced using distributed manufacturing PLA + PV and ABS + PV, as shown in Figure 3.7. The production of an entire watering can was 7.5 times higher than that of a spout produced out of PLA with conventional electricity, which implies that reducing the amount of raw materials used in production by replacing a large volume object with a post-consumer good that requires little to no additional processing, will dramatically decrease the environmental impact associated with the end product.

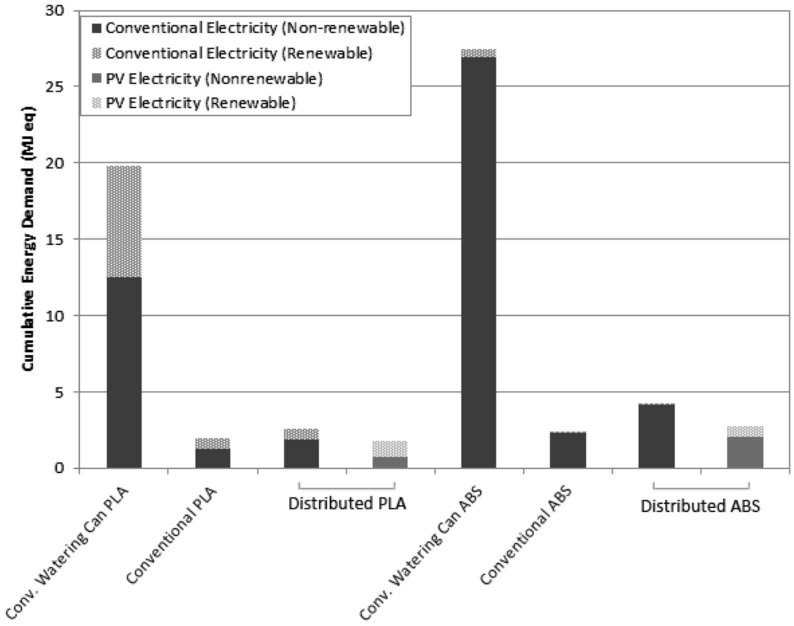

Fig. 3.6: CED of the spout showing conventional PLA and ABS at 100% fill, distributed PLA and ABS at 100% fill, along with the effect of PV electricity.

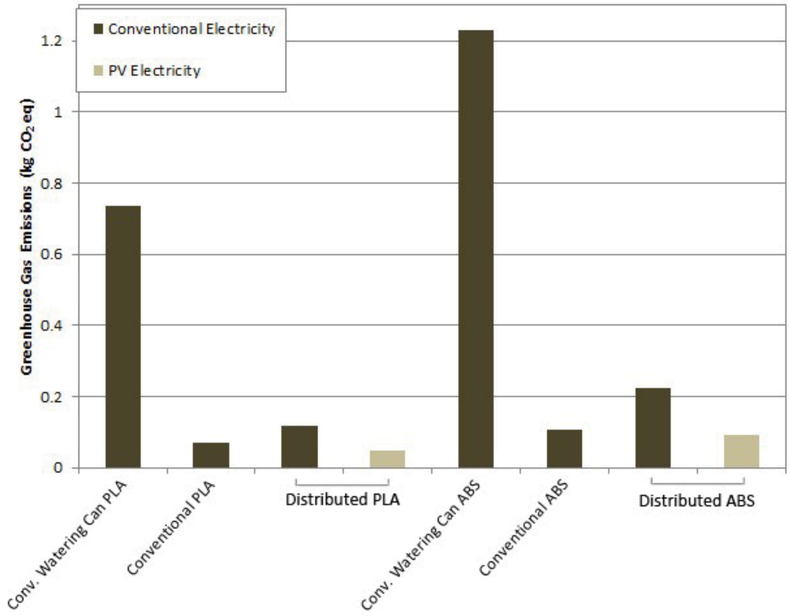

Fig. 3.7: Greenhouse gas emissions in kg CO_2 eq (GWP 100a) for the watering can and spout for conventional PLA and ABS 100% fill, distributed PLA and ABS at 100% fill, along with the effect of PV electricity.

3.3.3 Citrus juicer

Conventional PLA and ABS citrus juicers at 100% fill had CED of 11.58 and 13.71 MJ, respectively; while distributed PLA and ABS juicers at 15% fill and made with conventional electricity decreased these values by 25% and 6%. The addition of a PV system reduced the values an additional 20-29 percent. Similar results were seen for emissions as can be seen in Fig 3.9. The energy is minimized using distributed manufacturing for the juicer and is made possible by using a smaller fill percentage. This not only reduces material use in the product itself, but also the environmental impact of the processing and embodied energy use in the raw material extraction and transportation. The use of PV to power the RepRap minimizes both the emissions and the energy use for distributed manufacturing even further.

The emissions are lower for the distributed manufacturing systems for all cases except the ABS juicer without PV. This is due to the relatively large amount of energy needed to keep the heated build platform at operating temperature for the ABS. Future work is necessary to reduce the energy needed for the build platform. This can be done by using chemical means to enable better adhesion, using zoned heating so only the parts of the bed under the part are heated, better insulating the bottom of the bed, or using a controlled environmental chamber to insulate the entire RepRap from cold ambient temperatures.

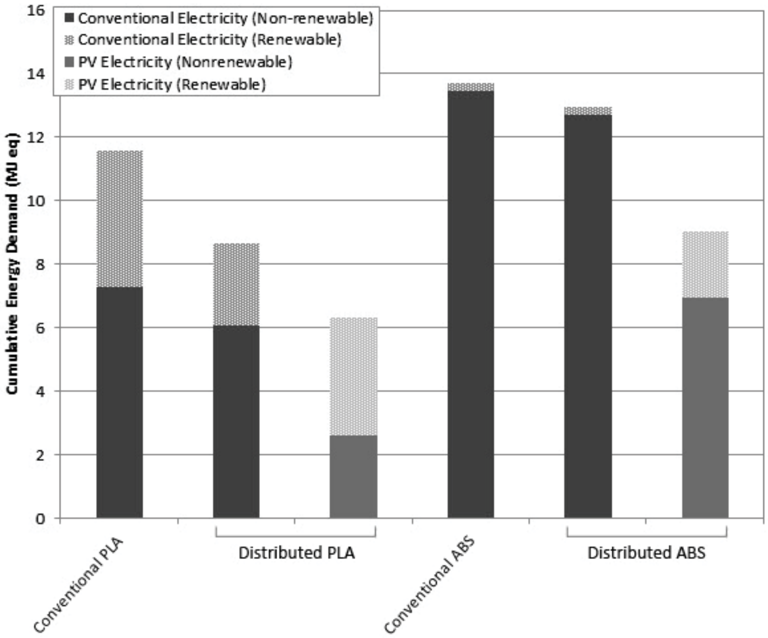

Fig. 3.8: CED of the juicer showing conventional PLA and ABS at 100% fill, distributed PLA and ABS at 15% fill, along with the effect of PV electricity.

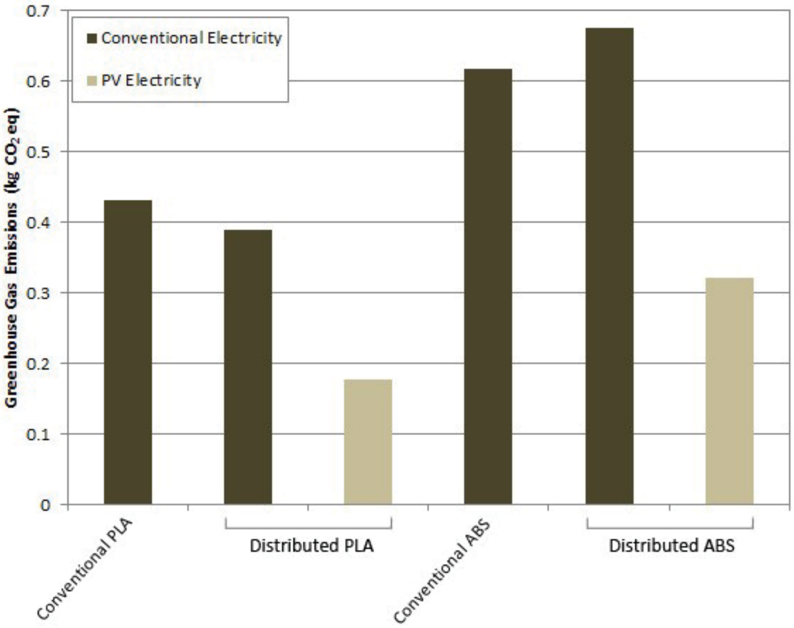

Fig 3.9: Greenhouse gas emissions in kg CO_2 eq (GWP 100a) for the juicer for conventional PLA and ABS 100% fill, distributed PLA and ABS at 15% fill, along with the effect of PV electricity.

3.4 Discussion

Conventional manufacturing is limited on internal manipulation of a product, however with the use of the RepRap, this is no longer a barrier to improved material efficiency. The use of 3-D printers allows for previously impossible shapes under conventional manufacturing methods (e.g. injection molding) along with the ability to manipulate the inside of an object during production in multiple ways, such as, adding internal parts or fill composition, which can be altered by pattern (rectilinear, honeycomb, etc), angle, percentage, along with adding solid fill layers when necessary.[10,18,36] This ability has the potential to reduce additional machining during processing, since holes and other needs that were impossible using methods similar to injection molding had to previously be done using tools, such as, drill presses. These steps are now able to be created during the design step, have the digital design files shared and automatically produced using any, open-source 3-D printer.[10]

The results of this study show that distributed manufacturing with a 3-D printer requires less cumulative energy than conventional manufacturing when products are made from PLA and ABS for a fill composition less than 0.79. For many products or components that do not have a need for significant mechanical strength may be possible to print considerably below 79% fill, indicating that it may be possible to 3-D print products at a lower environmental impact than conventional manufacturing. It should be pointed out that if more products are printed simultaneously on the heating bed, it is possible to reduce the energy to print even further due to the initial heating energy being dispersed among more individual products. For example, when printing two blocks simultaneously under the same conditions and settings as a single block made out of PLA at 10% fill under conventional electricity, there was an energy savings of 4% and an emission reduction of 5% over printing a single block. When distributed manufacturing is used in conjunction with a solar PV system, the cumulative energy is further decreased. This benefit could also be applied to the conventional system, although the scale of PV for conventional manufacturing makes this more difficult due to the high energy requirements associated with mass-scale production. PV is much more practical for distributed manufacturing, as there is a smaller energy requirement for production.

Distributed manufacturing creates fewer emissions than conventional manufacturing when PLA is used at a minimal fill composition and in cases using PV electricity with ABS. The environmental benefits of PLA are already being considered in the 3-D printing community due to the reduction of toxins, material use, and other impacts on the environment.

Distributed recycling is also being developed to recycle post-consumer products into filament for a 3-D printer, which could further reduce cost and resources required for distributed manufacturing.[37-40] The open-source small-scale models of commercial plastic extruders currently under development are the RecycleBot[41,42], the Filabot[43,44] and the MiniRecycleBot.[45] For the juicer, which requires 0.31 kWh to produce, if it could be produced for the same amount of electricity in recycled HDPE using the distributed recycling system, the juicer would cost only 4 cents, instead of $2.76 using PLA filament or $7-25 commercially.[40] All other products (water spout, blocks), under the same conditions, use less electricity to produce and less material, meaning that any of these items can be produced well under 4 cents, even at 100% fill. Similarly, for the water spout (watering rose) or the watering can, which can be bought retail for about $10, using the distributed water spout can save over $9.96 or 99%. If the blocks are compared to a set 16 Naef wood blocks which retail for $160, a set of 16 blocks using recycled filament would cost you less than 64 cents, that is $159.36 savings or over a 99% savings. Future work needs to be done to compare printer cost and maintenance per part manufactured and added to this preliminary cost analysis.

The 3-D printing community is fast growing and the amount of RepRaps in use has increased from 4 to 4500 between 2008 and 2011.[16] 3-D printing has the potential to revolutionize how people think about manufacturing. This allows people to make things within their own homes and as customized as they would like instead of buying mass produced items off the shelf. Almost any amount of plastic good can be produced using a RepRap and research is underway on using other printing materials. Since the RepRap community is open-source, this allows anyone to build and use their own 3-D printer and create any item that is on the Internet. This sharing is already quite established. For example, Thingiverse, a database of designs for real physical objects, the vast majority of which can be printed on a RepRap currently houses over 26,000 items. These designs are generally shared with some form of open license, thereby adding value to anyone that owns a 3-D printer. As this database and other similar efforts continue to grow the value of access to 3-D printing expands and thus creates a positive feedback loop.

This was a study on a limited number of products and future work is necessary to quantify the LCAs of distributed vs. conventional manufacturing of other types of products. An ideal study would consist of a cradle-to-grave analysis for both conventional and distributed manufacturing, including all infrastructure, packaging, and transportation. For distributed manufacturing, a various number of products being printed on several different printers in order to get an estimate of the average energy use for 3-D printers. For conventional manufacturing, a more accurate analysis could be done by communicating with plastics manufacturers to determine any additional inputs or processes required for manufacturing. Limitations with EcoInvent currently consists of a lack of available inputs for the country needed, such as China, as these inputs become available, the limitations of future studies can be minimized as the EcoInvent database grows.

The results of this LCA study indicate that the environmental impact of manufacturing polymer products can be reduced using distributed manufacturing with existing low-cost open-source 3-D printers when using PLA. This indicates that distributed manufacturing is technically viable and environmentally beneficial because of both reduced energy consumption and greenhouse gas emissions. These positive environmental results for distributed manufacturing are expanded to ABS, which demands hotter bed and extruder temperatures when low emission intensity sources of power are utilized such as solar photovoltaic technology. The results indicate that the ability of RepRaps and similar 3-D printers to vary fill percentage has the potential to significantly diminish environmental impact on many products. It can be concluded from the results of this study that open-source additive layer distributed manufacturing is both viable and beneficial from an ecological perspective.

Acknowledgements

The authors would like to acknowledge helpful discussions with D.R. Shonnard, B. Tymrak and G. Anzalone. This research was supported by Sustainable Futures Institute.

References

1. Mukherjee, S. *Modern Economic Theory*. New Age International. **2007**.
2. Miltenburg, J. *Manufacturing strategy: how to formulate and implement a winning plan*. Productivity Press. **2005**.
3. Pearce, J.M. Industrial symbiosis for very large scale photovoltaic manufacturing. *Renew. Energy.* **2008***, 33*, 1101-1108. DOI: 10.1016/j.renene.2007.07.002.
4. Kravis, I. B.; Lipsey, R. E. The location of overseas production and production for export by U.S. multinational firms. *J. of Int. Econ.* **1982**, *12* (3), 201-223.
5. Ruamsook, K.; Russell, D.; Thomchick, E. U.S. sourcing from low-cost countries: a comparative analysis of supplier performance. *J. of Supply Chain Management.* **2007**, *43*(4), 16-30. DOI: 10.1111/j.1745-493X.2007.00038.x.
6. Rees, J. F. The fate of carbon compounds in the landfill disposal of organic matter. *Journal of Chemical Technology and Biotechnology*. **1980**, *30* (1):161-75. DOI 10.1002/jctb.503300121.
7. Derraik, J. G. B. The pollution of the marine environment by plastic debris: a review. *Marine Pollution Bulletin*. **2002**, *44* (9), 842-852. DOI: 10.1016/S0025-326X(02)00220-5
8. Lewis, R.; Sullivan J. B. Toxic hazards of plastic manufacturing, in Sullivan JB, Krieger GR (eds): Hazardous Materials Toxicology: Clinical Principles of Environmental Health. Baltimore, Williams & Wilkins; 1992. p. 505–515.
9. Shen, L.; Haufe, J.; Patel, M. K. Product overview and market projection of emerging bio-based plastics. Copernicus Institute for Sustainable Development and Innovation-Utrecht University; 2009.
10. Gershenfeld, N. *Fab: The Coming Revolution on Your Desktop – from Personal Computers to Personal Fabrication*; Basic Books: New York, NY, 2005.
11. Corney, J. The next and last industrial revolution?. *Assembly Automation*. **2005**, *25* (4),

257.

12. Cano, J. The Cambrian explosion of popular 3D printing. *Int. J. of Artificial Intelligence and Interactive Multimedia*. **2011**, *1* (4), 30-32.
13. Bradshaw, S.; Bowyer, A.; Haufe, P. The intellectual property implications of low-cost 3D printing. *ScriptEd*. **2010**, *7* (1), 1-27; DOI 10.2966/scrip.070110.5.
14. Crane, N. B.; Tuckerman, J.; Nielson, G. N. Self-assembly in additive manufacturing: opportunities and obstacles. *Rapid Prototyping Journal*. **2011**, *17* (3), 211-217; DOI: 10.1108/13552541111124798
15. Petrovic, V.; Gonzalez, J. V. H.; Ferrando, O. J.; Gordillo, J. D.; Puchades, J. R. B.; Griñan, L.P. Additive layered manufacturing: sectors of industrial application shown through case studies. *Int. J. of Production Research*. **2011**, *49*, (4), 1061-1079; DOI:10.1080/00207540903479786.
16. Jones, R.; Haufe, P.; Sells, E. RepRap - the replicating rapid prototype. *Robotica.* **2011**, *29*(1), 177–191; DOI: 10.1017/S026357471000069X.
17. Arnott, R. The RepRap project – open source meets 3D printing. *Computer and Information Science Seminar Series*. **2008**.
18. Sells, E.; Bailard, S.; Smith, Z.; Bowyer, A. RepRap: the replicating rapid prototype maximizing customizability by breeding the means of production. *MCPC 2007*. **2007**. No. MCPC-045-2007. Cambridge, MA.
19. Pearce, J. M.; Morris Blair, C.; Laciak, K. J.; Andrews, R.; Nosrat, A.; Zelenika-Zovko, I. 3-D printing of open source appropriate technologies for self-directed sustainable development. *J. of Sust. Dev.* **2010**, *3*(4), 17-29.
20. Weber, C. L.; Jaramillo, P.; Marriot, J.; Samaras, C. Life cycle assessment and grid electricity: what do we know and what can we know?. *Environ. Sci. Technol.* **2010**, *44* (6), 1895-1901; DOI: 10.1021/es9017909.
21. *RepRap* Website; http://reprap.org/wiki/Main_Page.
22. Tabone, M. D.; Cregg, J. J.; Beckman, E. J.; Landis, A. E. Sustainability metrics: life cycle assessment and green design in polymers. *Environ. Sci. Technol.* **2010**, *44* (21), 8264-8269; DOI: 10.1021/es101640n.
23. *Thingiverse - Naef building block*; http://www.thingiverse.com/thing:31634.

24. *Thingiverse – Watering rose for plastic bottle with threads*; http://www.thingiverse.com/thing:10600.

25. *Thingiverse – Repaired Samuel Bernier orange juicer*; http://www.thingiverse.com/thing:21100.

26. Guinée, J. B.; Heijungs, R.; Huppes, G. Life cycle assessment: past, present, and future. *Environ. Sci. Technol.*, **2011**, *45* (1), 90–96; DOI: 10.1021/es101316v.

27. Miller, S. A.; Landis, A. E.; Theis, T. L.; Reich, R.A. A comparative life cycle assessment of petroleum and soybean-based lubricants. *Environ. Sci. Technol.* **2007**, *41* (11), 4143-4149; DOI**:** 10.1021/es062727e.

28. Boesch, M. E.; Hellweg, S. Identifying improvement potentials in cement production with life cycle assessment. *Environ. Sci. Technol.* **2010**, *44* (23), 9143-9149; DOI: 10.1021/es100771k.

29. *City distance calculator* Website; http://www.geobytes.com/citydistance.htm.

30. Pearce, J.M. Photovoltaics – a path to sustainable futures. *Futures* **2002**, *34*(7), 663-674.

31. Fthenakis, V. M.; Kim, H. C.; Alsema, E. Emissions from photovoltaic life cycles. *Environ. Sci. Technol*. **2008**, *42* (6), 2168–2174; DOI: 10.1021/es071763q.

32. Zhai, P.; Williams, E. D. Dynamic Hybrid Life Cycle Assessment of Energy and Carbon of Multicrystalline Silicon Photovoltaic Systems. *Environ. Sci. Technol*. **2010**, *44* (20), 7950–7955; DOI: 10.1021/es1026695.

33. Katzenstein, W.; Apt, J. Air Emissions due to wind and solar power. *Environ. Sci. Technol.* **2009**, *43* (2), 253–258; DOI: 10.1021/es801437t

34. Mobile solar powered 3D printer; http://www.appropedia.org/Mobile_solar_powered_3D_printer

35. 2L plastic garden watering can; http://www.b2bage.com/product-sprayers/1226896/2l-plastic-garden-watering-can.html

36. E. Sells, Z. Smith, S. Bailard, A. Bowyer, V. Olliver. RepRap: the replicating rapid prototype – maximizing customizability by breeding the means of production. In: Piller, F. T. and Tseng, M. M. eds. *Handbook of Research in Mass Customization and Personalization*, Vol. 1. World Scientific, pp. 568-580.

37. C. Baechler, M. DeVuono, J.M. Pearce. *Rapid Prototyping.* **2013.** *19* (2)(in press).
38. Kreiger, M. A.; Pearce, J.M. Environmental impacts of distributed manufacturing from 3-D printing of polymer components and products. *Mat. Res. Soc. Symp. Proc*. **2012** (in press).
39. Kreiger, M. A.; Anzalone, G. C.; Mulder, M. L.; Glover, A.; Pearce J. M. Distributed recycling of post-consumer plastic waste in rural areas. *Mat. Res. Soc. Symp. Proc*. **2012** (in press).
40. Kreiger, M. A.; Mulder, M. L., Glover, A.; Pearce, J. M. Life cycle analysis of distributed recycling of post-consumer high density polyethylene for 3-D printing filament. **2013**. (To be published).
41. Braanker, G. B.; Duwel, J. E. P.; Flohil, J. J.; Tokaya, G. E. Developing a plastics recycling add-on for the RepRap 3D-printer. Delft University of Technology. **2010**.
42. *RecycleBot blog* Website; http://recyclebot.tumblr.com/archive.
43. *Filabot Personal Filament Maker for 3D Printers* Website; http://filabot.com/.
44. *Lyman Filament Extruder*; http://www.thingiverse.com/thing:30642.
45. *MiniRecyclebot – RepRapWiki* Website; http://reprap.org/wiki/MiniRecyclebot.

4. Life Cycle Analysis of Distributed Recycling of Post-Consumer High Density Polyethylene for 3-D Printing Filament[3]

Abstract

Life cycle analysis studies were performed on the recycling of high density polyethylene (HDPE) 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 RepRap. The embodied energy and carbon dioxide emissions were calculated for HDPE 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. HDPE currently recycled, more than 100 million MJ of energy could be conserved per annum along with the concomitant significant reductions in greenhouse gas emissions. 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.

Keywords (6): distributed recycling; life cycle analysis; plastic; polymer; recycling; transportation energy

---

[3] "The material contained in this chapter has been submitted to *Resources, Recycling, and Conservation*."

4.1 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). Plastics are not only used for food packaging and cheap parts, but 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 (Arena et al., 2003; Björklund, 2005; Craighill, 1995; Perugini et. al., 2005; Powell, 2010; Reich, 2005; Ross, 2003; Rydberg, 1995; Song and Hyun, 1999; 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 (EIA, 2011) equivalent to the amount of oil Texas used in 2010 (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. 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 is recycled at such low rates in conventional centralized recycling is the challenge of collection and transportation for high volume, low weight polymers. 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. The development of additive manufacturing for rapid prototyping and 3-D printing in a number of technologies has been substantial (Crane et al., 2011; Gebhardt et al., 2010; Gibson et. al., 2010; 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, 2012; Kreiger and Pearce, 2013; 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., 2012; RecycleBot, 2010). As the RecycleBot is an open-source project there are several other variants under development: the Filabot, which includes an open-source shredder (McNaney, 2012), the Lyman Filament Extruder (Lyman, 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 currently work 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. Using the cut-off method of life cycle analysis (LCA), the embodied energy of recycled HDPE is 24% less than virgin plastic (Grant and James, 2005), 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.

4.2 Methods

The embodied energy and CO_2 emissions were calculated for HDPE recycling using SimaPro 7.2 and the database EcoInvent v2.0. The LCA began with collection and transportation of post-consumer plastic through the recycling process as indicated for the conventional recycling process shown in Figure 4.1. For the distributed recycling process, the LCA was calculated for the plastics from transportation through filament drawing in the RecycleBot as seen in Figure 4.2.

In the conventional recycling process (Figure 4.1), 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 either sorted on site or sent to a separation facility to sort and 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.

As can be seen in Figure 4.2, 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. This method produces 49g 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) , which melts them and forms a 3mm filament that is then used in a RepRap or other 3-D printer, as detailed in (Baechler et al., 2013; Kreiger, et al., 2012). 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, 2012).

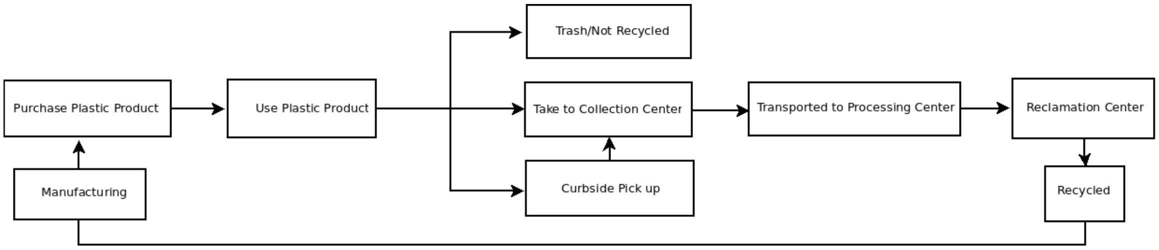

Figure 4.1: Schematic of Conventional HDPE Recycling

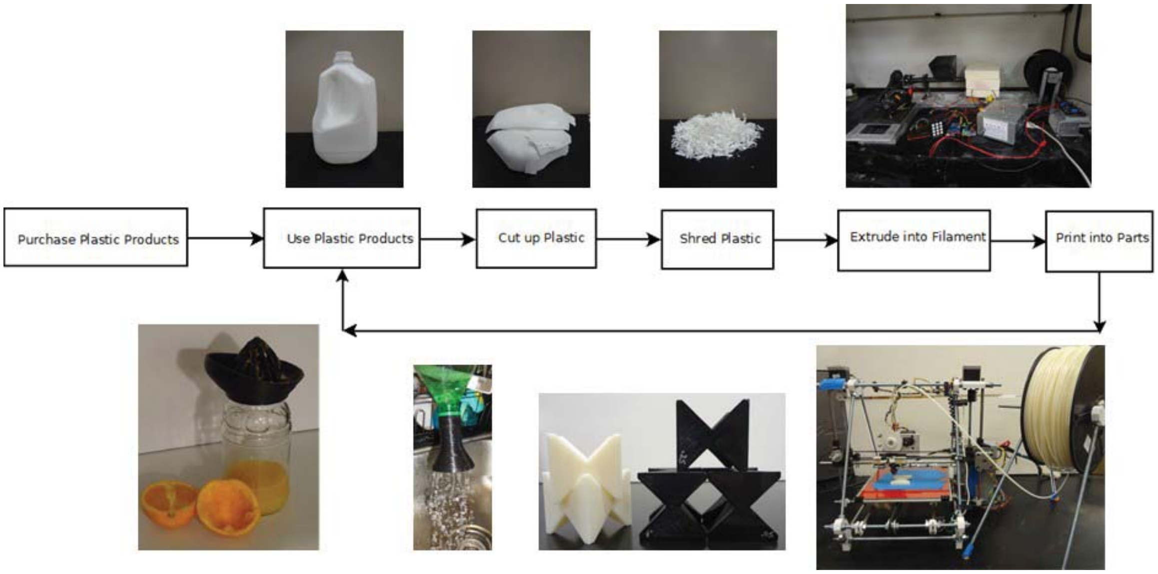

Figure 4.2: Schematic of Distributed HDPE Recycling

The energy consumption of the distributed recycling process was quantified experimentally using watt/electrical energy meters (±0.005 kWh) to monitor an insulated RecycleBot during extrusion of 10m 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).

LCAs were completed for both processes, with recycled pellets or filament as the end point, using a best and worst case scenario outlining the maximum and minimum collection distances in the U.S. An example of a "best case scenario" for conventional recycling is a city like Detroit, MI, where there are four collection centers in metro Detroit, as well as curbside pickup, which funnels into one processing center (Horton, 2009) for greater Detroit. After separation at the processing center, the plastic bales are sent to BATA plastics in Grand Rapids, MI, 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 on the scale of 1 kg output.

For the "worst case scenario" for centralized recycling, which represents a low population density, small, geographically isolated town of Copper Harbor, MI 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, MI and there is no curbside pickup. The sole purpose of this drive is assumed to be recycling. From Houghton, MI the plastics are then driven in a garbage truck to Green Bay, WI, 212 miles away, to the processing center. Transport after this point is included in the literature input (Franklin Associates, 2011). The average household generates 16.9 pounds of recyclables per week (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, MI, (Operation, lorry 3.5-20t, full, fleet average, Switzerland) for the drive from Houghton to Green Bay,WI, and a similar input for an empty truck for the return trip to Houghton. Assuming the average load for the truck was 38,990 lbs and a contamination amount of 8% (Franklin Associates, 2011).

4.3 Results

Table 4.1 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 5.64g/m, a kg of HDPE is 177.3 m of filament. The total energy use for filament production (including shredding(assumed negligible), 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 over 11 records 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 4.1. 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 (2012).

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 4.1
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 1kg output (Franklin Associates, 2011)
c. Percent reduction = (Central-Distributed)/Central*100

The amount of energy for the conventional cases attributed 7.51 MJ 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 4.1, when comparing the centralized recycling for low density population on either a bi-weekly 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. The transport from Houghton, MI to Green Bay, WI was found to be minimal at a value of 0.41 MJ eq. Every 2 weeks every kg of HDPE consumes 41 MJ from the round-trip drive from Copper Harbor to Houghton, MI. 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 20.5MJ/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.

4.4 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. The best case conventional method and distributed method are almost equal, however in any low population density area distributed manufacturing has an environmental advantage over conventional recycling for HDPE. 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 the savings of

116,000,000 MJ of energy, equivalent to the energy used by more than 2,800 American household's per year (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.

The distributed recycling advantage comes from both the low-overhead equipment 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 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. Similarity, when fewer plastics go through the large scale recycling system, less materials are 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 bottles 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. For example, at an average U.S. utility cost of $0.1153/kWh (Electric Choice, 2010), an orange juicer of volume 63.4 cm3 of PLA uses 0.31 kWh to produce on a RepRap (Kreiger and Pearce, 2012; Kreiger and Pearce, 2013). This would cost about 3.5 cents in electricity to print. If purchasing commercial filament at $36/kg of filament for a 75.47g juicer of 3mm 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 products if people are willing to invest their time to make them. The cost of the RecycleBot/RepRap system is approximately $700 and should be factored into this decision, if high value items are produced, the system cost is easily paid for. As has previously been shown such radical decreases in costs can be obtained for high-value items such as scientific equipment (Pearce, 2012) using only the RepRap and would be reduced even further using recycled post-consumer plastic for filament as shown in this paper. Yet it is not necessary for the RecycleBot operator to even make a finished product to profit financially. Even considering only the cost of commercial 3-D filament (ABS or PLA) that currently ranges from $36-50/kg, the RecycleBot is economic as it can produce 1 kg of filament from about 20 milk jugs for under 10 cents.

The economic advantages to moving to a distributed recycling/manufacturing process are clear. This method would especially appeal to those in the burgeoning 'make movement' who enjoy making things themselves over purchasing them. However, those involved with the more traditional informal economy would also potentially benefit 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, keyboard parts, etc. Other examples of people who would benefit from the use of the RepRap would be artists, as the RepRap has nearly unlimited possibilities for artistic creations. Thingiverse is a repository of digital designs, most of which can be printed on a RepRap, currently holds over 36,000 open-source designs and is growing rapidly (Thingiverse, 2012). 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.

With the open source 3-D printing network expanding rapidly the applications of 3-D printing for distributed manufacturing are also expanding rapidly. Dozens of new designs are shared on Thingiverse daily. In addition, the methods for inputting designs are expanding rapidly. Now rather than simply using existing CAD, Google Sketchup, or other drawing software, OpenSCAD is gaining popularity which allows for parametric computer coding of 3-D designs. Finally, there are also physical inputs. Development has started on open-source scanners that can produce 3-D meshes, which are compatible with RepRap printers. For example the MakerScanner uses a low-power laser and a webcam to scan a selected object into open-source software which translates it into a CAD design (MakerScanner, 2012). There is also a free commercial package from Autodesk, 123D Catch, which enables the same 3-D model making from combining digital photographs taken from many angles. These methods could be used to assist RepRap users in easily duplicating objects or customizing products for specific people or cultures. The use of fairly specialized tools such as the RecycleBot and RepRap are not developed enough for mass consumer appeal at the moment, although the trend in reliability is heading in that direction. Thus, it is likely that the tools would first become available for many communities in quasi-centralized facilities such as schools, libraries, companies, and maker spaces. Already Staples has announced they will be offering 3-D printing services similar to their historic 2-D printing services. As their utility and reliability expand the number of tools and their distribution would be likely to expand – again following current trajectories.

The low cost and reproducibility of the RecycleBot and RepRap and their product designs make them ideal for use in a developing world (Pearce, et al., 2010). A self-replicating 3-D printer could 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. A major concern in the developing world is water distribution. One of the PeaceCorps 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. 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.

4.5 Conclusions

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%. 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. 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.

Acknowledgements

The authors would like to acknowledge helpful discussions with D.R. Shonnard and G. Anzalone. This research was supported by Sustainable Futures Institute and the McArthur Research Internship at Michigan Tech.

References

American Chemistry Council and Association of Postconsumer Plastic Recyclers. 2010 United States national post-consumer plastics bottle recycling report. American Chemistry Council; 2011.

Arena U, Mastellone ML, Perugini F. Life Cycle assessment of a plastic packaging recycling system. The International Journal of Life Cycle Assessment 2003;8(2):92-8.

Baechler C, DeVuono M, Pearce JM. Distributed recycling of waste polymer into RepRap feedstock. Rapid Prototyping Journal 2013;19:2.

Björklund A. Recycling revisited - life cycle comparisons of global warming impact and total energy use of waste management strategies. Resources, Conservation and Recycling 2005;44(4):309-17.

Bow JK, Parvizi J. The History of Modern Total Knee Replacement. In: Parvizi J, Klatt B, editors. Essentials in Total Knee Arthroplasty. SLACK Incorporated; 2011.

Braanker GB, Duwel JEP, Flohil JJ. Developing a plastics recycling add-on for the RepRap 3D-printer. Delft University of Technology; 2010. [cited 2012 Sept 6] Available from: http://reprapdelft.files.wordpress.com/2010/04/reprap-granule-extruder-tudelft1.pdf

The Cambridge - MIT Institute. The ImpEE Project: Improving Engineering Education. The Cambridge-MIT Institute; 2005. [cited 2012 Sept 1] Available from: http://www-g.eng.cam.ac.uk/impee/?section=topics&topic=RecyclePlastics

Sugar Replaces Petroleum in Major Chemical Process. Chemical Engineering Progress 2008;104(10):19-20.

Craighill AL, Powell JC. Lifecycle assessment and economic evaluation of recycling: a case study. Resources, Conservation and Recycling 1994;17:75-96.

Crane NB, Tuckerman J, Nielson GN. Self-assembly in additive manufacturing: opportunities and obstacles. Rapid Prototyping Journal 2011;17(3):211-7.

Derraik JGB. The pollution of the marine environment by plastic debris: a review. Marine Pollution Bulletin 2002;44:842-52.

Electric Choice. Electricity Prices by State. Electric Choice; 2010. [cited 2012 Sept 5] Available from: http://www.electricchoice.com/electricity-prices-by-state.php

Franklin Associates. Life cycle inventory of 100% postconsumer HDPE and PET recycled resin from postconsumer containers and packaging. Kansas: Prairie Village; 2011. Available from: http://plastics.americanchemistry.com/Education-Resources/Publications/Life-Cycle-Inventory-of-Postconsumer-HDPE-and-PET-Recycled-Resin.pdf

Gebhardt A, Schmidt FM, Hotter JS, Sokalla W, Sokalla P. Additive manufacturing by selective laser melting the realizer desktop machine and its application for the dental industry. Physics Procedia 2010;5:543-9.

Gibson I, Rosen DW, Stucker B. Additive manufacturing technologies: rapid prototyping to direct digital manufacturing. Physics Procedia 2010;5:543-54.

Grant T, James K. Life Cycle Impact Data for Resource Recovery from C&I and C&D Waste in Victoria. RMIT University, Centre for Design 2005.

Hammond G, Jones C. Inventory of carbon & energy (ICE) Version 1.6a. Bath U; 2008.

Hood J. How green was my balance sheet. Policy Review 1995;74.

Horton T. Waste management opens detroit recycling center. Waste management; 2009. [cited 2012 Sept 2] Available from: http://www.wm.com/about/press-room/2009/20090617_WM_Opens_Detroit_Recycling_Center.pdf

Kreiger M, Anzalone GC, Mulder ML, Glover A, Pearce JM. Distributed recycling of post-consumer plastic waste in rural areas. Mat. Res. Soc. Symp. Proc. 2012 (in press).

Kreiger M, Pearce JM. Environmental Impacts of Distributed Manufacturing from 3-D Printing of polymer components and products. Mat. Res. Soc. Symp. Proc. 2012 (in press).

Kreiger M, Pearce JM. Life cycle analysis of distributed 3-D printing and conventional manufacturing of polymer products. 2013. To be published.

Lebreton LC-M, Greer SD, Borrero JC. Numerical modeling of floating debris in the world's oceans. Marine Pollution Bulletin; 2012:64(3):653-61.

Lewis R, Sullivan JB. Toxic hazards of plastic manufacturing. Hazardous Materials Toxicology: Clinical Principles of Environmental Health. Baltimore: Williams & Wilkins; 1992. p. 505–15.

Lotfi A. Plastic/Polymer Recycling; 1997. [cited 2012 Sept 1] Available from: http://www.lotfi.net/recycle/plastic.html

Lyman H. Lyman Filament Extruder. 2012. [cited 2012 Dec 2] Available from: http://www.thingiverse.com/thing:30642

MakerScanner. MakerScanner - open source 3d scanning. [cited 2012 Sept 12] Available from: http://www.makerscanner.com/

McCraw D, Motes JE. Use of plastic mulch and row covers in vegetable production. Division of Agricultural Sciences and Natural Resources - Oklahoma State University. [cited 2012 Sept 1] Available from: http://pods.dasnr.okstate.edu/docushare/dsweb/Get/Document-1099/F-6034%20web.pdf

McNaney T. Filabot Personal Filament Maker for 3D Printers. Filabot; 2012. [cited 2012 Aug 31] Available from: http://filabot.com/

MiniRecyclebot – RepRapWiki. RepRapWiki; 2012. [cited 2012 Sept 12] Available from: http://reprap.org/wiki/MiniRecyclebot

Missouri Department of Natural Resources. Recycling Economics: Higher Costs Are An Illusion. [cited 2012 Sept 2] Available from: http://www.dnr.mo.gov/env/swmp/pubs-reports/rececon.htm

Ohio Department of Natural Resources (DNR) - Division of Recycling & Litter Prevention. Plastics Recycling. [cited 2012 Sept 2] Available from: http://ohiodnr.com/tabid/17876/Default.aspx

Pearce Corps. Global Hunger and Food Security Initiative. President's global food security initiative feed the future. PAPA with USAID/Senegal; 2011.

Pearce JM, Blair C, Laciak KJ, Andrews R, Nosrat A, Zelenika-Zovko I. 3-D Printing of Open Source Appropriate Technologies for Self-Directed Sustainable Development. J of Sustainable Development 2010;3:17-29.

Pearce JM. Building Research Equipment with Free, Open-Source Hardware. Science 2012; 337(6100):1303–4.

Perugini F, Mastellone ML, Arena U. A Life Cycle Assessment of Mechanical and Feedstock Recycling Options for Management of Plastic Packaging Wastes. Environmental Progress 2005;24:137-54.

Petrovic V, Gonzalez JVH, Ferrando OJ, Gordillo JD, Puchades JRB, Grinan LP. Additive layered manufacturing: sectors of industrial application shown through case studies. International Journal of Production Research 2010;49(4):1061-79.

Powell JC. Lifecycle assessment and economic valuation of recycling. Journal of Environmental Planning and Management 1996;39:97-112.

RecycleBot Team. RecycleBot. RecycleBot blog; 2010. [cited 2012 Sept 2] Available from: http://recyclebot.tumblr.com/archive

Redd A. Regionalization brings economies of scale to east coast. World Wastes 1993;36:40-5.

Rees JF. The fate of carbon compounds in the landfill disposal of organic matter. Journal of Chemical Technology and Biotechnology 1980;30(1):161-75.

Reich M, Björklund. Economic assessment of municipal waste management systems—case studies using a combination of life cycle assessment (LCA) and life cycle costing (LCC). Journal of Cleaner Production; 2005;13(3):253-63.

Rosato D. Plastics Processing Data Handbook. 2nd ed. Springer – Verlag; 1997.

Ross S, Evans D. The environmental effect of reusing and recycling a plastic-based packaging system. J of Cleaner Production 2003;11(5):561-71.

Rydberg T. Cascade accounting in life cycle assessment applied to polymer recycling. Polymer Recycling (UK) 1995;1:233-41.

Sandhill Plastic. Bottle recycling rate rises to 27.8 percent. Sandhill Plastic 2010. [cited 2012 Sept 2] Available from: http://www.sandhillplastics.com/news/sandhill-plastics-tidbits/recycled-bottles-increase-27

Shen L, Haufe J, Patel MK. Product overview and market projection of emerging bio-based plastics. Copernicus Institute for Sustainable Development and Innovation-Utrecht University; 2009.

Sells E, Smith Z, Bailard S, Bowyer A, Olliver V. RepRap: The replicating rapid prototyper: maximizing customizability by breeding the means of production. Robotica 2011;29(1):177-91.

Song HS, Hyun JC. A study on the comparison of the various waste management scenarios for PET bottles using the life-cycle assessment (LCA) methodology. Resources, Conservation and Recycling 1999; 27:267-84.

Sparks D, Barnett ST. The informal sector in sub-saharan Africa: out of the shadows to foster sustainable employment and equity. International Business & Economics Research Journal 2010;9:1-11.

Subramanian PM. Plastics recycling and waste management in the US. Conservation and Recycling. Resources, Conservation and Recycling 2000;28(3-4):253-63.

Thingiverse. 2012. [cited 2012 Sept 2] Available from: http://www.thingiverse.com

Thymark M. DIY shredder crusher chopper grinder. GrabCAD. [cited 2012 Sept 12] Available from: http://grabcad.com/library/diy-shredder-crusher-chopper-grinder

Torcellini R. Plastic extruder for growing media. The Adventures of Bigelow Brook Farm blog. 2010. [cited 2012 Sept 2] Available from: http://web4deb.blogspot.com/2010/12/plastic-extruder-for-growing-media.html

Upcraft S, Fletcher R. The rapid prototyping technologies. Assembly Automation 2003;23(4):318-30.

U.S Energy Information Administration (EIA). State Energy Data System. EIA; 2010. [cited 2012 Sept 12] Available from:

http://www.eia.gov/state/seds/hf.jsp?incfile=sep_use/total/use_tot_TXa.html&mstate=Texas

U.S. Energy Information Administration (EIA). FAQ-How much electricity does an American home use; 2011. [cited 2012 Sept 11] Available from: http://www.eia.gov/tools/faqs/faq.cfm?id=97&t=

U.S. Environmental Protection Agency (EPA). Municipal solid waste in the United States: facts and figures. EPA; 2010. [cited 2012 Sept 2] Available from: http://www.epa.gov/epawaste/nonhaz/municipal/msw99.htm

U.S. National Park Service: Mote Marine Lab. Time it takes for garbage to decompose in the environment. [cited 2012 Sept 2] Available from: http://des.nh.gov/organization/divisions/water/wmb/coastal/trash/documents/marine_debris.pdf

Xue M. Research on polymer composites of replacement prostheses. International Journal of Biomedical Engineering and Technology 2011;7(1):18-27.

5. Conclusions and Future Work

5.1 Overview

There are aspects in manufacturing which have room for improvement in order to reduce environmental impact. The need to reduce, reuse, and recycle is pivotal. There are areas which could benefit from small improvements (ie. recycling or improving the efficiency of a system) and other areas where new technology can improve the environmental impact of manufacturing.

5.2 Conclusions

Based on the results of the case studies explored the following conclusions are drawn:

5.2.1 Silane Recycling

- Silane recycling allows Si:H-based PV manufacturers to become less dependent on silane cost volatility and reduces energy consumption along with emissions in Si:H-based PV production.

- In the case of a 1 GW a-Si:H plant this amounts to savings of approximately 81,700 GJ and over 4,000 metric tons of CO_2e per year and in a 1 GW-scaled tandem a-Si:H/μc-Si:H PV manufacturing plant the savings are increased: 290,000 GJ of energy savings and 15.6 million kg of CO_2 eq per year.

- Instead of discarding 85%, it is more environmentally-responsible for thin film Si:H-based PV manufacturers to recycle silane.

- Recycling reduces the cost of raw silane by 68 percent, or over $22 million/year for a 1 GW single-junction a-Si:H-based PV production facility and over $79 million/year for a tandem a-Si:H/μc-Si:H PV manufacturing plant.

- This could in turn make a-Si – based PV more competitive in the PV market and increase PV penetration in the overall grid, while at the same time reducing costs for distributed generation with PV of manufacturing processes.

5.2.2 Distributed Manufacturing

- The environmental impact of plastics manufacturing can be reduced using distributed manufacturing of polymers with existing low-cost open-source 3-D printers when using PLA.

- Control of the fill percentage with 3-D printing has the potential to decrease environmental impact from cumulative energy demand by up to 64.5% and greenhouse gas emissions by up to 57.7% due to reduced material and energy use.

- Solar photovoltaic technology used as distributed electrical generation for the 3-D printing can further decrease environmental impact of cumulative energy demand up to 74% and greenhouse gas emissions by up to 80.8%. These values can even be improved further if recycling and industrial symbiosis takes place at the PV manufacturing facility, as seen in Chapter 2.

- Distributed manufacturing is technically viable and environmentally beneficial due to reduced environmental impact

5.2.3 Distributed Recycling

- Distributed recycling of waste HDPE for 3D printing filament reduces embodied energy of conventional recycling in a high population area by 13.5%.

- Rural population use a substantial amount of energy for transportation and collection, which amount in a savings over 90% for distributed recycling.

- Potential for over 1.78 billion MJ of energy conservation and substantial GHG emissions yearly, which is over 6 times the amount of energy saved from the large-scale PV manufacturing facility from Chapter 2.

5.2.4 Overview

- The union of the improving electricity production, manufacturing, and recycling has tremendous possibilities. Using distributed recycling or manufacturing with PV dramatically improves environmental impact and by further reducing the environmental burden of PV production, this impact is reduced. Small changes for environmental good have wide-reaching and dramatic effects on not only the system directly affected, but any adjoining processes associated with it.

5.3 Future Work

This research was conducted as a preliminary study on recycling of silane, distributed manufacturing, and distributed recycling and there are several aspects which should be explored further.

5.3.1 Silane Recycling

- Setting up an experimental recycling system would give greater insight on the energy use and environmental impact of the silane recycling system. This would assist in solving the technical issues within the recycling system, which are discussed in the patent, in order to find solutions and improve the system.

- Look at other methods of decreasing waste by decreasing gas through the reactor (make reactor smaller).

- Make this a full analysis without the "cut-off" method to quantify the system entirely so that it can be compared to other systems beyond silane, by including inputs outside of the direct recycling system, such as the included the energy associated with the infrastructure, such as the technology (vacuum chamber, etc), and allocated energy from processing and transporting raw silane. This would expand the scope to include any additional inputs.

- A full life-cycle economic analysis of the recycling process would compare the economic benefit from recycling silane with the increased costs of capital equipment and operating energy costs needed to recycle the silane

- Further analysis of the silane system using experimental data would give a greater insight on the energy use and environmental impact on the recycling system.

- A full recycling system recycling not only silane, but the nitrogen, hydrogen, and any other resulting gas products that are wasted. Use the outlined methods in the patent to recover both nitrogen and hydrogen, which would continue to depress the already small embodied energy, energy payback time, and ecological footprint while increasing the already substantial energy returned on energy invested (EROI) of Si:H-based PV manufacturing.

5.3.2 Distributed Manufacturing

- A "cradle-to-grave" analysis to yield an energy use and emission value that would better describe the system as a whole. Conventional manufacturing would benefit from communications and experience with industry to get a more accurate number for conventional manufacturing of plastic goods. The amount of waste should be quantified for both systems to give a more accurate comparison. This should include infrastructure (build materials, labor, processes), actual overseas distance (using shipping paths), shipping over land, molds, packaging, and waste, as well as any additional processes to make the products food-grade or child-safe.

- Set up a RepRap + PV system and measure the electricity usage to get a more accurate number and better estimate the distributed manufacturing system. This would allow a life-cycle analysis to be done to include a solar panel and additional hardware, such as power and storage, instead of using the SimaPro input for PV generated electricity.

- Examine energy requirements to make parts traditionally to determine whether PV would be possible for conventional methods of manufacturing or whether electricity must come from the grid.

- Full economic analysis should be done. Compare printer cost and maintenance per part manufactured and examine the rate of production.

- More products should be looked at to further explore the benefits of fill and design. In addition to other plastics which should be investigated, such as HDPE, recycled HDPE filament, polycaprolactone, and polypropylene.

- Expand the materials currently available to be printed using a RepRap, by creating a system for printing ceramics, metals, composites, electronic materials, etc.

- Bed adhesion needs to be improved in order to reduce energy waste. This can be done by using chemical means to enable better adhesion, using zoned heating so only the parts of the bed under the part are heated, better insulating the bottom of the bed, or using a controlled environmental chamber to insulate the entire RepRap from cold ambient temperatures.

5.3.3 Distributed Recycling

- Similar methods to those mentioned for distributed manufacturing future-work would benefit the distributed recycling. Adding a PV system would improve the environmental impact. The recycling or creation of filament using other plastics and materials, such as PLA, ABS, polycaprolatone, and polypropylene. Then a full "cradle-to-gate" analysis including all build components and infrastructure associated with distributed and conventional recycling, as well as an allocated amount for the raw materials.

- Further advancement of the RecycleBot needs to be done, by making it cheaper, all-in-one (shredding/extruding/etc), automated, more accurate in filament size and consistency, in conjunction with a thermal chamber, and more energy efficient.

- Compare all current models of RecycleBot type plastic recycling systems to determine which is has the lowest environmental impact and issues, such as the FilaBot, MiniRecycleBot, and future models that will come available. In addition to exploring a system where the RecycleBot directly feeds filament into the RepRap.