Title
Analysis of Uganda’s Plastic Waste Challenge from an Exergy, Thermal Phase Change, and Development Perspective to Improve Resource Efficiency and Social Impact

Author
Balcom, Paige

Publication Date
2022

Peer reviewed|Thesis/dissertation

Analysis of Uganda's Plastic Waste Challenge from an Exergy, Thermal Phase Change, and Development Perspective to Improve Resource Efficiency and Social Impact

by

Paige Balcom

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Engineering —Mechanical Engineering

and Designated Emphases

in

Development Engineering and
Energy Science and Technology

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Van P. Carey, Chair
Professor Alice Agogino
Professor Ashok Gadgil

Spring 2022

Analysis of Uganda's Plastic Waste Challenge from an Exergy, Thermal Phase Change, and Development Perspective to Improve Resource Efficiency and Social Impact

Abstract

Analysis of Uganda's Plastic Waste Challenge from an Exergy, Thermal Phase Change, and Development Perspective to Improve Resource Efficiency and Social Impact

by

Paige Balcom

Doctor of Philosophy in Engineering —Mechanical Engineering

and Designated Emphases in

Development Engineering and
Energy Science and Technology

University of California, Berkeley

Professor Van P. Carey, Chair

In low-income countries, 93% of waste is burned or dumped while only 2% of waste in high-income countries is improperly disposed of in this manner. This research focuses on the plastic waste problem in Uganda—a country where 600 tonnes of plastic waste is generated daily and only 6% is collected. Polyethylene terephthalate (PET) is the most prevalent type of plastic waste in Uganda, but it cannot be recycled anywhere in East Africa. Plastic waste in developing countries is a complex, multifaceted problem, and little comprehensive research exists on the subject. Through a technical, social, and business approach, I attempt to present a holistic analysis.

An extended exergy analysis was conducted to quantify the resource use and environmental impact of seven different disposal and recycling options for plastic waste that are feasible with Uganda's limited infrastructure. The results revealed that recycling into a new product is the most resource efficient end-of-life option for PET plastic in Uganda and that transportation can be a major exergy cost. To reduce transportation and keep economic benefits within a community rather than exporting the majority of the profits, a local, circular economy recycling solution was proposed. Additionally, a fundamental phase change heat transfer analysis was used to model the solar drying process many Ugandan recyclers use to dry their plastic after washing.

To demonstrate the feasibility of this proposed distributed recycling model, I co-founded a social enterprise in Gulu, Uganda. We developed a process and built local machines to transform PET waste into durable, beautiful wall tiles making us the only recyclers of PET in

Uganda. Using a community-based approach, emphasizing product-market fit, and pushing the bounds of recommended polymer processing practices, we developed and proved the viability of a solution that did not before exist. This dissertation presents a framework and an example of how to create sustainable solutions for complex technical and social problems that are technically viable, financially sustainable, and embraced by community members.

To all the mentors who have helped open doors of opportunity for me.

Thank you for sacrificing your time to guide, encourage, and impart your wisdom to me.
Thank you for pushing me and believing that I could do more than I ever thought I could.

Contents

List of Figures

List of Tables

Acknowledgments

Obtaining a PhD is terribly hard—partly because it must be done so independently. But this individual journey is not possible without the help and support of so many.

I am deeply indebted to my EMT labmates—Dre, Sam, Alanna, Emma, Lauren, Ursan, Anisa, Alan, Zach, and Claire. Thank you for all of your encouragement and support, help with homework and projects, guidance in research, and advice as we figured out academia together. I would not have gotten through this PhD without you. Also thank you to my fellow InFEWS/Development Engineering graduate students—Casey, Haley, Evan, Joel, Areidy, Isa, Julia, and many others. Thanks for your encouragement and stimulating discussions as we navigate the challenges of balancing this burgeoning interdisciplinary work with our traditional fields.

Thank you to my advisor, Dr. Van P. Carey, and my committee members, Dr. Ashok Gadgil, Dr. Alice Agogino, Dr. Chris Dames, and Dr. Alastair Iles for your guidance and support. I am also deeply grateful to Philip Denny of the Big Ideas program for his sincere and constant encouragement, feedback, and help in growing Takataka Plastics from an idea into a thriving social enterprise. Thanks for always being willing to write a recommendation, make a connection, and pause for a chat. Also thank you to Yael Perez for helping oversee and support the InFEWS/Development Engineering students at the Blum Center. And thank you to all the Etcheverry and Hesse Hall machine shop staff—your work, patience, and dedication to students is incredible. Likewise, thank you to the mechanical engineering graduate support staff—Yawo, Isabel, Sheila, Ana, and Ricky—thank you for knowing our names, advocating for us, guiding us in navigating the labyrinth of official university forms, and helping us feel seen in the sea of hundreds of graduate students.

I owe a huge thank you to all of the Takataka Plastics staff—thank you for assisting with my research, teaching me about Uganda, and encouraging me to keep working hard on my PhD. Thank you for taking care of me when I'm in Uganda and helping make Gulu my second home. Especially Patrick, Jacob, and the engineering team—thank you for all your help with experiments and machine design. And to Peter, this dissertation wouldn't be half of what it is without you. Thank you for all of your encouragement, support, feedback, and valuable advice. Thank you for all of our discussions that have helped shape my thinking about development and all of your suggestions for my research. You have helped me put theory into practice, and your genuine, deep desire to help your people is inspiring. Thank you for your honesty, your crazy ideas, your constant support, and your friendship. Apwoyo matek.

Also thank you to the Gulu University Biosystems Engineering Department, especially Dr. Collins Okello, Peter Mwa, Dr. Odoch, and Jennifer for all of your support, time, and help with my research.

Thank you to all the undergraduate students from Berkeley and Gulu who have assisted with my research—Juliana, Jeremy, Patrick, Felix, Bonny, Simon, Mugaiga, Amba, Paul, and Herbert. Your efforts have greatly contributed to this Dissertation.

I am grateful to the many funding sources that have supported me and allowed me to pursue this research during graduate school: the National Science Foundation Graduate Research Fellowship, Berkeley Chancellor's Fellowship, the Big Ideas Competition, USAID Global Development Fellowship, InFEWS Travel Grant, Tau Beta Pi Graduate Fellowship, Berkeley Haas Social Innovation Fund, Lemelson-MIT Student Prize, and IIE Centennial Fellowship. I am deeply grateful for Church Without Walls in Berkeley—thank you for your openness, generosity, and community. I have learned so much from you and felt loved and blessed by you all. Especially Tracy Ashlock, Jodi & Gary, and the Ahn Family—thank you for all of the encouragement, meals, car borrows, teachings, and prayers.

Thank you to my undergraduate professors and mentors at UNH—Jeanne Sokolowski, Barbaros Celikkol, Brad Kinsey, and others—thank you for pushing me and helping open the doors for me to attend graduate school. And to The Inventioneers coaches in middle and high school—Lisa Evarts and Luan Heimlich—thank you for introducing me to inventing and engineering at an early age, teaching me how preparation leads to excellence, and instilling in me a spirit of boldness and perseverance—that some rules are just guidelines and that "'No' is a request for more information."

I am deeply indebted to my parents—I wouldn't be here at the finish line of a PhD without you. Thank you for your constant support and for instilling in me an attitude of hard work, love for learning, curiosity to explore, faith in God, and desire to help others. Thank you for encouraging me to go to graduate school and allowing me to work in Uganda even though it takes me far away from you. To my Dad, thank you for always giving me wise advice and creative ideas. To my Mom, thank you for always being there for all your girls—for driving me to the airport at all hours of the day and night, always cooking my favorite food when I'm home, sending me off with weekly notes to make me smile, spending days inputting citations for this dissertation, and everything in between.

To my sisters, Emily and Kate, I love you deeply. Thank you for taking the time to listen and for all of your encouragement and advice. I am so grateful to have sisters like you.

To my friends, thank you for all of your encouragement and for believing in me. Tayler, Olivia, Sid, Allison "Hermione", Pelagie, Power, and Peter—thanks for always making me feel refreshed and that I can make it one step further after talking to you and for reminding me of what really matters in life.

And most of all, to God. Thank you for Your never-ending love, grace, and forgiveness. Thank You for always being there, especially when I was alone and felt like no one else was. Even when I don't pursue You, You're walking right beside me the whole time and always welcome me back with a warm embrace. Thank you for growing and stretching me and deepening my faith. Thank you for opening so many doors and guiding my path even when I had no clue how everything would fit together. May this PhD and my life bring honor and glory to You.

Chapter 1

Introduction

1.1 Approach and Roadmap for Dissertation

Disposing of plastic waste in developing countries is an enormous problem, and little comprehensive research exists on the subject. Over the last five years, I have analyzed the plastic waste situation in Uganda from a holistic perspective because although I am an engineer, it is not just a technical problem–it is a complicated, multi-faceted challenge. Therefore, a sustainable solution must consider and draw from a multitude of disciplines.

I have analyzed Uganda's plastic waste problem from a technical, social, economic, environmental, policy, and resource-use perspective. My research majorly focuses on a technical energy and resource use analysis combined with a development engineering/social impact/entrepreneurship approach. I incorporated Human-Centered Design (HCD) principles throughout to understand the problem and develop a collaborative solution with potential users.

In this dissertation, I will first present a summary of Uganda's plastic waste problem, then use exergy analyses to quantify the big picture resource use and environmental impacts of disposal of plastic waste in Uganda. I also present a thermal phase change model and experiments I conducted to analyze and improve the process of solar drying of wet plastic flakes–a process that many Ugandan recyclers employ. Next, I present my hypotheses for how to solve Uganda's plastic waste challenge and describe how I have practically implemented and refined these hypotheses by co-founding a social enterprise in Uganda. Finally, I will share some reflections on development work and offer practical lessons and a framework for development engineers and practitioners to guide them towards creating more sustainable, just projects.

1.2 Background of Problem

In low-income countries, 93% of waste is burned or dumped in roads, open land, and waterways while only 2% of waste in high-income countries is improperly disposed of in this manner [96]. Compounding this disposal problem, Africa has the highest projected percent increase demand for plastic products. A 2019 Nature paper projected that by 2060, consumer demand for plastic on the African continent would increase by 375%, the highest of any region in the world. The global average projected increase was only 210%. [16]

My research focuses on the plastic waste problem in Uganda—a country where 600 tonnes of plastic waste is generated daily (the equivalent weight of 331 cars) and little to no recycling infrastructure exists [27, 31]. The most common type of plastic waste in Uganda are plastic water and soda bottles (made from PET plastic) and kaveeras (thin LDPE plastic bags); they are generally thrown anywhere after use. [164] Figure 1.1 describes the current disposal situation of plastic waste in Uganda.

In the last six decades, 8.3 billion metric tons of plastic were produced worldwide, equivalent in weight to 55 million jumbo jets [71]. Only 9% was recycled [127]. When China banned the importation of most plastic waste in 2018 [95] [70] and India followed suit in 2019 [37], the plastic waste crisis became more dire and more visible to Western nations since they could no longer export their trash. The plastic waste issue is even more severe in developing countries because waste is generally not collected and recycling options are extremely limited [120] [167].

Sub-Saharan Africa is thought to have the worst solid waste management (SWM) of any region in the world [36]. For example, Kampala, the capital city of Uganda, generates approximately 180 tons of plastic waste daily [99] and only 40–50% of the city's waste is collected and brought to Kiteezi landfill [133] [164]. Gulu, the second largest population center after Kampala, has only a 20% waste collection rate [85]. Open burning in homes and landfills is the primary method of waste disposal, but burning plastic releases lethal carcinogens, other toxins, and greenhouse gases [168]. One landmark study found that 40% of the world's garbage is burned in open piles releasing greenhouse gases and other pollutants unaccounted for in most global inventories. [168] In Uganda particularly, 74.1% of the country's uncollected waste is burned in open fires [36]. Additionally, plastic is often littered, so it clogs drains leading to flooding and breeding grounds for malaria-bearing mosquitoes or gets embedded in the soil and disrupts crops [123]. Over 75% of Ugandans live in rural areas and rely on subsistence agriculture [65], so this is a significant issue. One study found that 60% of stray cattle in Uganda die from consuming polyethylene bags [115]. Plastic waste is causing a host of environmental and public health issues in Uganda, so environmentally friendly disposal options that are feasible in a developing country context are needed.

The little plastic that is collected is brought to official landfills or dumpsites. Most cities in Uganda just have dumping sites outside of town, and even in the dumpsites, the waste is often burned to make room for new garbage. So even plastic that reaches landfills is burned, and since the dumpsites are unlined, chemicals and additives in the plastic can leach into the soil affecting groundwater.

In Kampala, the capital city, Kiteezi landfill is the only officially recognized landfill. Although it has a liner, there are reports that the leachate treatment plant does not work properly and waste overflows into the community. Opened in 1996, Kiteezi is located 12

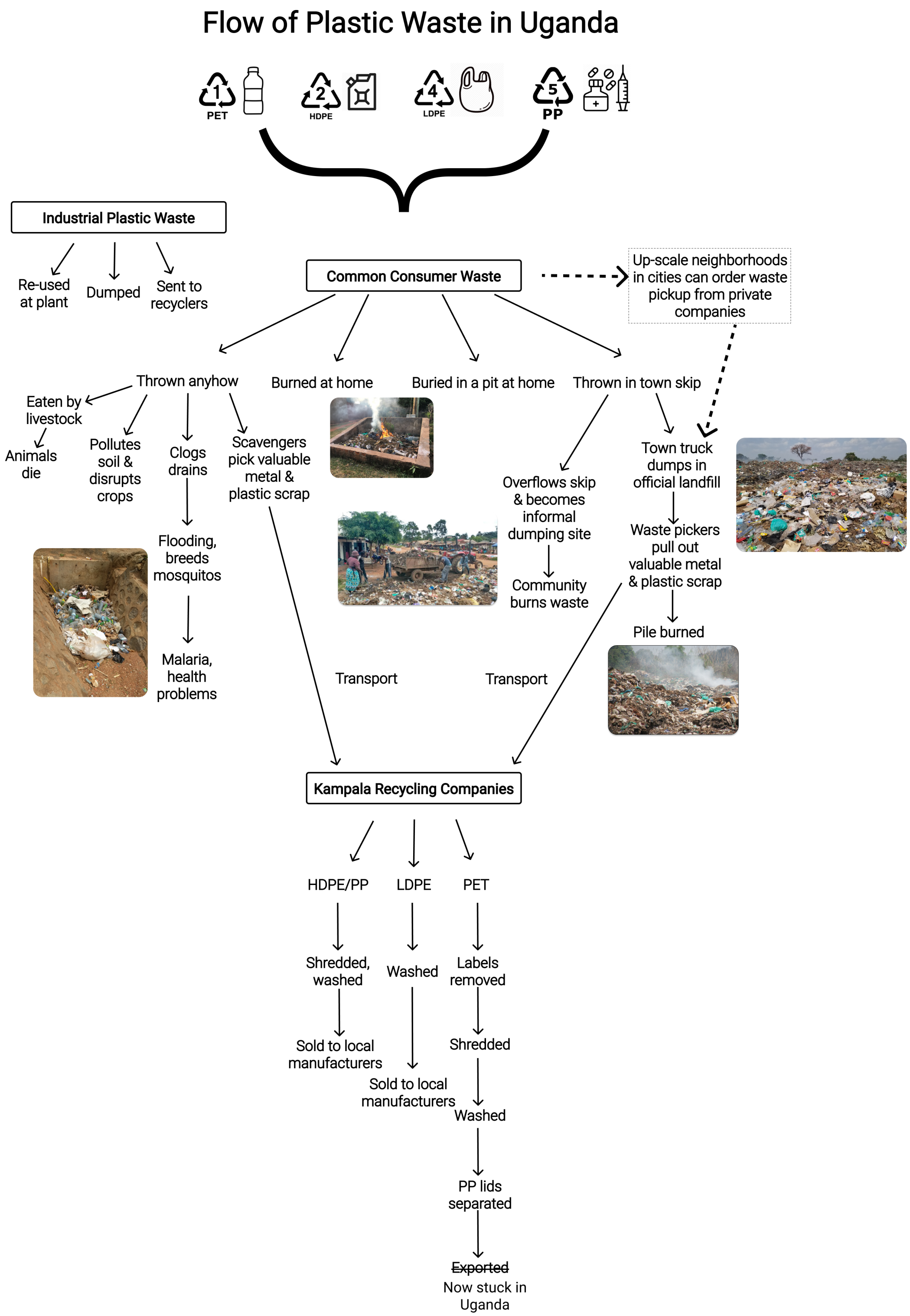


Figure 1.1: Flow Diagram of Plastic Waste in Uganda

(a) Official Dumping Site Outside of Gulu, Uganda

(b) Waste Burning in a Ugandan Community

Figure 1.2: Plastic Waste Disposal in Uganda

km north of the city. The 2016/17 State of the Environment Report published by Uganda's National Environment Management Authority (NEMA) stated that Kiteezi landfill is full to capacity and plans are underway to open a new landfill site in Ddundu 40 km outside of the city [18] [19]. The site was scheduled to open in April 2019, but as of February 2020, a contractor to develop the project had not yet even been identified. As of September 2021, residents of Ddundu were protesting and trying to stop the government's plans of creating a landfill for Kampala's waste around their homes. Officials said processing of waste still won't start for another two years (at best). [112] All waste that is collected in Kampala is still being sent to Kiteezi landfill, which is already beyond capacity. Waste pickers comb through the landfill picking out plastics, aluminum, steel, textiles, and other valuables to sell. The remaining waste is covered by soil and compacted [99]. In private homes, many individuals dispose of their own waste by burning. For the plastics that are not collected or burned, an informal economy of street pickers finds employment by picking plastic off the streets, pre-sorting the waste into high and low value plastics, and bringing them to a recycling plant. Street youth pick bottles and sell them to people for carrying kerosene or filling with local juice. However, this is a small number of bottles and only those in good condition can be used.

Community collection centers have been setup throughout Kampala through a partnership between Coca-Cola and the Kampala City Council Authority (KCCA). Coca-Cola trains an existing community group how to operate the collection center by weighing and sorting the plastic brought in by the community then the KCCA provides transport of the plastic

Figure 1.3: Waste Overflowing a Community Dumping Site in Gulu, Uganda

to the Coca-Cola recycling plant [91].

Kampala has 40-50 plastic recycling enterprises [26], but many are not profitable [91]. People who bring the plastics receive a few hundred shillings (1 USD 3550 Shs) per kilogram depending on the type of plastic and the current market which is driven by petroleum prices. Some industries send their plastic waste directly to the recycling plants. At the plants, the plastic waste is sorted by type, cleaned, shredded, and packaged. HDPE and PP flakes have a market in Kampala because a few large companies can mix the recycled HDPE or PP with virgin material to make products such as conduits. Recycled LDPE also has a small market in Kampala. Recycled PET flakes were formerly exported to Asia [91], but since many countries banned plastic waste imports (China in 2018 [95] [112], India in 2019 [37]), Uganda has been stuck with no way of recycling PET for the last several years. Bottles have been piling up and overflowing out of the gates of these Kampala recyclers. Finally, after several years, some of Uganda's plastic exporters have found a market for their rPET (recycled PET) flakes. As of spring 2022, Kampala's largest PET exporter, Plastic Recycling Industries (PRI) operated by Coca-Cola is exporting their rPET flakes to a recycling plant in South Africa.

In Uganda and other developing countries, solid waste management is an ever-changing, multi-stakeholder landscape implemented primarily by an informal picker economy. In cities and large towns, the municipality usually hires street cleaners to sweep the streets and dump the waste in large skips. A truck will then transport the skips to a dumpsite. At the dumpsite, the waste is eventually burned or buried. It is burned to create new space in the landfill and to combat flies [80]. Some businesses hire private waste companies to clean and transport their waste to the landfill, but many of these companies illegally dump the waste

Figure 1.4: Plastic Bottles Piling up at PRI without an Export Market

they collect to avoid paying fees at the official dumpsites.

In the last few years, several organizations and companies have sprung up in Uganda trying to recycle plastic waste into new products. Many are trying to make compound pavers by melting and mixing plastic waste with sand. Some are beginning to produce plastic lumber and beams. One company Resintile, was making roof tiles from plastic waste and sand, but they have recently gone out of business. A university research project used a small-scale reactor to pyrolysize plastic bags into fuel. Several NGOs and community organizations use art and education campaigns to raise awareness about plastic waste and encourage people not to litter or burn their plastic. They make sculptures from plastic waste and teach people how to make little objects such as brooms and toothbrush holders from discarded bottles. Many children also build toy trucks from waste bottles, caps, and jerry cans and soccer balls by tightly winding plastic bags together.

However, these existing solutions do not address the root of the problem–plastic waste is still being burned and littered across Uganda. I believe the unaddressed core issues are:

1) No PET recycling plant in East Africa

2) Long distance transportation of low-value plastic waste is not economical

3) Lack of awareness among community members about a) the *dangers* to their health from burning and littering plastic and b) the *value* of plastic waste

4) The value in plastic waste is extracted from communities and the majority of the

Figure 1.5: Plastic Waste Burning in a Ugandan Landfill

Figure 1.6: Plastic Waste Clogging Drains in Gulu, Uganda

profits are exported. This leaves waste pickers, who do the most dangerous and laborious work in the plastic waste value chain, with the lowest share of the profits.

These issues are expounded upon and solutions are proposed in Section 5.

Unemployment in Uganda

In addition to problems caused by plastic waste, Ugandans suffer from lack of employment opportunities, especially among youth.

Although the official unemployment rate in Uganda is 9.2% (13.3% for youth aged 18-30), these statistics are misleading. Most Ugandans are underemployed. [97] According to the World Bank, 43% of people in Sub-Saharan Africa live in extreme poverty. [139]

41% of Uganda's total working-age population is engaged in subsistence farming, meaning that a substantial proportion of the workforce does not generate an income nor engage in markets. [97]

83.5% of Ugandan youth work in informal jobs, and that figure is 10% higher for young women than men. [97] These informal jobs offer little, if any, pay and have high turnover rates.

Uganda has one of the youngest populations in the world–76% of the population is under the age of 30 [146], and Uganda has the fourth fastest population growth rate in the world [22]. "About 400,000 youths are released annually into the job market to compete for approximately 9,000 available jobs." [48] According to ACODE, a highly regarded think tank in Uganda, youth unemployment in Uganda stands between 64-70%. And "About 30% of the youths who are institutionally qualified in Uganda are unable to find jobs, and the situation is even worse for semiskilled and unskilled youths. Youths who remain unemployed or underemployed and do not exploit their full potential, are often associated with high incidences of drug abuse and gambling." [48]

"Uganda hosts the greatest number of young entrepreneurs on the continent – in reality, most youth-run businesses are small-scale and informal, with little employment-generating effect and a very high discontinuation rate. Like many low-income countries, Uganda's economy is dominated by these micro-firms, the vast majority of which emerge through necessity, rather than opportunity." [97]

Even Ugandans who have skills cannot find jobs. Many organizations have sponsored skills intervention projects thinking that the Uganda's unemployment problem is a supply issue, but "with no clear link to a real job in the labour market, young people found that opportunities to apply (and earn a wage from) their newly acquired skills were extremely limited." [97]

It is clear that Uganda does not have enough jobs for its growing population. And in Gulu, the region where my field research is focused, the unemployment rate is more than twice the national average. [8] [97] [146] Sadly, unemployment breeds a host of social issues – crime, domestic violence, alcohol and drug abuse, depression, malnutrition and poor medical care, broken families, child abuse, increased numbers of pregnancies, as well as other problems.

And when underemployed parents are unable to provide their children with quality education, the issues are passed on to the next generation.

1.3 Introduction to Development Engineering

Since my research is focused on Uganda and my work somewhat differs from traditional mechanical engineering PhD projects, an introduction to Development Engineering is warranted.

Development engineering is an emerging field defined as "creating solutions that improve human development at scale in low-resource settings." [46] Human centered design is the starting point of development engineering because HCD emphasizes iterative phases of prototyping and feedback from users, provides tools for deep needs assessment and engaging with local stakeholders, and catalyzes sustainable, creative solutions through local input. Human centered design requires quantitative [72, 136] and qualitative data, [46] and although the community-driven development of HCD requires lengthy amounts of time [55], the end results better fit the users' needs, are more likely to be maintained and used, and last for longer than a non-human centered design approach.

Development engineering began with the announcement of the Millennium Development Goals in 2000. The direct giving of aid or technology transfers without adapting to local contexts in previous decades had failed to deliver sustainable development, so the MDGs proposed smaller, more local solutions. [55]

Development engineering is inherently multidisciplinary because it seeks to address fundamental issues of poverty which cannot be solved solely by technology. [73] Working in a developing country involves many challenges, such as "institutional voids" of ineffective governments and markets [98]; poor infrastructure resulting in delays, lack of power, and interrupted communication; less access to markets, supplies, labor, capital, and distribution; liquidity constraints because of low income, gender inequality and ethnic/tribal discrimination, cultural differences in time, and issues of trustworthiness. However, working in a developing country also has many opportunities. Many donors, governments, and even investors find development engineering projects attractive [46] because of the social goals and the opportunity to tap into new markets. Development engineers need to understand the local culture, develop business models to scale solutions, monitor impact, and secure funding in addition to delivering rigorous technical work of the highest quality.

While development engineers should be highly skilled in a technical field, they should also have a broad understanding of entrepreneurship, economics, anthropology, social constraints, interview skills, history, impact assessment, and project management. Easterly [56] proposes the idea of Planners and Searchers. Planners think they are the experts who know the answers and dictate the answers. Searchers admit poverty is complex and requires an understanding of the political, social, historical, institutional and technological factors. Easterly asserts that local knowledge, local skills and local circumstances are imperative for sustainable success. [80]

The multidisciplinary skills gained in development engineering actually equip students to be better engineers in traditional settings as well. In 2004, an archetype for the ”2020 engineer” was created by ABET, the National Academy of Engineering, industry, academia, and government representatives because they realized 21st century engineers are facing a variety of real-world, global problems which can only be addressed holisitcally. [73] Students in the development engineering program at UC Berkeley were better able to meet the criteria of the 2020 engineer than students in traditional engineering programs.

Ultimately, development engineering provides a rigorous framework for technical thinkers to initiate and engage in social change while acknowledging the limitations of technology and need for multidisciplinary solutions. [55]

This dissertation presents my PhD research where my major is heat transfer and energy systems supported by a designated emphasis in development engineering and a minor in design.

1.4 Research Questions

In my research over the last five years, using exergy analysis, first-hand interviews, extensive fieldwork, and phase change modeling and experiments, I seek to answer the following research questions:

I. How can Uganda properly recycle/dispose of its plastic waste in an environmentally acceptable manner that is feasible with the country's limited infrastructure and in a manner accepted by community members?

II. How can manufacturing processes of recyclers in Uganda be improved to increase efficiency and resource use?

My research is directly relevant to discussions currently happening in Uganda and across the world about how to properly dispose of the plastic waste currently being burned or piling up across the developing world. The Ugandan people, government, and multilateral aid organizations are increasingly concerned about the plastic waste crisis in their country. Recycling and solid waste management (SWM) is a pressing topic in developing countries with many stakeholders interested in funding and searching for practical, cost-effective solutions to protect their citizens and the environment.

Chapter 2

Extended Exergy Analysis Comparing Various Disposal Options for Plastic Waste in Uganda

The world is facing an increasingly dire plastic waste crisis that affects people in developing countries disproportionately more than those in industrialized nations. To compare the environmental effects of end of life disposal and recycling options for plastic/sand roof tiles in Uganda, we use an extended exergy analysis (EEA) to quantify the resources used in the disposal process, the resources saved from replaced virgin materials by recycling, and any additional resources needed to bring the tiles, byproducts, and pollutants to an environmentally acceptable end state. We evaluated disposing of waste plastic/sand roof tiles through open burning, burying, landfilling, pyrolyzing, incinerating in cement kilns, mixing into asphalt to pave roads, and recycling into plastic pavers. With a net exergy avoided of 16,462 MJ/tonne of tiles, mixing the waste plastic/sand tiles into asphalt roads proved to be the best option followed by pyrolysis with 11,303 MJ/tonne of net exergy avoided (including remediation). Recycling the tiles into pavers also saved net exergy while burying, landfilling, and incinerating all had negative net exergy values showing that inputting some thermal energy to recycle waste can add value and save net resources. We determined it is not practically feasible to bring all of the pollutants from open burning to an environmentally acceptable end state with the limited technology available in Uganda. However, the method we recommend for remediating CO_2 *by planting trees requires only 0.7% of the exergy used in* CO_2 *scrubbers currently used in developed countries. Such an empirical study focusing specifically on plastic products and disposal options feasible in developing countries has not been done before, so our results can be useful to policy makers, multilateral organizations, and NGOs making decisions about solid waste management practices in less-industrialized nations. The results from this chapter are valid for HDPE, LDPE, and PP plastics but not for PET or PVC.*

2.1 Introduction

This chapter seeks to answer the research question: What is the most environmentally friendly approach that is feasible and appropriate in the developing country context of Uganda to dispose of plastic waste? We use a quantitative, empirical approach through an extended exergy analysis (EEA) to compare the natural resources and energy required to reach an environmentally-acceptable end state through different disposal methods. This EEA analysis uses roof tiles made of recycled plastic and sand as a case study. The roof tiles we analyzed are manufactured by the Kampala company, Resintile LLC. This chapter was published in the peer-reviewed *Journal of Development Engineering*. [20]

Samples of the Resintile roof tiles are shown in Figure 2.1.

Figure 2.1: Resintile Roof Tiles [114]

This work focuses on practical end of life disposal options for the Resintile roof tiles which will eventually crack and break from UV degradation and weathering. We propose seven different end of life options that are either already practiced in Uganda or are feasible in the limited industrial capacity of a developing country context. In this EEA, we analyze each disposal process and calculate the exergy needed for each step, including heating with electricity (hydropower), wood, plastic, recycled fuel oil, and diesel, to compare the different options and find means of efficiently using power and heat flow to conserve energy. We use exergy as a single metric to also calculate and compare virgin resources used, resources saved from replacing them with new recycled product alternatives, and the exergy needed to properly remediate all pollutants and by-products emitted. This complete picture includes resource conservation through recycling and gives insights into how to minimize the exergy input required to deal with handling and retiring the material in an environmentally sustainable way.

This work adds to current literature by analyzing plastic waste disposal options appropriate to developing countries, such as Uganda. To our knowledge, no other paper compares resource or environmental cost of disposal options in Uganda and no other extended exergy analyses have been published on waste disposal methods for developing countries. Other studies have used life cycle analysis (LCA) [130] [143] and a few used exergy analyses [52]

[138] [171] [49] to compare the resources used in landfilling versus incineration versus recycling but all in scenarios of developed countries with access to sophisticated, modern technology, and none specifically calculate the remediation costs. None consider only technologies available in developing countries. We devoted significant effort to researching what disposal methods are currently used in Uganda and their environmental effects. We also creatively conceived new disposal and remediation options that are currently not used in Uganda and present rationale for why they could be feasible. Additionally, our study examines plastic waste alone whereas most studies look at municipal solid waste (MSW) as a whole, which significantly influences results because the environmental effects of burning or otherwise disposing of solely plastic are much more detrimental than disposing of general MSW where plastic represents only a small percentage.

Additionally, our paper expands on the typical EEA approach by calculating the net avoided exergy of a disposal option. To give a complete picture, we include the exergy value of the resources saved from replacing fuel and products with recycled alternatives. None of the previously referenced works specifically calculate remediation costs, so we apply previous frameworks [44] [137] of defining two different ground states to calculate the costs of properly disposing of all pollutants and by-products according to environmentally acceptable standards.

Our results are directly relevant to discussions currently happening in Uganda and across the world about how to properly dispose of the plastic waste currently being burned or piling up all across the world. The Ugandan people, government, and multilateral aid organizations are increasingly concerned about the plastic waste crisis in their country. Recycling and SWM is a pressing topic in developing countries with many stakeholders interested in funding and searching for practical, cost-effective solutions to protect the environment. This extended exergy analysis can inform policymakers and project managers on the most resource efficient and environmentally friendly method of disposing of plastic waste in Uganda. It should be noted however, that this analysis does not apply to polyethylene terephthalate (PET) or polyvinyl chloride (PVC) plastic.

2.2 Material and Methods

Exergy Analysis Framework

When considering sustainability in an environmental and ecological sense, an appropriately defined exergy is a useful concept to analyze the overall use of resources in a process and its impact on the environment. Exergy differs from energy in that exergy considers the quality of energy with respect to the environment. Exergy differentiates energy that is actually available to do work from energy that is lost and cannot be recovered due to irreversibilities or technology limitations. When analyzing a manufacturing process, the thermodynamic inefficiencies stand out as destroyed exergy—energy that has lost quality or usefulness (e.g. wasted shaft work or waste heat that cannot be recovered). Exergy identifies energy that is low in entropy and helps engineers identify the amount, type, location, and causes of losses in a system to help identify means of improvements [53].

Exergy for a closed system (non-flow) with mass m is defined in terms of physical, chemical, kinetic, and potential exergy as:

$$Ex_{non-flow} = Ex_{ph} + Ex_o + Ex_{kin} + Ex_{pot} \tag{2.1}$$

where

$$Ex_{pot} = PE \tag{2.2}$$

$$Ex_{kin} = KE \tag{2.3}$$

$$Ex_o = \sum_i (\mu_{io} - \mu_{ioo})N_i \tag{2.4}$$

$$Ex_{ph} = (U - U_o) + P_o(V - V_o) - T_o(S - S_o) \tag{2.5}$$

The terms with o subscripts are associated with the ground state. μ_{io} is the chemical potential of substance i, N_i is the number of moles of substance i, U is the internal energy, P is the pressure, V is the volume, T is the temperature, and S is the entropy. For an incompressible substance, equation 3.12 can be written as

$$ex_{ph} = c(T - T_o - T_o * ln\left(\frac{T}{T_o}\right)) \tag{2.6}$$

where C_p is the specific heat. As outlined by Creyts [44], there are two methods for calculating the exergy of a process: theoretically or with a process path. Since exergy represents the amount of reversible work that keeps a system from its ground state, the minimum exergy value of a process is the difference in exergy values between the initial and final state. However, this represents an ideal process and does not account for practical irreversibilities. Real exergy values can be calculated by applying a generic efficiency factor to the theoretical exergy change between initial and final states, but this does not provide detailed insights. The process method is a better approach where a series of reversible process steps are constructed between the initial and final states, so that the consumed and lost exergy can be calculated for each step. The process for each step can be an imagined, hypothetical approach (useful for identifying areas of potential research and development) or based on practical, existing technology (useful for identifying inefficiencies in an existing process).

Extended Exergy Analysis

The exergy value of a process or resource also depends on how the environment or ground state is defined because exergy is a property of both the system and the environment. Extended Exergy Analysis (EEA) was first introduced in 1998 by Sciubba to include the material and labor resources, environmental costs, and upstream processing of materials [40] [140]

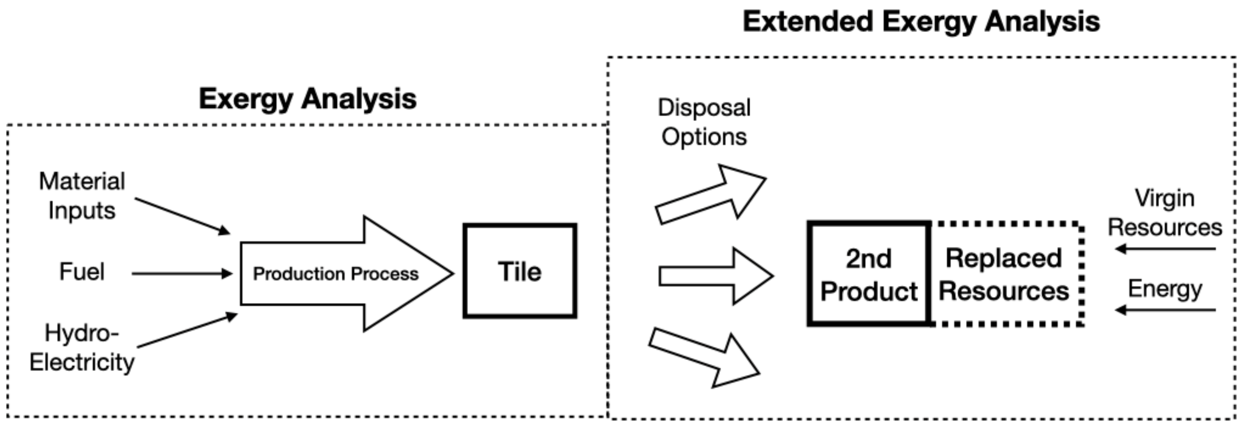


Figure 2.2: Diagram of Extended Exergy Analysis Concept

in traditional exergy analyses. Using EEA, the lifetime extended exergy of a product can be calculated as a sort of life cycle analysis [78]. By conducting the same exergy calculations for a process with different ground states, one can calculate the exergy cost between different scenarios, such as at process release conditions versus at ambient conditions. In a manner similar to the approach taken by Creyts [44], here we adopt a definition of Extended Exergy that embodies exergy relative to an *environmentally acceptable* ground state based on various health, occupational, and ecological criteria. Comparing exergy analysis results between different process release conditions and an environmentally acceptable ground state provides manufacturers and regulators insights into the cost of doing the right thing by achieving environmentally benign production [140] [137].

The definition of EEA adopted here is an exergy analysis extended to include physically returning all streams of the control volume to the defined ground state. In this paper, we explore different process paths for disposing of Resintile recycled plastic/sand roof tiles that have reached the end of their life and use two different ground states to calculate the remediation costs of properly returning all materials, by-products, and pollutants to an environmentally acceptable end state.

Figure 2.2 visually shows the difference between a traditional exergy analysis (as described in the authors' previous paper on the Resintile manufacturing process [20]) and an extended exergy analysis (as presented in this paper). We define the initial state as the old plastic/sand tiles removed from the roofs but still at the site of the individual homes where they were installed. The homes are all in the Kampala region, up to 35 kilometers from the Resintile manufacturing site. We considered the control volume to be all of the Resintile tiles sold in a year. One ground state does not consider environmental effects and releases all pollutants without remediation, while the second ground state is an environmentally acceptable ground state defined as standard atmospheric pressure, ambient temperature (25 C), and air, soil, and ground water quality standards as set by the EPA and WHO [14] [63].

Net Exergy Avoided

In this paper, we introduce the concept of including avoided exergy costs to an EEA to find the net exergy cost of bringing a discarded product to an environmentally acceptable end state. Instead of simply calculating the exergy used in each disposal process as in a traditional EEA [135], we also consider the products that the Resintile tiles are replacing in some of the disposal options and subtract the exergy value of those replaced products to give a full picture comparison of resources used. For instance, in the incineration disposal scenario, the tiles are burned as fuel in place of biomass, petcoke, and furnace oil, so we subtract the exergy value of the fuel that is not burned to get the net exergy cost because the natural resources embodied in the current fuel mix are saved. The products replaced in each disposal option are explained in their respective sections.

We represent the exergy value of the replaced resources with the Cumulative Exergy Consumption (CExC) measure. CExC is defined as the raw materials plus fuel and energy inputs required to produce a product [152]. Other researchers have calculated the CExC value for many substances using the chemical exergy formula which represents the inherent exergy embodied in the substance plus the fuel and other resource inputs needed to obtain, produce, or refine the substance. For instance, the CExC for gravel is calculated from the chemical exergy of the various minerals in the rock plus the fuel needed to run the machines to extract the rocks and grind them to gravel. In our analysis, we calculated the CExC for many substances from Tables II and III in Szargut et al [152]. A few substances in our analysis are not listed in Szargut, so the alternative sources are noted and a description of how we calculated values for bitumen, sand, and concrete is included in Section 2.4 Calculations below. Table 2.1 summarizes the CExC values used.

Table 2.1: Summary of CExC Values for Materials

Material	**CExC (MJ/kg)**	**Source**
Sand	0.12	[88]
Concrete (for pavers)	3.99	calculated
Cement (wet method)	10.18	[152]
Coal	30.44	[152]
Coke	30.50	[152]
Bitumen	47.52	[152] [24]
Diesel	51.74	[152]
Fuel Oil	51.74	[152]
Cellulose (used for biomass)	60.03	[152]
Plastic (PE)	92.30	[152]

Thus, we define the exergy net avoided as

$$Ex_{net\ avoided} = Ex_{net\ process} + CExC_{resources\ avoided} \tag{2.7}$$

$$\{Ex_{net\ process} = Ex_{pr\ current} - Ex_{pr\ w.\ tiles}\}^1 \tag{2.8}$$

$$\{Ex_{net\ process} = Ex_{pr\ current} + Ex_{rem\ current} - (Ex_{pr\ w.\ tiles} + Ex_{rem\ w.\ tiles})\}^2 \tag{2.9}$$

$$Ex_{net\ rem} = Ex_{rem\ current} - Ex_{rem\ w.\ tiles} \tag{2.10}$$

where $CExC_{resources\ avoided}$ is the exergy value of the virgin resources and the exergy cost of production of the products being replaced or saved in each disposal scenario. Ex_{pr} is the exergy cost of the process, and Ex_{rem} is the exergy cost of the remediation process to bring all inputs, by-products, and pollutants to an environmentally acceptable end state. The braces and exponents ^{1} and ^{2} refer to the ground states—the first with no environmental considerations and the second as an environmentally acceptable ground state as previously defined.

Our formula is based on the work presented by Dewulf [51] but modified to fit our specific scenario where the disposal option is not defined as one method but instead is the object of study. Dewulf adds a $CExC_{end-of-life\ disposal}$ value to account for the exergy avoided by no longer needing to dispose of waste (instead he assumes it is recovered or recycled into new products), but I do not include this term because the disposal option is the object of study in this paper, so it would be incorrect to assign a specific disposal method to obtain a value for exergy avoided from disposal. Additionally, the most common current disposal method in Uganda of piling up and leaving the roof tiles in an open space has negligible exergy cost.

Calculating the raw materials and energy inputs for disposal and remediation processes including waste residuals and pollutants compared to a consistent, environmentally acceptable ground state provides objective, big picture insights not available through other types of analyses. Including the CExC value of avoided resources and the exergy cost of production processes from products we are replacing takes most previous Extended Exergy Analyses a step further and makes our analysis even more holistically informative. To our knowledge, this is also the first extended exergy analysis for disposal options specifically for plastic waste (as opposed to all MSW) that considers what could be feasible in a developing country context, such as Uganda.

Thus, we employ equations 2.6-2.10 as the basis for our EEA as described in Section 2.4 Calculations below. As noted in each calculation, we gathered the data from literature reviews and 10 months of field work in Uganda. Temperature data for various parts of the Resintile manufacturing process was obtained during a site visit, and the engineer and general manager at Resintile, LLC were especially helpful in providing other production data.

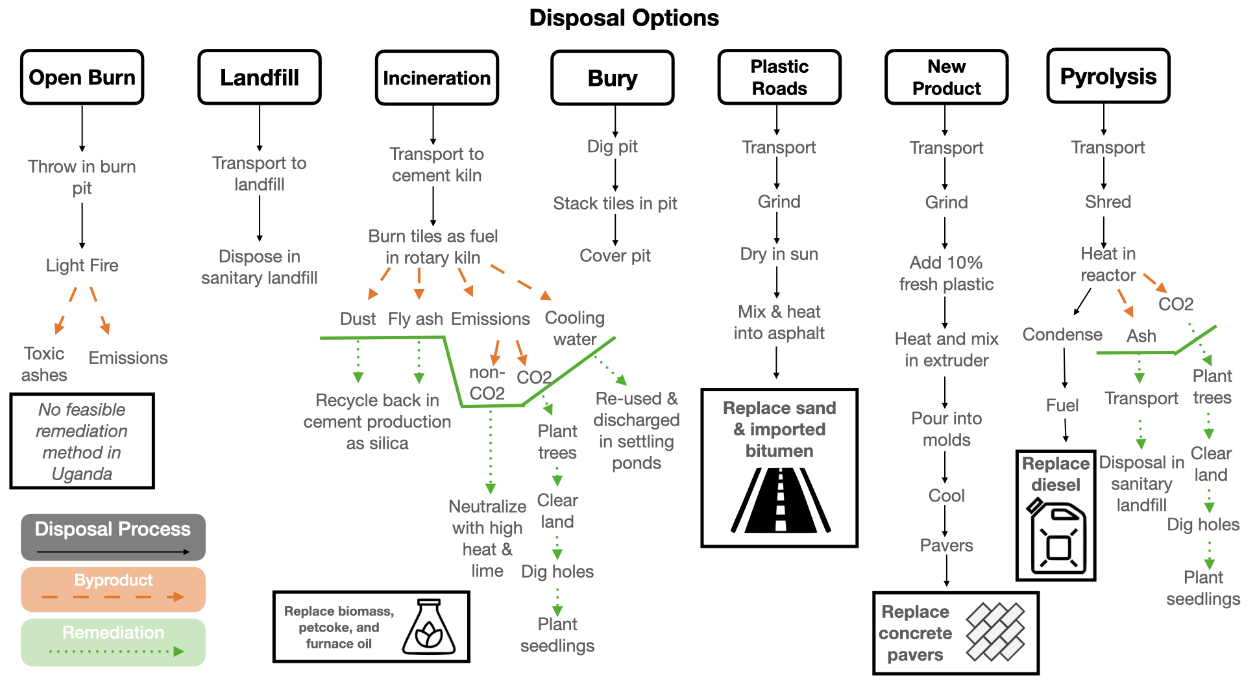


Figure 2.3: Flow Diagram of Proposed Disposal Options for Plastic Waste in Uganda

2.3 Theory/Model for EEA of Various Disposal Options

We identified seven different end of life disposal options for the Resintile plastic/sand roof tiles that are either already practiced or could be feasible in the developing country context of Uganda. The general process of each option is shown in Figure 2.3 and described below. This section presents the theory behind why and how we modeled each disposal option, and Section 2.4 presents the detailed calculations. In this section, each disposal method is introduced, the process for environmental remediation in each method is discussed, and the considerations for each process in the context of a developing country (specifically Uganda) are presented.

Open Burning

The most common method of waste disposal in Uganda and developing countries is open burning. Homes and businesses in both rural and urban settings engage in this practice. Even in most landfills, waste is openly burned to reduce the size of the trash and make room for more. More than 40% of the world's garbage is burned in open piles emitting carbon dioxide, mercury, particulate matter, and polycyclic aromatic hydrocarbons (PAHs)

[168]. The greenhouse gas emissions from burning trash are not counted in global inventories. PAHs are highly dangerous pollutants as they can cause cancer, birth defects, neurological disorders, and other health issues [36].

To determine if plastic/sand tiles can physically burn in an open burning scenario and assess if this disposal option is relevant to roofing tiles, we conducted an experiment to determine the flammability of the Resintile tiles. Due to the significant amount of sand in the tiles, they do not continuously burn on their own. Even when kerosene is added, our experiments showed the fire extinguishes when the kerosene is finished burning, but when the tile is surrounded by organic material or other fuel, the fire sustains itself. Since burn pits in Uganda contain all types of waste (a large percentage being organic matter), we determined that the tiles could be burned. However, we estimated 10% of the energy required to burn the plastics in the tiles would be needed to start the fire.

Environmental Remediation for Open Burning

We conducted extensive research to quantify the emissions and pollutants left in the ashes from open burning. We determined that CO_2, PAHs, particulate matter, lead, NOx, and SO_2 are the major pollutants [14] [158]. According to experiments that simulated open burning conditions, carbon monoxide is not an issue because virtually no carbon is left in the ashes meaning that all carbon present in the polymer chains is converted to CO_2 [15]. Only PET had 5% of its carbon remaining in the ashes; other plastics had 0% [158]. Therefore, the amount of CO_2 released from open burning of the tiles was calculated from the direct stoichiometry of each plastic present in the tile multiplied by the oxidation factors of 1 for HDPE, LDPE, and PP and 95% for PET. The next section discusses the various ways of remediating the CO_2 released to prevent negative environmental impacts.

For PAHs, Benzo[a]pyrene (BaP) was used as a proxy in accordance with procedures from other studies [63] [101]. We compared the amount of BaP released from open burning of plastics with the World Health Organization 1 in 1 million cancer risk guideline [62]. The lead, NOx, SO_2, and particulate matter released from burning tiles was compared to the U.S. Environmental Protection Agency (EPA) critical air pollutant standards [14]. The PAH, Pb, NOx, and particulate matter emissions from open burning of Resintile tiles far exceeded the WHO and EPA standards. Only the SO_2 emissions are within the guidelines. To properly remediate all of these pollutants to ensure no environmental damage, scrubbers and filters would be needed.

Ugandan Context for Open Burning

Across the world, various Negative Emission Technologies (NETs) are utilized or under development to capture CO_2, such as direct carbon capture where CO_2 is chemically scrubbed from ambient air, magnesite —a carbon capturing mineral currently only made at lab-scale, iron spread on oceans to encourage the growth of carbon-absorbing phytoplankton, and tree planting [169]. However, most of these technologies are not feasible in Uganda. For the developing country context, we identified tree planting as a possible carbon offsetting strategy and suggested growing algae on fish ponds as a new solution tailored for Uganda. Aquaculture is extensively practiced in Uganda, algae can be used as fish feed, and up to 50% of algal biomass weight can be carbon absorbed from the atmosphere [92] [28]. Algae can be intensively grown in bioreactors, but this technology is not available in Uganda [2]. Ugandan aquaculture is limited primarily to open ponds, where algae cannot be grown intensively. We calculated that the surface area of open ponds necessary to grow enough algae to capture all the CO_2 released from burning Resintile tiles in a year exceeds the amount of land in the whole country of Uganda. Therefore, growing algae for CO_2 offsetting is not a feasible solution in Uganda. Cultivating trees is still a viable carbon sequestration option and is discussed more in Section 2.5.

The significant amounts of PAHs, Pb, NOx, and particulate matter can only be properly handled with extensive filter and scrubber systems which are not available in Uganda [13]. We explored the possibility of utilizing locally available filters, such as using catalytic converters from vehicles, but those only remove NOx and convert CO to CO_2. Additionally, it would not be feasible to erect filters over every burn pit across the region where tiles would be burned. Therefore, there is no feasible solution to realistically handle the emissions from open burning tiles, so exergy calculations were halted for this disposal option.

Landfilling

In Kampala, 40% of the city's waste is delivered to Kiteezi landfill [100] located outside of the city 13.8 km from the Resintile factory. We therefore considered throwing the whole tiles in the landfill as a possible disposal option. The 2016/17 State of the Environment Report published by the National Environment Management Authority (NEMA) stated that Kiteezi landfill is full to capacity and plans are underway to open a new landfill site in Ddundu 40 km outside of the city [21, 18, 19]. The site was scheduled to open in April 2019, but as of February 2020, a contractor to develop the project had not yet even been identified. All waste that is collected in Kampala is still being sent to Kiteezi landfill.

Environmental Remediation for Landfilling

The Kiteezi site 13 kilometers outside of Kampala was designed to be a sanitary landfill with a leachate treatment plant, but it is currently not operating properly. There is no proper liner for the landfill [18], the daily chemicals for the leachate plant are often lacking [113], and unstable slopes of the piled waste have reportedly breached the boundary of the landfill [41].

Although Kiteezi landfill is not operating properly, we still considered it a sanitary landfill because some of the infrastructure of a sanitary landfill is still in place and we deemed the environmental hazards from throwing the tiles into a landfill to be minimal. Leaching and microplastics are the only environmental risks in this scenario. There are no harmful leaching effects from the plastic polymers themselves—the risks come only from additives

[101]. Since the tiles are made from post-consumer plastic waste, the additives are not highly dangerous. Additionally, EnviroShake, a Canadian company manufacturing roofing materials from plastic waste, conducted lab-certified toxicology tests proving that the rainwater runoff from their products is potable and there is no harmful leaching from the tiles [82]. For the issue of microplastics, measuring microplastics is very difficult, so no conclusive studies have yet been done to determine the real environmental effects or to set acceptable standards.

Ugandan Context for Landfilling

We conducted extensive research on the state of Kampala's landfill as described in previous sections. These details enabled us to tailor our analysis to the Ugandan context. For future analyses outside of the Kampala area, other landfills across Uganda have even less infrastructure than Kiteezi and are more like open dumping and burn pits.

Incineration in Cement Kilns

Incineration was analyzed by using the tiles as fuel in cement kilns. Cement is a binder and the main ingredient in concrete. Its production requires a source of calcium which usually comes in the form of limestone and a source of silicon which comes in the form of clay or sand. The raw materials are ground, mixed, and then fed into a rotary cement kiln. Different sections of the kiln progressively heat up until they reach temperatures up to 1480 C. After the raw materials are completely melted, they cool and solidify into pellets called clinker. This clinker is then ground into a fine powder. Gypsum is added at the final stages of production during the grinding of the clinker to control the settling of the cement. Throughout the process, water is first used to cool the equipment, and then recycled and reused [32].

Many cement kilns use coal as their primary source of fuel to heat the rotary kiln [34], but in Uganda, alternative sources are often used. For this study, we use Hima Cement Ltd, one of the largest and most advanced cement manufacturers in Uganda, as a case study. Hima uses a mix of agricultural waste, petcoke, and furnace oil to heat their kiln. In this EEA, we propose replacing the current fuel with the Resintile roof tiles made from recycled plastic and sand. Due to the high temperatures reached in the kiln, most types of waste can be burned in cement kilns as is already being done in India and encouraged by the Indian government [33]. The only major exception is PVC.

Environmental Remediation for Incineration in Cement Kilns

Cement manufacturing produces solid wastes and air emissions mostly in the form of cement kiln dust and gaseous emissions from burning fuel. Kiln dust consists of alumina, silica, clay, and metallic oxides with small traces of dioxins, furans, cadmium, lead, selenium, and radionuclides. However, the EPA determined that cement kiln dust is not hazardous to human health if disposed of in a properly lined landfill [166]. Fly ash left behind after burning the fuel can be used as a source of silica in cement production or in concrete mixtures to substitute 15-35% of the cement [30].

Incinerating the plastic/sand tiles in the rotary kiln would release CO_2. We propose remediating the CO_2 released from incinerating the tiles by planting trees to absorb an equivalent amount of carbon dioxide. Other emissions, such as heavy metals and dioxins, are not an issue because the high temperatures (1250-1450 C), long residence time, and oxygen rich environment in the cement kiln destroy all waste and ensure complete combustion. Additionally, adding lime neutralizes pollutants to keep the emissions within accepted standards [84] [153]. Water used to cool the equipment is reused and water used for equipment cleaning is discharged into settling ponds. The EPA does not consider this hazardous unless the pH of the waste water is less than 12.5 [32].

Cement kiln co-processing (burning waste as an alternative to fossil fuels to heat cement kilns) is approved by the Basel Convention for disposal of hazardous wastes and the Montreal Protocol for disposal of persistent organic pollutants (POPs). Co-processing plastic waste in cement kilns can be better for the environment than landfilling or incineration, and is encouraged by the Indian government [33]. India is even piloting co-processing hazardous plastic wastes containing bromide flame retardants in cement kilns (under specified emissions monitoring procedures) [84].

Ugandan Context for Incineration in Cement Kilns

In developed countries, incineration in waste to energy plants is a common method of disposing of plastic waste. However, there are very few incineration plants near Uganda, and the ones available are not in operation. Incineration plants are costly to build and operate and are not a viable option for developing nations. Ugandan hospitals and health clinics often have incinerators for burning medical waste, but the furnaces are usually not well designed and there are no filters. Therefore, the emissions are not properly remediated, and the process is more like open burning.

To tailor our analysis to the Ugandan context, we identified cement kilns as a feasible alternative to traditional incinerators. The high temperatures required in cement kilns are representative of incinerators, and other studies have cited using plastic waste as fuel in cement kilns [34]. The cement production industry is already well established in Uganda with six different manufacturing plants across the country. Raw materials used in the manufacturing of cement such as lime and gypsum can be found in Uganda and Egypt respectively.

Pyrolysis

Researchers at the University of Kentucky and Makerere University developed a low-cost, locally fabricated reactor to transform plastic waste into fuel through pyrolysis [89]. Pyrolysis refers to the heating of plastic in the absence of oxygen to achieve thermal decomposition. The University of Kentucky Appropriate Technology and Sustainability (UKATS) reactor uses a rocket stove as the main source of heat and is insulated using vermiculite. The process begins by loading a propane cylinder, which acts as the reaction chamber, with shredded waste plastic. Next, the reaction chamber is placed inside the processor, covered with a lid, and heated steadily until it reaches 400 C - 450 C. The vapor created is condensed in an ambient temperature water bath and the top fuel oil layer is separated from the water using gravity. After discussions, the designers of the UKATS reactor confirmed that their device can work with plastic roof tiles ground into pieces [3].

Environmental Remediation for Pyrolysis

The fuel produced by the UKATS reactor is similar to diesel or kerosene and the potential byproducts are wastewater, off-gases, and ash [89]. The water bath used in the reactor to condense the vapor can be reused for multiple batches, eliminating the need for wastewater disposal. The off-gases secreted are routed back into the heatbox using a pipe to increase system pressure to improve efficiency and eliminate air pollution. Approximately 1% of the mass of the original waste input is leftover as fine powder residue between batches [3]. This residue is mostly caused by impurities in the plastic such as dyes, colorants, labels, and dirt. The residue is disposed of by burying it alongside the ash from the wood fire used to heat the process. According to the designers, no harmful environmental effects have been observed from this process. In this paper, we include the exergy cost of transporting and disposing of the ashes in a sanitary landfill to ensure all byproducts reach an environmentally acceptable end state.

Ugandan Context for Pyrolysis

The UKATS reactor was specifically designed for underdeveloped regions. It is simple, non-automated, and uses a local wood fueled rocket stove as the primary heat source. All of the materials needed to build the reactor can be sourced locally. Due to the regional limitations, the reactor has no precise temperature control, and it cannot be operated completely oxygen free. Since it is locally made without filters for emissions, PET and PVC plastics cannot be used, but polyethylene and polypropylene are acceptable. The UKATS reactor is still a small scale machine, but it proves the concept of pyrolysis as a valid approach for disposing of plastic waste.

Gasification was considered as a potential disposal option for the plastic/sand tiles. However, gasification plants in Uganda are small or medium scale machines designed to use biomass fuel. They would not be able to properly handle the pollutants and fuel separation of hydrocarbon-based plastic waste. We therefore decided gasification would not be a feasible option for disposal of plastic waste in Uganda.

Road Paving

Across the world plastic waste has been used to replace bitumen when making roads [142] [121]. HDPE and LDPE carrier bags are generally used, but PP could also be possible because the bitumen is melted at 180 C. Laminated thin film plastics are avoided. The plastic modified roads are stronger than traditional asphalt roads and absorb less water, so the plastic roads last longer and require less maintenance [68] [35].

In road construction, the wet method or the dry method can be used. The wet method, generally used in more developed regions, involves heating and mixing the bitumen, plastics, sand, and aggregates in a large mixer. The dry method is used in areas where such mixing equipment is not available or where rough road surfaces are required. In the dry method, the road is built in layers as hot bitumen is sprayed directly onto aggregate and rolled. An Indian professor invented an inexpensive way of melting plastic bags on hot stones and using them as plastic-coated aggregate [160]. The hot plastic-coated aggregate can then fuse with hot bitumen. India made plastic roads the default construction method in 2015, and as of 2017, the country had over 21,000 miles of plastic-asphalt roads [149].

The Scottish company MacRebur produces plastic modified bitumen that has been implemented across the world. They take discarded plastic bags, extrude them into pellets, and mix them at 6% wt composition with bitumen and activator additives. Macrebur's products meet various worldwide road standards and have been installed in many countries [108].

Environmental Remediation for Road Paving

The potential environmental hazards associated with plastic roads are leaching and microplastics. In the wet method, there is less possibility of leaching because the plastic breaks down and completely mixes with the bitumen. Both plastic and bitumen are mostly hydrocarbons derived from petroleum. When heated together to a liquid state, they become an inseparable mixture of polymer modified bitumen with no risk of leaching or microplastics. Macrebur also adds an activator when heating the mixture to help the plastic fully degrade and compatibilize with the bitumen [108]. The compatibilizer helps the immiscible materials bond together to strengthen stability.

There is less conclusive evidence about the environmental effects of the dry method used on Indian roads. Since the bitumen is only sprayed on the hot plastic at 160-180 C, the plastic does not break down, so there is still a possibility of leaching and microplastics. Activists fear that the plastic roads exposed to sunlight, heat, and water could leach chemicals. However, no conclusive research has been done to prove if hazardous chemicals are leaching from the roads [151]. In 2012, the technique of laying the plastic road was accepted by the Central Pollution Control Board in New Delhi [160].

Ugandan Context for Road Paving

Literature reviews and in-person interviews were conducted to verify the feasibility of plastic road technology in Uganda and other developing countries. As described previously, the dry method is already extensively used in India, although there remains some lingering questions about the environmental impacts. In Kampala, all roads are made with the wet method, except major highways that require a rough surface. Outside of Kampala, both methods are used depending on if the mixer and funds are available (the wet method is more expensive than the dry method) [5]. Since this analysis focuses on Kampala, we based our calculations on the wet method which has less negative environmental impacts.

Local Transformation to New Products

Another disposal option is locally transforming old roof tiles into a new product. Since the tiles have been exposed to sunlight and weathering for many years, the polymer chains will be shortened compromising the strength of the plastic. We identified compound pavers as an appropriate product that could be made with the old tiles. Other companies in Uganda already make plastic/sand pavers with a composition similar to the Resintile roof tiles [132]. The thickness of the pavers (7 cm) and the compression-only loading compensates for the weakened state of the polymers and still delivers a functional product.

The pavers can be manufactured at the Resintile facility in nearly the same process as the roof tiles outlined in our previous paper [21]. Old roof tiles would be transported back to the Resintile factory, crushed into small pieces, fed into the extruder to be re-melted, and placed in molds to cool. The only difference from the roof tile process is that a hydraulic press is not needed to form the pavers and an extra 10% of fresh plastic waste should be added to the ground up tiles prior to extrusion to add additional bonding strength.

Environmental Remediation for Local Transformation to New Products

There are no harmful environmental effects from the production of the pavers because the melting temperature is precisely controlled with the extruder to prevent off-gasses. When the pavers are installed in compounds, there is a possibility of leaching and microplastics, but as described above, there is no conclusive evidence showing that these phenomena occur or what their impacts are. Several companies in Kampala are already marketing plastic pavers.

Ugandan Context for Local Transformation to New Products

Plastic/sand pavers are already made by several companies in Uganda, and the process we outlined in this analysis uses the Resintile machines. While these machines were expensive to import and are difficult to maintain in Uganda making them out of the reach of most developing country entrepreneurs, many large cities across Africa have industries with imported machinery. Smaller initiatives have made plastic pavers with improvised equipment by melting the plastics in an oil drum over a fire, but this is hazardous to the environment and workers' health. Since the temperature cannot be controlled, the process is virtually the same as open burning. Thus, the method we proposed to manufacture pavers with the Resintile extruder is safe and appropriate for large cities in developing countries with access to investor capital.

Pit Burial

Similar to landfilling, another disposal option is burying the roof tiles in a pit. The tiles from each house would be buried near the house to eliminate the need for transportation. The only cost is the labor of manually digging the pit and covering the tiles with soil.

Environmental Remediation for Pit Burial

Plastics break down primarily through UV and thermal degradation and somewhat from water and oxygen exposure. Unlike organic materials that decompose by being eaten by naturally-present bacteria, if plastics are not exposed to sunlight or heat, they do not degrade [141]. Therefore, burying plastics in the ground and covering them to create an anaerobic environment can be an environmentally acceptable disposal option. The only potential environmental hazard would come from pigments in the plastics containing heavy metals or other toxins. For the post-consumer waste plastics used by Resintile, this is not an issue. In our analysis, we based calculations on burying the roof tiles with 0.5 m of soil cover, deep enough below the zone heated by the sun's rays to ensure that the tiles are buried in a cool place.

Ugandan Context for Pit Burial

In Uganda and other developing countries, digging a pit and burying waste is already a common disposal option. The only challenge comes when future development requires building on, planting in, or digging up the pit. For disposal of the roof tiles in this analysis, the site for burying must be carefully chosen to avoid this challenge. However, burying the tiles with 0.5 m of soil cover is deep enough to mitigate many of those challenges.

2.4 Calculations

Open Burning

The exergy cost of open burning includes the energy to start combustion and the cost of properly remediating all of the pollutants released, including those in the ashes. To find the energy required to initiate combustion, we used Equation 2.11 based on the enthalpy required for thermal decomposition of plastic from Joshi and Seay's paper on pyrolysis [90]. The sensible heating of the plastic is broken up into a solid and liquid phase where T_{m} is the melting temperature of the plastic and T_{rxn} is the temperature at which the reaction occurs (in this case of combustion, we used the flash point of the plastic to find the heat needed to bring the plastic up to the temperature of ignition and then the combustion reaction could continue on its own if exposed to an open flame). ΔH_{F} is the enthalpy of fusion representing the energy required for the phase change from solid to liquid, and E_{a} is the activation energy of the reaction. Peterson gives experimentally measured activation energy values for thermal degradation of polyethylene and polypropylene in air as 80 and 90 kJ/mol respectively [119]. We also included sensible heating of the sand to bring the temperature of the sand up to the temperature of the reaction. Since the sand in the tiles is inert and slows the spread of flames, the tiles must be surrounded by other fuel, such as organic waste, to keep the fire going. We approximated this additional fuel as 10% of the energy needed for combustion of the plastic in the tiles.

Heat energy, Q, was converted to exergy as described by Equation 2.15 by imagining a theoretical heat engine could capture the heat and convert it into usable work. The carnot efficiency is calculated with the temperature values in Kelvin, and an η_{real} efficiency factor of 0.6 is included because in reality, heat engines generally operate at 60% of carnot efficiency depending on the type of modifications to the basic Rankine Cycle used [145].

$$Q_{plastic} = \sum_{i=1}^{n} m_i * C_{p\ solid_i} * (T_{m_i} - T_o) + m_i * \Delta H_{F_i} + m_i * C_{p\ liquid_i} * (T_{rxn} - T_{m_i}) + m_i * \frac{E_{a_i}}{M_i} \quad (2.11)$$

$$Q_{sand} = \sum_{i=1}^{n} m_i * C_{p_i} * (T_{rxn} - T_o) \quad (2.12)$$

$$Q_{extra\ fuel} = 0.1 * Q_{plastic} \quad (2.13)$$

$$\eta_{carnot} = 1 - \frac{T_o}{T_{rxn}} \quad (2.14)$$

$$Ex_{process} = \eta_{carnot} * \eta_{real} * (Q_{plastic} + Q_{sand} + Q_{extra\ fuel}) \quad (2.15)$$

Significant amounts of toxic fumes are released from burning plastic, so remediation is necessary to reach an environmentally acceptable end state. When plastic is burned in open environments, the carbon in the polymer chains breaks off and mixes with the oxygen in the air to form CO_2. Molecular weight and stoichiometry reveal the mass of CO_2 that is formed when all of the carbon in a polymer is converted to carbon dioxide. Depending on the amount of oxygen present during burning, some of the carbon can be converted to carbon monoxide instead of CO_2. We calculated the oxidation factor for open burning of the various polymers in the Resintile tiles based on the percentage of carbon left in the ashes from open burning experiments [158]. The remaining carbon in the ash represents the amount of carbon in the polymer chain that was not converted to CO_2, so the amount of CO_2 calculated from direct stoichiometry multiplied by the oxidation factor gives the real amount of CO_2 released by each polymer in open burning as described in the following equation where f_{ox_i} is the oxidation factor for polymer i, N_{C_i} is the number of carbon atoms in the repeat unit for polymer i, M_{CO_2} is the molar mass of CO_2, and M_i is the molar mass of one repeat unit of polymer i.

	PE	PP	PET
Oxidation Factor, Open Burning	1.00	1.00	0.95
Repeat Unit	C_2H_4	C_3H_6	$C_{10}H_8O_4$
CO_2 emitted (Eqn. 2.16) [kg]	3.14	3.14	2.29
CO_2E emitted (EPA) [kg]	3.08	3.32	2.25

Table 2.2: Comparison of CO_2 emitted from burning plastic

$$kg\ CO_2\ released = f_{ox_i} * N_{C_i} * \frac{M_{CO_2}}{M_i} \tag{2.16}$$

As shown in Table 2.2, we found that our calculated values agreed with the EPA's values of kg of CO_2E (carbon dioxide equivalent) released per kg of plastic for each polymer type [15]. It should be noted however, that the equivalent CO_2 in the EPA statistic includes impacts from other greenhouse gases emitted.

As described in Section 2.3 Open Burning, we identified growing algae and trees as potentially feasible options for remediating CO_2 in Uganda. Very little data exists on algae cultivation in East Africa, but an exergy analysis of growing algae in open raceways in India and harvesting for fuel reported that an open raceway could sequester 163,800 kg of CO_2/hectare/year [129]. If the CO_2 inputs required for cultivating, harvesting, and processing the algae into fuel are subtracted, a net 91,196 kg of carbon dioxide/hectare/year can be sequestered. In terms of exergy, the paper reports the exergy cost of cultivating and processing subtracted from the exergy value of the biofuel product gives a net exergy profit of 980,038 MJ/hectare/year. However, open raceways are not currently available in Uganda. Another study on small Malaysian phytoplankton ponds is more applicable to the scenario in Uganda [134]. The paper reported that unenriched and enriched ponds could sequester 0.9 and 6.0 g C/m^2/day respectively. However, even with the enriched number, more hectares of ponds would be needed to sequester the CO_2 released from open burning of the Resintile tiles sold in one year than the land available in the whole country of Uganda. Thus, growing algae to sequester CO_2 is not yet a feasible option in Uganda.

However, growing trees to absorb CO_2 is a plausible option. Eucalyptus woodlots in Uganda can absorb 4 tonnes of carbon/ha/yr [87], and 2.35 tonnes of C/ha/yr is the average sequestration value for trees in Mt. Elgon and Kibale national parks in Uganda [117]. When planting woodlots, chain saws, pangas, and manual labor are used to clear the land, and manual labor is used to dig the holes and plant the seedlings [4]. In Uganda, one person can clear half an acre of land per day, dig 80 holes per day spaced 2.5 meters apart, or plant 240 seedlings per day. Chain saws require approximately 6 liters of petrol per acre cleared. Using 3,483 kJ/person/day as the exergy cost for manual labor [103] and fuel exergy costs found using Equation 2.17 where V is the volume of fuel used, ρ is the density of the fuel, and b^{ch}_{fuel} is the specific chemical exergy, we calculated the exergy cost for planting trees is 11.1 kJ/m^2 of trees planted.

$$Ex_{fuel} = V * \rho * b^{ch}_{fuel} \tag{2.17}$$

To sequester 1 tonne of CO_2, we calculated 27.65 MJ and 47.06 MJ of exergy and 2,500 and 4,255 m^2 of land would be needed for eucalyptus woodlots and national parks respectively. There is no exergy loss from land use because land used to grow trees or other biomass is not taken into account when calculating land use exergy loss to avoid double-counting [148].

Other pollutants emitted from burning plastic are smaller in mass but more toxic than CO_2. The amount of lead, NOx, SO_2, PAHs (BaP is used as a proxy), and particulate matter emitted from open burning of plastics was found from experiments reported in literature [158] [42] and was compared to the acceptable air standards set by the WHO and EPA [60] [25] [61]. All pollutants except SO_2 were drastically over the acceptable limits.

As stated in Section 2.3 Open Burning, there is no realistically feasible way in Uganda to bring all the pollutants from open burning to an environmentally acceptable end state. However, in an attempt to quantify the exergy costs of this disposal option, we searched literature and found a couple of recent papers presenting AbatEx, abatement exergy, values for certain gaseous pollutants [12] [107]. They define AbatEx as the internal energy needed to abate air emissions to an accepted limit for the environment using available technology. They report values of 5.9 MJ/kg for CO_2 from fossil fuel abatement based on CO_2 recovery via ethanolamine absorption and stripping followed by compression to 80 atm for underground storage [147] [50] [69], 57 MJ/kg for SO_2 abatement based on 90% removal of SO_2 in a flue gas desulphurisation unit of a coal-fired power plant using limestone and converting to gypsum [147] 86], and 16 MJ/kg for NOx based on 80% removal in a DeNOx unit of a coal-fired power plant [147] [38]. None of these remediation technologies are feasible for Uganda, but they offer some idea of the exergy cost of burning recycled plastic roof tiles. However, the picture is further incomplete because no data yet exists for abatement exergy of other types of gaseous pollutants, which can cause misleading results because PAHs are the most toxic to human health of all the pollutants released from burning plastic, but no exergy remediation cost is available for PAHs. Results and comparisons are presented in Section 2.5.

Since open burning is one of the most common disposal methods currently used in Uganda, we provided the detailed calculations in Table 2.3 as an example of the calculations for the other disposal methods. The temperature measurements of the materials at various stages of the production process and the mass of the materials are the only measured values in our analysis. Other numbers are obtained from literature or calculated. The mass of the materials is estimated to 1 kg precision, and temperature measurements were obtained to 1 C precision with +/- 0.5 C uncertainty.

Table 2.3: Extended Exergy Calculations for Open Burning Disposal Option

Stage	**Comments**	**Equations Used**	**Exergy Contribution (MJ/tonne tiles)**
Heat	Sum the amount of sensible and latent heat and activation energy required to heat each material i in the tiles (sand, pigment, and three types of plastics) from 25 C to the flash point for PE of 341 C [170]. Convert the heat to exergy with an ideal heat engine multiplied by η_{real} of 60%. C_p values are 0.739 kJ/kg-K for sand [170] and 0.650 kJ/kg-K for pigment [45]. Property values for PE and PP are taken from [90] except the activation energy for combustion is 80 and 90 kJ/mol for PE and PP respectively [119].	$Q_{plastic} = \sum_{i=1}^{n} m_i * C_{p\ solid_i} * (T_{m_i} - T_o) + m_i * \Delta H_{F_i} + m_i * C_{p\ liquid_i} * (T_{rxn} - T_{m_i}) + m_i * \frac{E_{a_i}}{M_i}$ $Q_{sand} = \sum_{i=1}^{n} m_i * C_{p_i} * (T_{rxn} - T_o)$ $Q_{extra\ fuel} = 0.1 * Q_{plastic}$ $\eta_{carnot} = 1 - \frac{T_o}{T_{rxn}}$ $Ex_{process} = \eta_{carnot} * \eta_{real} * (Q_{plastic} + Q_{sand} + Q_{extra\ fuel})$	405
Net Process Exergy[1]	Sum all the exergy contributions to the process. $Ex_{pr\ current}$ equals 0.	$\{Ex_{net\ process} = Ex_{pr\ current} - Ex_{pr\ w.\ tiles}\}^1$	**-408**
Remediation: Transport Ash	Transport ash (1% of plastic & 100% of all sand and pigment) to Kiteezi Landfill (avg 13.8 km). Use CExC transport value of 3.13 kJ/kg-km for 28t truck from [88]. m is the mass of goods transported and d is the distance travelled.	$Ex_{rem} = CExC_{transport} * m * d$	30
Remediation: Landfill Ash	Dispose of all ash (1% of plastic & 100% of sand and pigment) in Kiteezi landfill. Use 0.35 MJ/kg CExC value for disposal of mixed debris in a sanitary landfill [51].	$Ex_{rem} = CExC_{landfill} * m$	247
Remediation: Emissions	Calculate m_i, the kg of airborne pollutant i emitted from burning tiles then multiply by the $AbatEx_i$ value for that pollutant. AbatEx is 0.028 MJ/kg CO_2 for absorption by trees in eucalyptus woodlots [calculated], 57.0 MJ/kg SO_2 scrubbing [38], and 16.0 MJ/kg NO_x scrubbing [38].	$Ex_{rem} = \sum_{i=1}^{n} AbatEx_i * m_i$	45

Table 2.3: Extended Exergy Calculations for Open Burning Disposal Option

Stage	Comments	Equations Used	Exergy Contribution (MJ/tonne tiles)
Net Remediation Exergy	Sum all the exergy contributions to remediation. $Ex_{rem\ current}$ is 0.	$Ex_{net\ rem} = Ex_{rem\ current} - Ex_{rem\ w.\ tiles}$	**-322**
Net Process Exergy²		$\{Ex_{net\ process} = Ex_{pr\ current} + Ex_{rem\ current} - (Ex_{pr\ w.\ tiles} + Ex_{rem\ w.\ tiles})\}^2$	**-730**
Avoided Resources	There are no avoided resources because burning does not replace any products.	N.C.	**N.C.**
Net Avoided Exergy¹		$\{Ex_{net\ avoided} = Ex_{net\ process} + CExC_{resources\ avoided}\}^1$	**-408**
Net Avoided Exergy²		$\{Ex_{net\ avoided} = Ex_{net\ process} + CExC_{resources\ avoided}\}^2$	**-730**

[1] *Ground State 1: current scenario of emitting all pollutants and by-products without remediation*

[1] *Ground State 2: bringing all inputs, pollutants, and by-products to an environmentally acceptable end state as defined by EPA and WHO guidelines*

N.C.: No Contribution

Landfill

For the landfill calculations, we considered the fuel exergy cost of transporting the old tiles from the homes where they were installed to Kiteezi landfill (approximately 13.8km) plus the cost of disposal in a sanitary landfill. The CExC value of transportation in a 28t truck is 3.13 kJ/kg-km [88], and the CexC value for disposing of mixed debris in a sanitary landfill is 0.35 MJ/kg [51]. Since the tiles do not replace any product, there is no value added, so we do not consider the CexC value of any saved resources. In developed countries, biogas is often collected from degrading waste in landfills, but Kiteezi landfill does not have this technology. In the landfill scenario in Uganda, there is no new product gained from the waste; there is only the exergy cost of disposal.

Incineration in Cement Kilns

The exergy cost of incineration in cement kilns begins with the transportation of tiles from Resintile, lime from Hima lime plant, and Gypsum from Egypt. The transportation of materials, rotating of the kiln, heating of the clinker, and all other parts of the manufacturing process are the same regardless of if the current fuel mix or the tiles are burned, so the net exergy of the process is zero. We assumed the transportation of the tiles approximately equaled and negated the transportation of the current fuel. We equated the higher heating values of the tiles and the current fuel mix to calculate how many kilograms of the current fuel we could save by burning the tiles.

For this study, we used Hima Cement Limited as a case study because they are one of the largest and most advanced cement manufacturers in Uganda. They currently use a fuel mix of 60% biomass (coffee husks, rice husks, gnut husks, baggase and saw dust), 30% petcoke, and 10% furnace oil [6].

The CO_2 emissions from burning plastic for fuel to heat the kiln are remediated by planting trees as explained in Sections 2.3 and 2.4. We simply calculate the amount of CO_2 released from complete combustion of the plastic fuel and the exergy cost of planting enough trees to absorb that amount of CO_2. The CO_2 emissions from burning plastic are greater than the CO_2 emissions from burning Hima's current fuel mix. 1.69 kg of CO_2 are released for every kg of the current fuel burned [39] while 3.14 kg of CO_2 are released for every kg of plastic burned. The exergy cost to plant trees to absorb those amounts of CO_2 were calculated according to the procedures outlined in Section 2.4 then the remediation exergy cost with the tiles was subtracted from the current remediation exergy cost to get the net remediation cost. The fly ash and sand from the tiles can be added back to the cement during the ball mill process, and the wastewater is discharged to ponds on site which has negligible exergy costs [154].

The product replaced by the plastic/sand tiles in cement kilns is the fuel currently burned. For Hima Cement, this fuel is biomass, petcoke, and furnace oil, but many cement plants burn coal. We calculated the higher heating value (HHV) of the plastic/sand tiles then found the kilograms of current fuel mix that would give an equal HHV. The resources saved by not burning the current fuel were calculated from their CexC values multiplied by the kilograms of fuel saved.

Pyrolysis

In the pyrolysis process, the tiles are first transported to the UKATS reactor at Makerere University and then shredded. The exergy cost of shredding the tiles was calculated using a CexC value of 22.2 MJ/tonne for crushing aggregate [24]. To calculate the exergy cost of heating the tiles in the UKATS reactor, we used equations 2.11-2.12 and 2.14-**??** (without the $Q_{extra\ fuel} term$) with T_{rxn} equal to 450 C. The condensation portion of the manufacturing process has no exergy cost because it lacks a temperature change. The ash leftover from the pyrolysis process—consisting of plastic residue (1% of all the plastic in the tiles), all the sand, and all the pigment [3]—is an environmentally harmful byproduct, so the exergy cost to landfill the leftover ash was calculated using the method described in Section 2.4.

Additionally, CO_2 is emitted by the fuel burned to heat the reactor. Joshi and Seay, the designers of the UKATS reactor recently published a paper on the emissions of their process [90], so we used that data to calculate the kg of CO_2 that would be released from pyrolisizing the tiles and found the remediation exergy cost by multiplying by our calculated 27.6 kJ/kg of CO_2 remediation value for planting trees in eucalyptus woodlots. For the different fuels presented by Joshi and Seay, we calculated the exergy needed to remediate the CO_2 released in the production of recycled fuel oil from the Resintile tiles is 2.3, 0.8, and 0.9 MJ/tonne tiles for wood, propane gas, and recycled fuel oil respectively. We used the recycled fuel oil value for our calculations because it is the middle value and the most economical fuel choice for production. Financially, it makes sense to use some of the recycled fuel oil produced instead of buying fuel to heat the reactor.

The product produced by burning the plastic/sand tiles in the UKATS reactor can replace diesel. The CExC value of the diesel saved was calculated by multiplying the kg of diesel avoided (based on an equivalent LHV of recycled fuel oil) by the CExC value of diesel in Szargut et al. Detailed calculations and explanations are provided in Table 2.4 for the pyrolysis option as an example of the calculations performed for other disposal options.

Table 2.4: Extended Exergy Calculations for Pyrolysis Disposal Option

Stage	**Comments**	**Equations Used**	**Exergy Contribution (MJ/tonne tiles)**
Transport	Transport old tiles from homes where they were installed to Makerere University (avg 35 km). Use CExC transport value of 3.13 kJ/kg-km for 28t truck from [88]. m is the mass of goods transported and d is the distance travelled.	$Ex_{pr} = CExC_{transport} * m * d$	110
Shred	Shred the tiles into small pieces to make the heating process faster. Use CExC value of 22.2 MJ/tonne for crushing aggregate from [24]	$Ex_{pr} = CExC_{crush} * m$	22

Table 2.4: Extended Exergy Calculations for Pyrolysis Disposal Option

Stage	Comments	Equations Used	Exergy Contribution (MJ/tonne tiles)
Heat	Sum the amount of sensible and latent heat and activation energy required to heat each material i in the tiles (sand, pigment, and three types of plastics) from 25 C to the flash point for PE of 341 C [170]. Convert the heat to exergy with an ideal heat engine multiplied by η_{real} of 60%. C_p values are 0.739 kJ/kg-K for sand [170] and 0.650 kJ/kg-K for pigment [45]. Property values for PE and PP are taken from [90].	$Q_{plastic} = \sum_{i=1}^{n} m_i * C_{p\ solid_i} * (T_{m_i} - T_o) + m_i * \Delta H_{F_i} + m_i * C_{p\ liquid_i} * (T_{rxn} - T_{m_i}) + m_i * \frac{E_{a_i}}{M_i}$ $Q_{sand} = \sum_{i=1}^{n} m_i * C_{p_i} * (T_{rxn} - T_o)$ $\eta_{carnot} = 1 - \frac{T_o}{T_{rxn}}$ $Ex_{process} = \eta_{carnot} * \eta_{real} * (Q_{plastic} + Q_{sand}$	807
Net Process Exergy[1]	Sum all the exergy contributions to the process. $Ex_{pr\ current}$ equals 0 because there is no current pyrolysis option.	$\{Ex_{net\ process} = Ex_{pr\ current} - Ex_{pr\ w.\ tiles}\}^1$	**-938**
Remediation: Transport Ash	Transport ash (1% of plastic & 100% of all sand and pigment) to Kiteezi Landfill (avg 13.8 km). Use CExC transport value of 3.13 kJ/kg-km for 28t truck from [88]. m is the mass of goods transported and d is the distance travelled.	$Ex_{rem} = CExC_{transport} * m * d$	24
Remediation: Landfill Ash	Dispose of all ash (1% of plastic & 100% of sand and pigment) in Kiteezi landfill. Use 0.35 MJ/kg CExC value for disposal of mixed debris in a sanitary landfill [51].	$Ex_{rem} = CExC_{landfill} * m$	247
Remediation: CO_2 from fuel	Calculate m, the kg of CO_2 emitted from burning fuel to heat the reactor from [90] then use our calculated value of 27.6 kJ of exergy required per kg of CO_2 absorbed for planting trees in eucalyptus woodlots.	$Ex_{rem} = \sum_{i=1}^{n} AbatEx_{CO_2} * m_{CO_2}$	0.9
Net Remediation Exergy	Sum all the exergy contributions to remediation. $Ex_{rem\ current}$ is 0 because there is no current pyrolysis option.	$Ex_{net\ rem} = Ex_{rem\ current} - Ex_{rem\ w.\ tiles}$	**-272**

Table 2.4: Extended Exergy Calculations for Pyrolysis Disposal Option

Stage	Comments	Equations Used	Exergy Contribution (MJ/tonne tiles)
Net Process Exergy[2]		$\{Ex_{net\ process} = Ex_{pr\ current} + Ex_{rem\ current} - (Ex_{pr\ w.\ tiles} + Ex_{rem\ w.\ tiles})\}^2$	**-1,210**
Avoided Resources	Calculate a weighted average LHV of 41,482 kJ/kg for the recycled fuel oil produced based on the LHV's and mass ratios of the plastics in the tiles [90]. Use an experimentally measured LHV for diesel of 41,500 kJ/kg [90] and CExC value of 51.74 MJ/kg [152] for the resource being replaced. $m_{fuel\ oil}$ is found by multiplying the kg of plastic pyrolysized by yield efficiency of 81.22% [89].	$m_{avoided} = \frac{m_{fuel\ oil} * LHV_{diesel}}{LHV_{fuel\ oil}}$ $CExC_{resources\ avoided} = CExC_{resource} * m_{avoided}$	**12,513**
Net Avoided Exergy[1]		$\{Ex_{net\ avoided} = Ex_{net\ process} + CExC_{resources\ avoided}\}^1$	**11,575**
Net Avoided Exergy[2]		$\{Ex_{net\ avoided} = Ex_{net\ process} + CExC_{resources\ avoided}\}^2$	**11,303**

[1] *Ground State 1: current scenario of emitting all pollutants and by-products without remediation*

[1] *Ground State 2: bringing all inputs, pollutants, and by-products to an environmentally acceptable end state as defined by EPA and WHO guidelines*

N.C.: No Contribution

Road Paving

For the plastic road scenario in Kampala, we used the wet method of asphalt production for calculations. The road construction company has all of their equipment at the quarry and mixes the asphalt from there [5]. The transportation of the tiles to the quarry was calculated based on the previously cited truck transportation CExC value of 3.13 kJ/kg-km. The tiles and aggregate are then crushed in a grinder with a CExC value of approximately

22.2 MJ/tonne [24]. The ground up tiles and aggregate are then dried in the sun to remove moisture. Bitumen is the most exergy-intensive element of asphalt roads because it requires extraction and extensive refining of petroleum. A tabulated CExC value of bitumen was not available, so we used a weighted ratio between the CExC value of coal and gasoline similar to Berthiaume Bouchard's process for estimating the exergy value of bitumen [152]. We used 47.52 MJ/kg for the CExC value of bitumen because it should lie between the values for coal and gasoline but weighted more towards gasoline. We also added the exergy cost of transporting the bitumen because it cannot be made in Uganda. Uganda gets its bitumen from Kenya, but Kenya often imports bitumen from Egypt, Saudi Arabia, Iran, and Turkey [83]. We used an exergy shipping transportation cost of 0.833 kJ/kg-km (an average of exergy shipping costs in [78] [88]). We used nautical distance from the ports of Jeddah, Saudi Arabia to Mombasa, Kenya then trucking distance from Mombasa to Kampala. We chose Jeddah as an origin port because it is one of the top ports in the world and relatively in the center of all the countries from which Kenya imports bitumen. The bitumen, tiles, aggregate, and sand are then mixed and heated in a large mixer. The mixer consumes 751 MJ of exergy per m^3 of mixture [24], and we used a mixture density of 2.5tonnes/m^3 [108]. The exergy required for heating each of the individual materials was calculated according to equations 2.11-2.12 and 2.14-2.15 (without the $Q_{extra\ fuel}$ term) with T_{rxn} equal to 180 C.

Using the tiles in road construction saves a significant amount of resources because the tiles replace some of the bitumen and sand required to make the asphalt mixture. Macrebur reports plastic can comprise 0.3% of the total asphalt mixture, replacing 6% of the bitumen [108]. If the plastic in all the Resintile tiles sold in a year is transformed into asphalt at 0.3% plastic content, it could pave 111,826 m^2 of road at 10 cm thickness. Plastics also have a lower C_p value than bitumen, so some exergy is saved in heating when plastics are used. The total exergy saved is the CExC values of the replaced bitumen and sand, plus the transport of the bitumen from Saudi Arabia, plus the exergy saved in heating, minus the transport of the tiles to the quarry.

Local Transformation to New Products

The process of transforming the old tiles into compound pavers could be done at the Resintile factory. The required machines are already there except for the molds to make the pavers, but those can be easily fabricated by local metal workers. To calculate the exergy consumed in the process, we first consider the cost of transporting the tiles by truck from the various houses to the Resintile factory. The tiles are then crushed into small pieces with a crasher (we used a CExC of 22.2 MJ/tonne as reported in the road calculations for grinding gravel). The ground up tiles are then fed into the extruder and melted. In this analysis, we included an extra 10% of fresh plastic waste to be mixed with the tiles to provide extra binding strength. The exergy calculations for running the extruder screw and heaters are outlined in the authors' previous paper [21]. The melted plastic is then put into the paver molds and allowed to cool.

The plastic pavers would replace the pavers currently made with concrete. Using the ratio of cement and sand used to make concrete pavers in Uganda (38% cement and 62% sand) [7], we calculated a CExC value of 3.99 MJ/kg for this concrete mix from a weighted ratio of the CExC value for cement (wet method, med rotary kiln) in Szargut and a CExC value for limestone from DeWuluf [88] which we used to represent the CExC value for sand. We subtracted the CExC value of the 10% fresh plastic waste added to the plastic pavers to get the net CExC of virgin resources saved.

Pit Burial

For the scenario of burying the tiles, we assumed each home would dispose of their own tiles in their own pit, so the only exergy consumed is in digging the hole. In Uganda, pits are dug manually with a pickaxe. Lu et al gives the exergy expended in digging as 3,483 kJ/person/day [104]. The average house where Resintile tiles are installed is a 3 bedroom bungalow with 250 square meters of tiles and 60 meters of ridge tiles [1]. The volume of all the tiles would occupy a 15.5 m^3 pit. In Uganda, it would take two men approximately 5 days to dig a hole of that size assuming they hit some murram—if there is no murram, it would be faster.

Exergy can also quantify the cost of using land, but since the tiles would be covered with at least 0.5 meters of soil, the land on top of the tiles could still be used for other purposes. Further research is needed to understand if the land could safely be used for growing crops or if it could support a large structure, but it could definitely be used for other purposes such as raising chickens, parking vehicles, cooking or washing, or relaxing in an open compound. The land could even be used as a football pitch or park. Therefore, we did not include the exergy cost of occupying the land.

2.5 Results and Discussion

The comparison of various CO_2 abatement methods for open burning and the net avoided exergy for the whole process is presented in Table 2.5 and Table 2.6 respectively. In Table 2.5, the abbreviation "calc" means the numbers were calculated in this paper. As noted in Section 2.4, the abatement exergy values for scrubbing emissions are not representative of Ugandan conditions, but they help give an indication of the remediation cost for open burning (although the analysis is limited to only CO_2, SO_2, and NO_2 emissions because of lack of AbatEx values for other pollutants). The method we proposed in this paper of planting trees to abate CO_2 emissions in a manner feasible for the developing country context of Uganda is worth exploring more because for every kg of plastic burned, our method could require only 0.7% of the exergy currently used by scrubbing techniques in developed countries. The precision of the calculations is noted by the number of significant digits presented in the tables. We maintained the precision reported in all sources and used the number of significant digits in the least precise value to report our calculation results.

Table 2.5: Comparing Emissions Abatement Exergy Costs and Methods

	AbatEx (MJ/kg pollutant)[a]	**kg pollutant /kg fuel fed[b]**	**AbatEx (MJ/kg PE burned)**	**AbatEx (MJ/tonne tiles)**	**Source [a, b]**
CO_2, planting trees eucalyptus woodlots	0.028	3.14	0.09	25.9	[calc, calc]
CO_2, planting trees Ugandan national parks	0.047	3.14	0.15	44.2	[calc, calc]
CO_2, scrubbing	5.9	3.14	13.0	5,535.7	[[50] [69]] , [calc]
SO_2, scrubbing	57	0.00014	0	2.0	[[38], [122]]
NO_x, scrubbing	16	0.0035	0	17.0	[[38], [42]]

A comparison of our other proposed disposal methods with remediation methods that are feasible in Uganda is presented in Table 2.7. The results show that when the exergy saved from replaced virgin resources and processes are considered, the net exergy cost is lowest for processes that recycle the tiles into a new product. This is consistent with DeWulf's findings for developed countries that the exergy ratio of outputs to virgin resource intake for different disposal methods is highest for recycling plastics [49]. In our results, mixing the tiles into asphalt to make roads and pyrolisizing the plastic into fuel are the best scenarios. Melting and re-shaping the tiles into compound pavers also results in a positive net exergy avoided. The current disposal methods of landfilling, burying, and open burning require very little exergy input for disposal, but no new product is produced and no resources are saved in the process. The other options we propose replace products and materials currently being used, so they can have a net positive exergy saved (except incinerating in cement kilns because the remediation exergy cost is so high). Therefore, inputting thermal energy can add value to the waste and save net resources.

The net process exergy cost of making the tarmac/plastic mixture for paving roads is relatively small because most of the costs negate each other—they are the same regardless of if tiles are included or the current bitumen/sand mixture is used. The C_p value of plastic is lower than that of bitumen, so heating the mixture with tiles takes slightly less energy than the current energy required, but the exergy cost of transporting the tiles to the quarry where the mixture is produced makes the net process exergy negative. However, adding tiles to the mixture saves significant resources because bitumen has a high CExC value, and in Uganda, bitumen must be imported from as far away as Saudi Arabia making the transport exergy costs extremely high. Replacing some of the bitumen and sand with the tiles saves

Table 2.6: Comparison of Net Avoided Exergy for Open Burning with Different Remediation Methods

All units reported as MJ/tonne of tiles

Disposal Options for Plastic Tiles	**Avoided Resources**	**Net Process Exergy[1]**	**Net Remediation Exergy**	**Net Process Exergy[2]**	**Net Avoided Exergy[1]**	**Net Avoided Exergy[2]**
Open Burning, CO_2 abated w/ eucalyptus woodlots	N.C.	-408	-322	-730	-408	-730
Open Burning, CO_2 abated w/ trees in Ugandan parks	N.C.	-408	-341	-748	-408	-748
Open Burning, CO_2 abated w/ scrubbing	N.C.	-408	-5,832	-6,240	-408	-6,240

[1]Ground State 1: current scenario of emitting all pollutants and by-products without remediation

[1]Ground State 2: bringing all inputs, pollutants, and by-products to an environmentally acceptable end state as defined by EPA and WHO guidelines

N.C.: No Contribution

some of those resources. In other locations where the transport costs for bitumen are not as high, plastic roads could be a less favorable disposal option compared to other disposal options.

Pyrolysis is a desirable option because the product produced replaces diesel fuel, which has a very high CExC value (the exergy value of the virgin resource is high and the refining process is exergy-intensive). Heating the tiles and disposing of the ash in a landfill are the most exergy intensive parts of the process. The ashes and sand leftover after pyrolisizing the plastic should be remediated by disposing of them in a sanitary landfill, but the exergy cost of that is only 2.4% of the net exergy avoided. In terms of exergy cost, it is worth it to do the environmentally responsible option.

The process of turning the tiles into pavers is one of the most net exergy intensive of the options because the current process of making concrete pavers uses only manual labor while the plastic paver production process requires electricity for grinding and heating. However, a significant amount of virgin resources are saved if the cement and sand for concrete pavers are no longer needed. Thus the net exergy avoided is positive, making recycling the tiles into pavers an attractive disposal option.

For incinerating in a cement kiln, the exergy of the manufacturing process is the same regardless of if the tiles or the current fuel mix is burned, but the resources avoided and remediation costs depend on the type of fuel burned. In this scenario, where biomass, coke,

Table 2.7: Comparison of Net Avoided Exergy for Different Disposal Options With and Without Remediation

All units reported as MJ/tonne of tiles

Disposal Options for Plastic Tiles	**Avoided Resources**	**Net Process Exergy[1]**	**Net Remediation Exergy**	**Net Process Exergy[2]**	**Net Avoided Exergy[1]**	**Net Avoided Exergy[2]**
Landfill	N.C.	-393	N.C.	-393	-393	-393
Pit Burial	N.C.	-7	N.C.	-7	-7	-7
Incinerate in Cement Kiln	84	N.C.	-61,839	-61,839	84	-61,755
Make Pavers	1,579	-764	N.C.	-764	815	815
Pyrolisize into Fuel	12,513	-938	-272	-1,210	11,575	11,303
Road Paving	16,499	-37	N.C.	-37	16,462	16,462

[1]Ground State 1: current scenario of emitting all pollutants and by-products without remediation

[1]Ground State 2: bringing all inputs, pollutants, and by-products to an environmentally acceptable end state as defined by EPA and WHO guidelines

N.C.: No Contribution

and fuel oil all have CExC values lower than plastic, the replaced resource value is not very significant. The CO_2 emissions from burning plastic are roughly twice the emissions from the current fuel mix, so the net remediation exergy for burning the tiles is negative. Therefore, in this case, if remediation is considered, incinerating the tiles in a cement kiln is clearly the most exergy intensive disposal option.

The two non-recycling options—landfilling and burying—are negative because no products are produced that can replace and save virgin resources. (Syngas can be captured from more sophisticated landfills, but Kiteezi does not have this capability. The plans for Kampala's next landfill at Ddundu include the possibility of such syngas capture, but no plans have been finalized yet.)

Table 2.7 also shows the cost of changing the ground state from current, ambient conditions to an environmentally acceptable end state. Two of the disposal options require some form of remediation. Properly disposing of the ashes and sand after pyrolysis costs 2.4% of the net exergy avoided, but planting trees to remediate the CO_2 released from incinerating the plastic in a cement kiln is extremely costly and makes the option unfavorable if remediation is considered. The other disposal options have no remediation costs as explained in the Remediation sub-sections of Section 2.3.

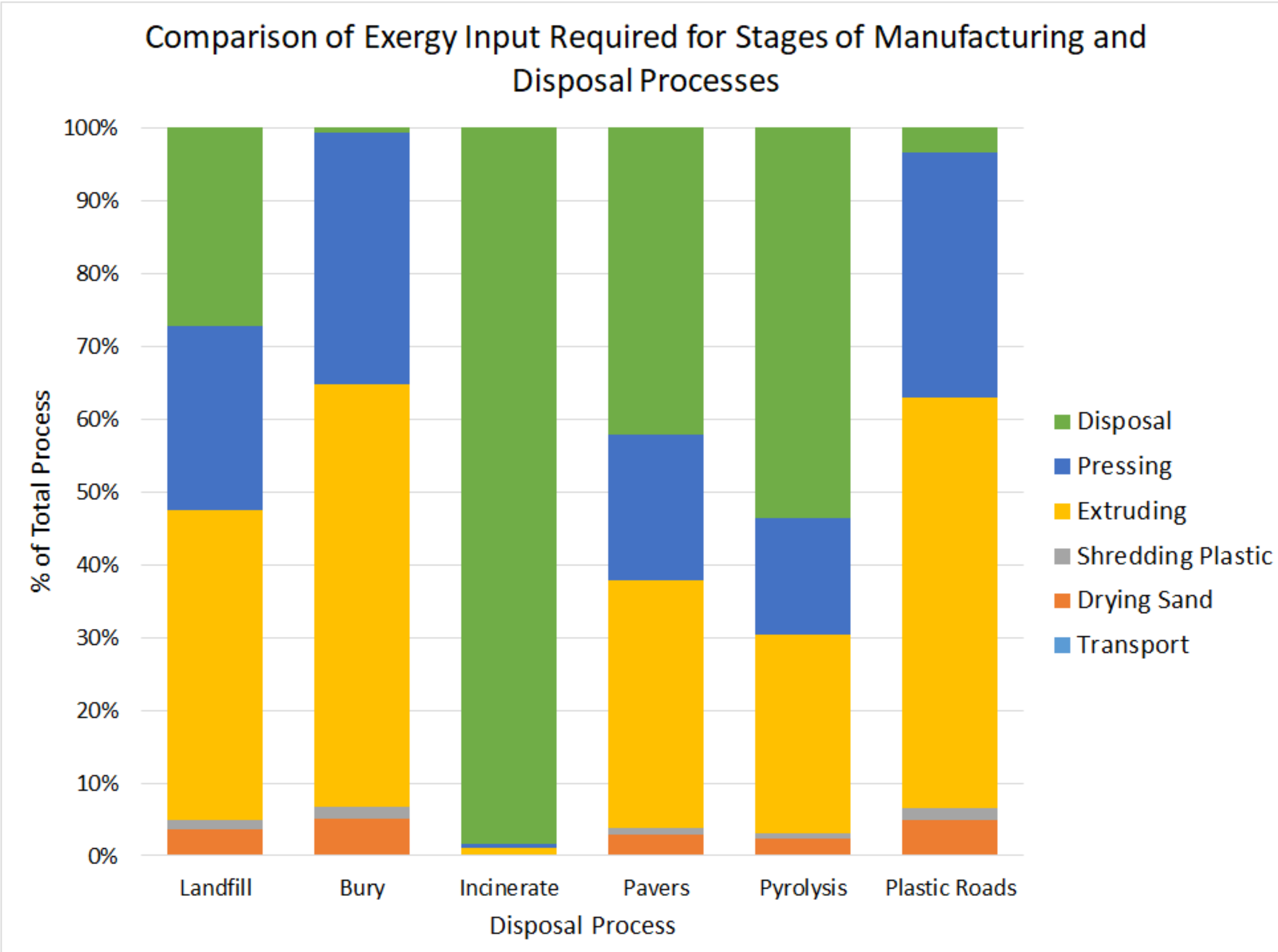


Figure 2.4: Comparison of Exergy Input Required for Stages of Manufacturing and Disposal Processes

When compared to the manufacturing of the tiles, the exergy input required for different disposal methods range from 0.6% to 98.3% of the whole cradle to grave process as shown in Figure 2.4. The exergy inputs required for the different stages of the tile manufacturing process are explained in the next chapter. Additionally, Ground State 2–bringing all the inputs, pollutants, and by-products to an environmentally acceptable end state–was used for the disposal methods in this graph.

If all of Uganda's 600 tonnes of plastic waste generated per day was converted into Resin-tile roof tiles and disposed of according to our proposed methods, Uganda's current electricity resources would be enough, but Uganda would have to import more diesel. Although the 600 tonnes/day number technically includes PET and PVC plastics which should not be recycled using the exact processes described in this paper, no data is available on the exact percentages of PET, PVC, and other plastics in Uganda's country-wide waste stream. Thus we continue the following analysis using 600 tonnes of plastic per day to estimate if Uganda's resources are enough to recycle all of its plastic waste.

For the best disposal option of paving roads with the old tiles, 158,108,819 L of diesel would be needed per year to melt all the plastic and bitumen. Electricity could be used to melt the mixture, but many road construction sites do not have access to reliable three phase electricity, so a diesel generator is used. Approximately 30 L of diesel can melt 1,800 kg of bitumen. [5] Uganda imports all of its petroleum products; in 2018, Uganda imported and sold 1,012,541,798 L of diesel [146]. The amount of diesel needed to heat all the plastic and bitumen to make roads with the old tiles from all of Uganda's plastic waste is 15.6% of the amount of diesel Uganda currently imports. For this disposal option, Uganda would have to import more diesel, but it would save importing 219,150,000 kg of bitumen per year by melting the tiles for roads.

If all of the old tiles from all of Uganda's plastic waste were made into pavers, 89.9 GWh of electricity would be needed per year to shred and melt the tiles. This is 2.2% of Uganda's current electricity generated because in 2018, Uganda generated 4,038.8 GWh of electricity [146].

If the pyrolysis disposal option was used, some of the recycled fuel oil produced could be used to run the process to pyrolysize the tiles and make more fuel. The other disposal options do not require electricity or thermal energy inputs. Therefore, all of Uganda's plastic waste could theoretically be made into roof tiles and safely disposed of even with Uganda's limited infrastructure.

2.6 Concluding Remarks

This paper utilized an extended exergy analysis (EEA) to quantify and compare the environmental effects of possible end of life disposal options for recycled plastic/sand roof tiles in the developing country context of Uganda. Our extended exergy analysis quantifies the energy-relevant resources used in the disposal process, resources saved from replaced virgin materials by recycling, and any additional resources needed to bring the tiles, byproducts, and pollutants back to an environmentally acceptable end state. We considered seven disposal options that are already used or could be appropriate for Uganda's less industrialized infrastructure. With a net exergy avoided of 16,462 MJ/tonne of tiles, mixing the tiles into asphalt roads proved to be the best option followed by pyrolysis with 11,303 MJ/tonne of net exergy avoided (including remediation). The remediation exergy cost for pyrolysis was predicted to be 2.4% of the net exergy saved. Recycling the tiles into pavers was the next best option with 815 MJ/tonne of net exergy avoided. Burying, landfilling, and incinerating in a cement kiln were all negative net exergy processes when remediation was considered with -7, -393, and -61,755 MJ/tonne of tiles respectively showing that inputting thermal energy can add value to the waste and save net resources. If all of Uganda's plastic waste was made into roofing tiles, Uganda theoretically has sufficient resources to safely dispose of all of the old tiles. The common practice of open burning was also considered, but we determined it is not practically feasible to bring all the pollutants from open burning to an environmentally acceptable end state with the limited technology available in Uganda. However, the method we proposed for remediating CO_2 by planting trees requires only 0.7% of the exergy used in CO_2 scrubbers currently used in developed countries.

This paper demonstrates how a thermodynamic extended exergy analysis can use empirical data to quantify the resource use of different disposal and recycling options for products made from plastic waste. Such a study focusing specifically on plastic products and disposal options applicable to developing countries has not been done before, so our paper can be useful to policy makers, multilateral organizations, and NGOs making decisions about solid waste management practices in less-industrialized nations. This paper presents results specifically for Kampala, Uganda, which cannot be accurately generalized to all developing countries because each nation's source of materials and technological infrastructure differ. However, with appropriate data, the calculations can be easily updated to provide accurate results for other countries. Additionally, the disposal options considered in this paper cannot be used for all types of plastic; for instance, pyrolyzing PET or PVC has negative environmental effects. The results from this paper are valid for HDPE, LDPE, and PP plastics.

Acknowledgement

We would like to thank Resintile, LLC. for their cooperation and support. We are especially indebted to William Namakajjo, Engineer, and Alex Mboijana, General Manager, for providing data and organizing site visits.

Funding for this project was provided by the NSF Graduate Research Fellowship (grant number DGE 1752814), the Big Ideas Competition at Berkeley, a USAID Global Development Fellowship (a subgrant from UC Berkeley under USAID Agreement Number AID-OAA-A-14-00072), and the Rodman C. Rockefeller Centennial Fellowship from the Institute for International Education.

Chapter 3

Exergy Analysis of Manufacturing Sand/Plastic Roof Tiles from Plastic Waste in Uganda

Since the EEA analysis revealed that transforming plastic waste into a new product was one of the most resource efficient methods for disposing of plastic waste in Uganda, I took a closer look at this process by conducting an exergy analysis of the manufacturing process to identify the inefficiencies and suggest potential improvements. As a case study, I analyzed the production process of a company in Kampala, Uganda that manufactures roof tiles by melting and compressing plastic waste with sand. (The same process is used to make pavers, so the results of this analysis directly apply to the EEA study described in the previous chapter.) The company, called Resintile, was the only producer of plastic roof tiles in Uganda. They operated in the Lugogo industrial area of the capital city from 2007 to approximately 2019 when the company closed. They used an industrialized extruder and press process to create plastic roofing tiles that look like the clay roofing tiles popular in Uganda. They learned the process and technology from a company in South Africa who first learned it from factories in Europe. We proposed conducting an exergy analysis of the Resintile fabrication process to understand the energy and resources used to manufacture plastic roofing tiles with the hopes of improving efficiency and reducing operational energy costs.

The total exergy consumed to produce one batch of seventy-five roof tiles is over 280 MJ, the potentially recoverable exergy is nearly 17 MJ (6% of consumed exergy), and the realistically recoverable exergy is over 6 MJ (2% of consumed exergy). Recycling plastic waste into roof tiles saves a net 188 kg of CO_2 *from entering the atmosphere per batch compared to open burning. If all of Kampala's plastic waste was converted to roofing tiles, nearly 560 tons of* CO_2 *could be saved per year.*

Additionally, a summary and analysis of the Ugandan roofing market is also presented in this chapter to complement the technical exergy analysis.

3.1 Introduction

Motivation

As described in Section 1, Uganda and the entire world face a massive plastic waste problem. Recycling the plastic waste into new products reduces pollution, generates environmental and community health benefits, creates local jobs, and closes a loop in the circular economy.

Scope of This Chapter

The scope of this chapter is to analyze the sustainability impact of manufacturing roofing tiles from plastic waste in Uganda. The core of the analysis is an exergy consumption study to analyze the overalll efficiency in use of resources. The exergy analysis study identifies the largest sink of resources and means to improve their efficiency thereby increasing sustainability and reducing operational costs. The exergy consumption study is supported by an overview of the Ugandan market for roofing tiles.

Recycling plastic into roofing tiles helps alleviate a host of environmental issues caused by littering and burning waste plastic, and the company must be able to sell their roofing tiles to continue positively impacting environmental sustainability. Selling more roof tiles equates to diverting more waste plastic from causing environmental harm.

Production Process Description

Resintile LLC. in Uganda produces roofing tiles from waste plastic using industrial machinery requiring over 120,000 USD in startup costs. They employ 5 managers, 2 assistants, and 16 shift workers and sell between 90,000-120,000 tiles per year.

Resintile is the only producer of plastic roof tiles in Uganda. They have been operating in the Lugogo industrial area of Kampala since 2007. They use an industrialized extruder and press process to create plastic roofing tiles that look like the clay tiles popular in Uganda. They learned the process and technology from a company in South Africa who first learned it from factories in Europe. An exergy analysis of the Resintile fabrication process evaluates the energy and resources used to manufacture plastic roofing tiles with the hopes of improving efficiency, reducing operational energy costs, and understanding its overall contribution to environmental sustainability.

Resintile creates roofing tiles from plastic waste and sand using an industrial process based on an extruder and press as described in Fig. 3.2. In the first step, moisture must be removed from the sand. This is done outside with solar energy by spreading out the sand on a tarpaulin. However, in rainy season when there is a lack of solar energy, the sand can be dried through electric heating in the extruder. Second, the sand is sieved to remove large chunks. Next, some of the plastic is shredded, and all the input materials are mixed by a worker using a spade. All of the materials are then fed into an extruder which heats, melts,

Figure 3.1: Resintile roof tiles [114]

and fuses all the inputs into a hot putty. A specified mass of this putty is weighed, placed in a mold, and pressed. After pressing, the mixture is now a roof tile. It is removed from the mold and set to cool.

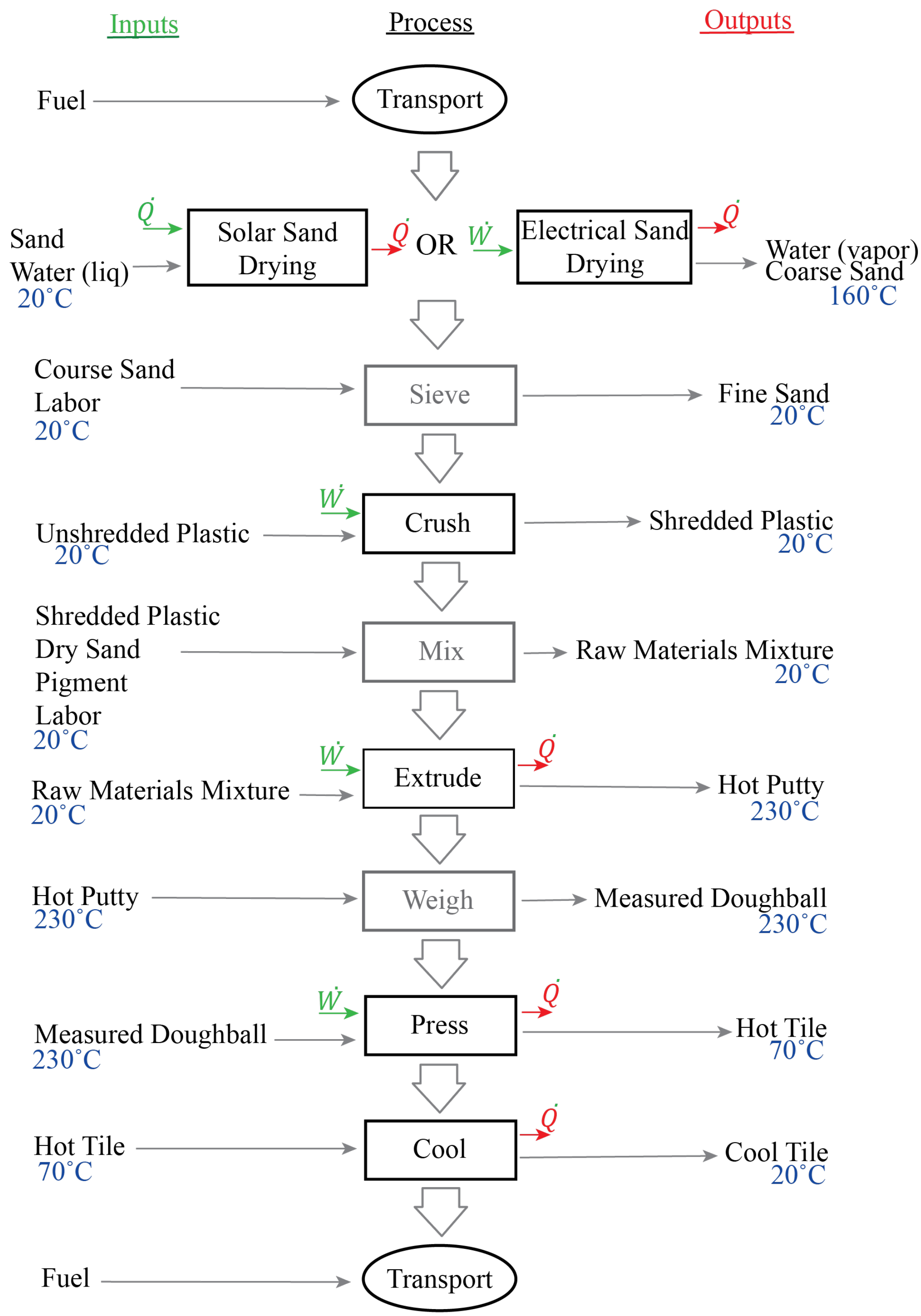


Figure 3.2: Resintile process flow diagram

Figure 3.3: Photo of tile forming press used at Resintile

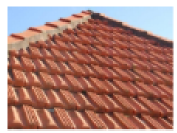
Roofing Market in Uganda

Roofing tiles are an economically feasible product to make from plastic waste because the Ugandan construction sector is expected to grow in excess of 8% annually for the next ten years. "Uganda faces an 8 million unit housing shortage," so "commercial...and residential construction in Uganda are booming." [64]

Figure 3.4 summarizes information on the prices, quality, and user perception of different roofing options in Uganda.

In villages, most people have thatch roofs because they cannot afford a better option, but thatch is susceptible to fire. Metal sheets are an intermediate price and quality option, but they make rooms oppressively hot and are very loud during rainstorms. Although some metal sheets can last for 25+ years, many people opt for cheaper, lower quality gauges with poor protective coatings that can rust. Clay tiles are the most desired roofing option for their beautiful appearance and long lifespan. However, they are very expensive, heavy (requiring more roofing timber supports), and must be periodically checked and scrubbed for fungus growth.

According to the 2016/17 Uganda National Household Survey of over 15,000 households, iron sheets account for 75% of Ugandan roofs and thatch accounts for 24%. [156] The other category includes clay tiles, concrete tiles, asbestos, and tin, so Resintile could potentially

Comparison of Major Roofing Options				
	Resintile	**Clay Tiles**	**Metal Sheets**	**Thatch**
Photo				
Cost (USD/sq m)	$10.15	$12.17	$2.09-$5.94	$0.63 / $0.89
Lifespan (yrs)	20	50+	15-25+	5 / 15
Density* (kg/m^2)	19.8	41.6	1.5-4.75	34
Advantages	Keeps rooms cool, insulates against noise, looks beautiful, uses 25% less roofing support than clay tiles.	Keeps rooms cool, insulates against noise, looks beautiful.		
Disadvantages		Prone to fungus growth.	Cheaper gauges prone to rust.	Susceptible to rats and insects; can't collect water for domestic use.
Ease of Manufacture	Industrialized	Industrialized	Industrialized	Local
Size (tiles/sq m)	9	16	3m lengths	-----
Flame Resistant	Somewhat (class B2, same as wood)	Yes	Mostly	No

*denser roofing materials require more support structure--a cost not factored into the price.

Figure 3.4: Comparison of roofing options in Uganda

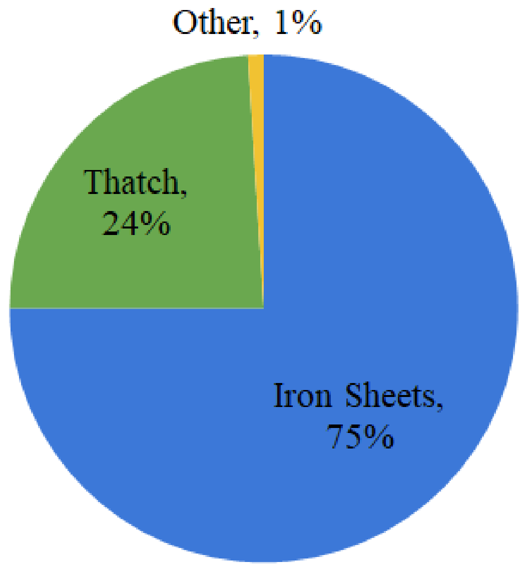


Figure 3.5: Breakdown of Ugandan Roof by Type

capture up to 1% of the Ugandan roofing market (75,400 roofs).

Because of their pricing, Resintile tiles fall in the same customer bracket as clay tiles, but the Resintile ones are cheaper and resistant to fungus growth. For a 250 sq m house, Resintile tiles are 7.3% cheaper than clay tiles when including the cost of timber supports (Resintile plastic tiles need fewer timber supports than clay tiles).

Resintile's highest cost in the production process is electricity. This could be reduced with more modern, efficient machines and with the process modification suggestions outlined in this paper. Obtaining the plastic waste through cheaper sources could also help reduce production costs.

3.2 Exergy Analysis Framework

As described in the previous chapter, exergy is a useful concept to analyze the overall efficient use of resources in a process. It helps identify useful energy that is low in entropy. Exergy is more than a thermodynamic property–it is a property of both the system and the environment because it considers the *quality* of the energy with respect to the environment. Exergy reveals how much energy is actually *available* to do useful work because thermodynamic inefficiencies stand out as destroyed exergy–energy that has lost quality or usefulness (e.g. wasted shaft work or waste heat). Exergy analysis helps engineers identify the amount, type, location, and causes of losses in a system to help identify means of improvements. [54]

Exergy should not be confused with energy. Table 3.1 taken from Dincer & Rosen (p.

13) clearly explains the differences between these two concepts.

Energy	**Exergy**
Dependent on properties of only a matter or energy flow, and independent of environment properties	Dependent on properties of both a matter or energy flow and the environment
Has values different from zero when in equilibrium with the environment (including being equal to mc^2 in accordance with Einstein's equation)	Equal to zero when in the dead state by virtue of being in complete equilibrium with the environment.
Conserved for all processes, based on the First Law of Thermodynamics	Conserved for reversible processes and not conserved for real processes (where it is partly or completely destroyed due to irreversibilities), based on the Second Law of Thermodynamics
Can be neither destroyed nor produced	Can be neither destroyed nor produced in a reversible process, but is always destroyed (consumed) in an irreversible process
Appears in many forms (e.g., kinetic energy, potential energy, work, heat) and is measured in that form	Appears in many forms (e.g., kinetic exergy, potential exergy, work, thermal exergy), and is measured on the basis of work or ability to produce work
A measure of quantity only	A measure of quantity and quality

Table 3.1: Comparison of Energy and Exergy [54]

For this exergy analysis of the Resintile plastic roofing tile manufacturing process, the environment or the ground state is defined as standard atmospheric pressure and either 30 or 33 (the average temperatures inside the manufacturing room away from and near the extruder). The value of the thermal material properties and their sources used in this analysis are listed in Tab. 3.2. For the specific heat of the plastics, values at 400 K were used since this is the average of the temperatures the plastics experience throughout the manufacturing process.

Consumed Exergy

Electrical Power

To find the exergy used by the machines, their power ratings and efficiency factors for hydropower were utilized. Electrical energy is equal to exergy (electricity has an exergy conversion factor of 1), so the electrical power used by machines in the manufacturing process can be converted to electrical energy (and exergy) by multiplying the machine's power rating by the time of operation. However, there are conversion losses in producing and transporting electricity. Since 78% of Uganda's electricity comes from hydropower [125], a conversion loss of 15% due to losses in potential energy at the dam, transformer losses at the power station, and pumping losses in the pumping station was used. [162, 163] Additionally, electrical energy is lost when transporting through power lines from the dam to the factory. Conductivity losses of 10% were used. [161]

$$Ex_{elec} = \frac{E_R}{\eta} = \frac{Pt}{\eta} \tag{3.1}$$

where P is the rated power of the machine in kW, t is the time of operation in s, and η is the efficiency after conversion losses, which is $(1 - .15) * (1 - .10) = 0.765$. The exergy used by the machines is greater than the electric energy consumed because of conversion and transportation losses.

Drying Sand

To calculate the exergy for drying the sand in the sun, phase change principles were used. The damp sand is actually comprised of two inputs: solid sand particles which undergo sensible heating and water which undergoes sensible and latent heating as it transforms from liquid water to water vapor. The sensible heat of the sand and water was calculated using equation 3.2, and the energy required to evaporate the water was found using equation 3.3 [54].

$$Q_{sens} = m * C_p * (T - T_o) \tag{3.2}$$

$$Q_{evap} = m_w * h_{lv}(T) \tag{3.3}$$

where h_{lv} is the latent heat of vaporization of water and m_w is the mass of the water. In equation 3.2, T_o is the ground state temperature of 30 C (and initial temperature of the sand and water) and T is the temperature at the end of heating. The final temperature of the sand after sitting in the sun was measured to be 48.5 C. In equation 3.3, a value for h_{lv} was looked up for 39 C, the average temperature that the water experiences. m_w was calculated from the moisture content of the sand

$$MC(\%) = \frac{M_w - M_d}{M_d} * 100\% \tag{3.4}$$

$$m_w = MC(\%) * m_{total} \tag{3.5}$$

where M_w is the mass of the wet sample, M_d is the mass of the dry sample, and m_{total} is the initial mass of the moist sand.

The latent heating of the water dominates over the sensible heating of both water and sand because h_{lv} is several orders of magnitude larger than either C_p and the temperature difference is small.

To calculate the exergy from the energy of vaporization and sensible heating, the carnot efficiency was used.

$$Ex_{evap} = \left[1 - \frac{T_o}{T}\right] Q \tag{3.6}$$

To find the exergy consumed in drying the sand, the final temperature of the sand when dried was used for T (48.5 C).

Transportation

When analyzing exergy of a process, the transportation of materials and end products should also be considered. The exergy consumed to transport the sand and plastic material inputs to the Resintile manufacturing site and then deliver the finished tiles to customers was calculated based on the CExC value of 3.13 kJ/kg-km for a 28t truck as described in [52].

$$Ex_{transport} = CExC * m * d \tag{3.7}$$

We assumed that the tiles would be purchased by customers within the Kampala area, so we used a distance of 35 km for delivery. Waste plastics are purchased from scrap dealers within Kampala at an average distance of 14 km from the production site, and sand must be brought from pits or rivers 140 km away.

Potentially Recoverable Exergy

Exergy for a closed system (non-flow) with mass m is defined as

$$Ex_{non-flow} = Ex_{ph} + Ex_o + Ex_{kin} + Ex_{pot} \tag{3.8}$$

where

$$Ex_{pot} = PE \tag{3.9}$$

$$Ex_{kin} = KE \tag{3.10}$$

$$Ex_o = \sum_i (\mu_{io} - \mu_{ioo}) N_i \tag{3.11}$$

$$Ex_{ph} = (U - U_o) + P_o(V - V_o) - T_o(S - S_o) \tag{3.12}$$

The terms with o subscripts are associated with the ground state.

Table 3.2: Thermal Material Properties

	HDPE	LDPE	PP	Sand (silicone dioxide)	Iron oxide
Specific Heat (kJ/kg K)	2.20 [43]	2.20 [43]	2.00 [43]	0.739 [170]	0.650 [45]

For this analysis of the Resintile manufacturing process, the control volume was defined as the materials needed to make one batch of 75 roof tiles. Since the chemical, kinetic, and potential energy of these materials do not change during the manufacturing process, equation 3.12 was used to find the exergy of this mass of materials at each stage of the manufacturing process. This represents the exergy that could potentially be recovered.

For an incompressible substance, equation 3.12 can be simplified as

$$ex_{ph} = c(T - T_o - T_o * ln\left(\frac{T}{T_o}\right)) \tag{3.13}$$

because the change in internal energy and entropy can be written using the specific heat of the material and various relationships of temperature [144]. This is specific exergy given in a per mass basis (kJ/kg). Since the specific heat is a material property, the Ex_{ph} for each input material used in making the tiles was calculated at each stage in the process then multiplied by the mass of that material needed to make one batch of 75 tiles. Each of these exergies was summed to give the total potential exergy recoverable at each stage of the process.

For melting and fusing the plastics together with the sand, the extruder exit temperature is set to 230 . This is hotter than the melting temperatures of the plastics (110, 135, 165) because the temperature of the materials at the center of the extruder is lower than the temperature at the extruder walls. The actual temperature of the cake coming out of the extruder was measured to be 181.4 . The higher temperature also allows proper mixing with the sand and enables the materials to be pushed through the extruder faster to increase production rates. However, lowering the extruder temperature settings could be explored to reduce exergy costs.

Realistically Recoverable Exergy

However, all of this exergy cannot realistically be recovered. Two practical methods of recovering exergy were analyzed.

Insulating Extruder

Wrapping the extruder barrel with insulation would minimize heat currently lost from convection with the surroundings and thereby reduce the exergy consumed by the extruder. The amount of exergy saved was calculated using a series of resistor networks with the current situation represented as a convection resistor equal to $\frac{1}{h*A}$ where A represents the surface area of the extruder barrel. The heat loss, Q was calculated as $Q = \frac{T_{extruder} - T_{ambient}}{R_{conv}}$. This Q was compared to the heat loss calculated when a conduction resistor ($R_{cond} = \frac{x}{k*A}$) representing the insulation was added in series with the convection resistor. x is the thickness of the insulation and k is its thermal conductivity (0.033 W/m K). A value for h was calculated using equations for natural convection boundary layers along a vertical isothermal wall. [23]

$$Ra_H = \frac{g\beta \Delta T H^3}{\alpha \nu} \tag{3.14}$$

where ΔT is the difference between the temperatures of the barrel and the ambient air and H, the characteristic length, is the length of the barrel.

$$Nu * Ra_H^{-1/4} = 0.387 \tag{3.15}$$

Equation 3.15 is valid when Pr=0.72 (the Prandtl number at room temperature air). The Rayleigh number from equation 3.14 was used in equation 3.15 which was solved for the Nusselt number. The Nusselt number can then be used to solve for h using the characteristic length and thermal conductivity of air ($Nu = \frac{hH}{k}$).

The extruder is broken into 3 different temperature zones, so to make calculations more precise, values for h were found for six different spots along the barrel of the extruder (each of the temperature zones and in between each zone). The calculated values for h ranged between 4.0-5.0 $\frac{W}{m^2K}$. The h values were used to find the heat lost, Q, with and without insulation at each of the six sections of the extruder barrel. The exergy lost was then calculated using equation 3.6 with the temperature of the barrel used for T in the carnot efficiency. The realistically recoverable exergy is the difference between the exergy lost in the current situation without insulation and the improved scenario with insulation.

Alternatively, a heat exchanger with copper coils of fluid with a high thermal conductivity value (such as ethylene glycol or water) could be wrapped around the extruder barrel. A thermal interface material could be used between the coils and the barrel to reduce the contact surface resistance. The waste heat from the extruder would warm the fluid which could then be used to pre-heat the input materials before they are fed into the extruder. This would reduce the overall exergy needed to operate the extruder. Another option is using a thermo-electric device to capture some of the waste heat from the extruder and produce electricity, but thermo-electrics are more capital intensive than heat exchangers.

Heat Engine

Currently, the sand is simply placed outside to dry in the sun. Instead, a heat engine could be used to capture the sun's energy and transform it into useful work. The heat engine could be made of carbon steel (stainless steel is not common in Uganda) and operate using a Rankine cycle.

When calculating the exergy potential of such a device, we used the same amount of solar energy currently used to dry the sand used in one batch of tile production and examined the ideal case and the best possible realistic scenario for a heat engine. To find the potentially recoverable exergy, the ideal case and equation 3.6 was used with T equal to the experimentally measured temperature of carbon steel exposed to the Ugandan sun (91).

The realistic scenario was calculated by multiplying the ideal case by an efficiency factor, η, equal to 0.6 because in reality, heat engines generally operate at 60% of carnot efficiency depending on the type of modifications to the basic Rankine Cycle used. [144]

Since a traditional heat engine would require significant capital investment, an alternative device could be considered that would be more applicable for the context of Uganda. For instance, PV solar panels could be turned upside down and elevated with concentrating mirrors or a parabolic trough placed underneath. When placed at the proper angles and distance from the solar panel, the mirrors could reflect the sun's rays onto the panel to create electricity. Sand could be placed on top of the panel, so the sand would be dried through direct exposure to sunlight and from the waste heat coming off the back of the panel. This alternative definition of a heat engine could be more applicable than traditional designs for a Ugandan setting.

CO_2 Emissions

To quantify the sustainability impact of the Resintile process, we wanted to calculate the amount of CO_2 emissions saved. The amount of exergy consumed in operating the machines was equated to kg of CO_2 emissions using a conversion factor of 4.9 g of CO_2/kWh of hydro electricity used (for run of river hydroelectric plants). [131] The same conversion was used to quantify the amount of CO_2 saved if the suggested recommendation to the manufacturing process were implemented. The fuel used in transportation was converted to CO_2 emissions using 8.89 kg CO_2/gallon of gasoline given by the U.S. Energy Information Association. [59] The sum of CO_2 emissions equivalently released by the Resintile production process was compared to the amount of CO_2 released by the open burning of plastic waste (a common disposal method for waste in Uganda).

Additionally, recycling plastic waste into roofing tiles prevents the plastic from being burned which would release CO_2. To understand Resintile's positive impact on sustainability, the amount of CO_2 that would have been released from burning the plastic used to make roofing tiles was calculated. The amount of CO_2 released from open burning was calculated using direct stoichiometric equations for each type of plastic. Since particulate soot emissions and residue solid ash measured in the open burning of plastic waste was less than 0.6%, complete combustion was assumed. [159]

3.3 Results of Exergy Analysis

The purpose of an exergy analysis is to identify areas in the process where destroyed exergy can be repurposed to useful exergy. Tables 3.3 and 3.5 and Fig. 3.6 display the results of this exergy analysis. All numbers were calculated for a batch of 75 tiles.

Extruding, transporting, and pressing consume the most exergy, but the process of drying the sand has the highest potentially and realistically recoverable exergy potential.

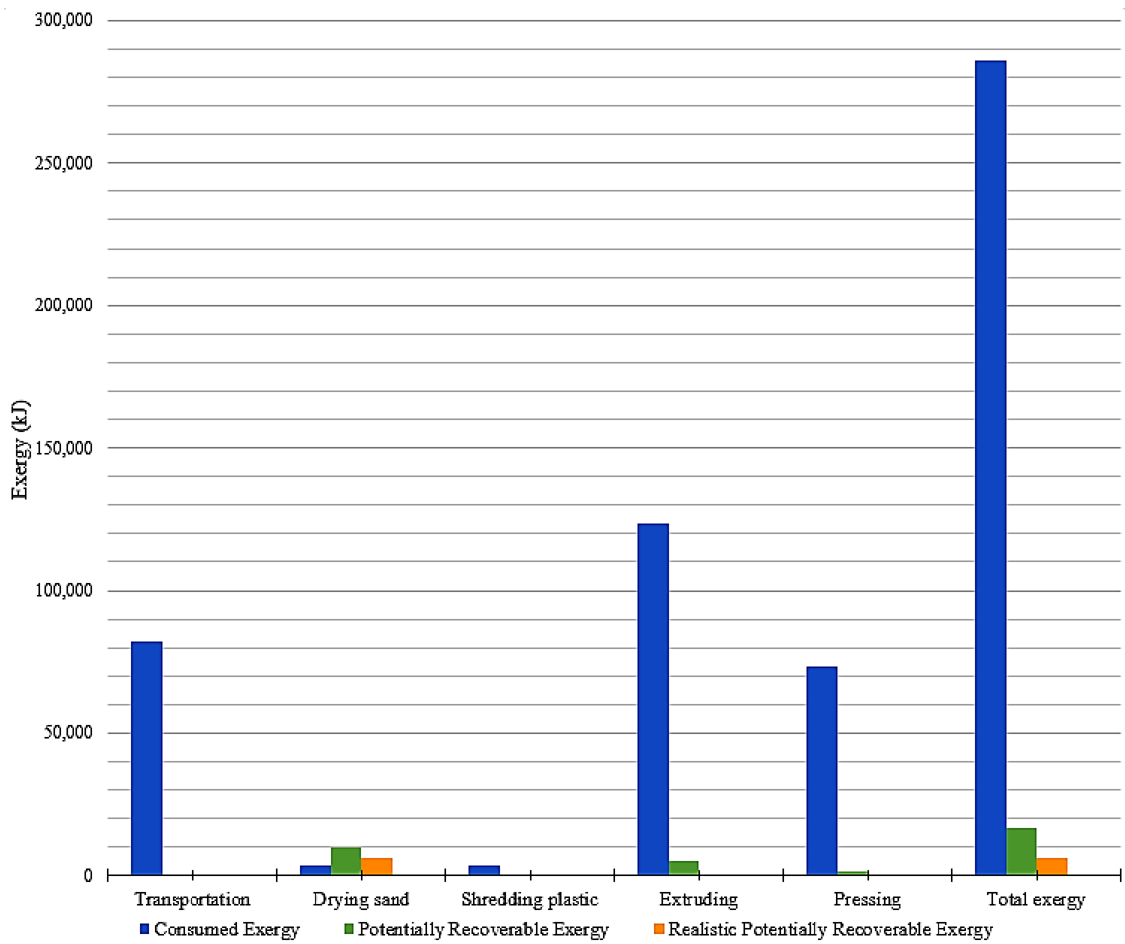


Figure 3.6: Resintile Production Process Exergy Analysis Results

To produce a batch of 75 tiles, the Resintile process consumes over 280 MJ of exergy. Nearly 17 MJ (6%) is potentially recoverable. To recover some of that exergy, we analyzed the largest exergy sink–the extruder. Table 3.6 shows how wrapping the extruder barrel in insulation could recover 190 kJ of exergy per batch–a 30% improvement compared to the current scenario of the extruder barrel exposed to natural convection.

Another way to recover exergy is by adding a heat engine where the sand is dried by the sun. Table 3.7 shows that if the same amount of solar energy currently used to dry the sand was instead applied to a heat engine, over 6 MJ of exergy could realistically be produced. This is 2% of the total exergy currently consumed in the whole production process and could be used to dry the sand or power some of the machines for free.

Table 3.3: Resintile Production Process Exergy Analysis Results

Exergy Consumed (kJ)	Process	Exergy Potential for Recovery (kJ)
82,053	Transportation	0
3,453	Drying Sand	10,056
3,482	Crushing Plastic	0.07
123,797	Extruding	5,200
73,529	Pressing	1,412
286,315	**Totals**	**16,668**

Table 3.4: Overall impact on CO_2 emissions

	One batch of tiles	All of Kampala's annual plastic waste
Kg CO_2 to produce tiles	2.2	6,457.7
Kg CO_2 released from burning	188.3	564,767.9
Net kg CO_2 saved	187.9	558,310.1
Kg CO_2 saved with recommendations	0.008	25.4
Net kg CO_2 saved with recommendations	**187.9**	**558,335.5**

The theoretical and realistic potentially recoverable exergy for drying sand is higher than the exergy currently consumed in the process because the current process of just laying the sand on a tarp exposed to sunlight degrades the solar energy–it doesn't utilize the full potential of the solar irradiation. Drying the sand takes 60,004 kJ of energy; the current process utilizes only 3,453 kJ of exergy of that–meaning that 94% of the solar energy is being wasted. A heat engine, even a very simple one, would allow more of that solar energy to be utilized.

If both the heat engine and insulation around the extruder barrel were added, over 6.2 MJ of exergy could realistically be recovered, which is 2% of the total exergy consumed.

Recycling plastic into roofing tiles prevents the open burning of plastic. Each batch of tiles utilizes 60 kg of plastic, which if burned, releases 188 kg of CO_2 while the equivalent of only 2 kg of CO_2 is released from Resintile's production process per batch. Therefore, recycling the plastic waste into a new product prevents the plastic from being burned and saves a net 188 kg of CO_2 per batch of Resintile roof tiles. If all of Kampala's plastic waste (180 tons/day) was made into roofing tiles, it would prevent nearly 560 tons of CO_2 from being released into the atmosphere due to burning. (This assumes that all of Kampala's waste is burned, so in reality, it is an upper limit.) It is reasonable to consider turning all of Kampala's plastic into roofing tiles because if Resintile captured 1% of Uganda's roofing

Table 3.5: Resintile transport exergy results

Material	Distance (km)	Exergy Consumed (kJ)
Inputs		
Sand	140	61,348
Plastic	14	2,629
Outputs		
Tiles	35	18,076
Total		**82,053**

Table 3.6: Exergy recovered through insulating extruder barrel

Exergy lost w/o insulation (kJ)	627.6
Exergy lost w/ insulation (kJ)	437.1
Exergy saved (kJ)	190.5
Improvement	29.5%

Table 3.7: Solar exergy

Solar Usage	Efficiency	Exergy (kJ)
Current	5.8%	3,453
Ideal Heat Engine	16.8%	10,056
Realistic Heat Engine	10.1%	6,033

market, they would need 135,720 tonnes of plastic or 754 days worth of Kampala's plastic. Table 3.4 summarizes the results of Resintile's contribution to reducing CO_2 emissions.

3.4 Developing Country Context

Special considerations must be taken because of Uganda's developing economy and geographic location. Power is unreliable, and when electricity is unavailable, companies must use generators, increasing production costs. Power in Kampala is also priced so it is cheaper at night, so Resintile tries to run production during these cheaper but less convenient hours.

Since Uganda's manufacturing sector is not well developed, they must import all their machines and pay large tariffs. There is also not a very large demand for expensive roofing (only 1% of the market). However, there is still enough of a market to potentially utilize all of Kampala's plastic waste. There are also benefits to manufacturing in Uganda. Labor is relatively cheap, and Uganda's location on the equator offers intense solar energy, which if utilized can reduce electricity costs.

3.5 Concluding Remarks

An exergy analysis of an industrial recycled plastic roof tile manufacturing process in Kampala revealed that the production of one batch of 75 Resintile roofing tiles consumes over 280 MJ of exergy. The potentially recoverable exergy is nearly 17 MJ (6% of consumed exergy), and the realistic recoverable exergy is over 6 MJ (2% of consumed exergy). Recycling plastic into one batch of roofing tiles prevents 188 kg of CO_2 from entering the atmosphere compared to open burning. If all of Kampala's plastic waste was converted to roofing tiles, nearly 560 tons of CO_2 could be saved per year.

Acknowledgment

I would like to thank Resintile, LLC. for their cooperation and support. I am especially indebted to William Namakajjo, Engineer, and Alex Mboijana, General Manager, for providing data and organizing site visits.

Funding for this project was provided by the NSF Graduate Research Fellowship, USAID Global Development Fellowship, and the Big Ideas Competition at Berkeley.

Chapter 4

Fundamental Heat Transfer Analysis of Solar Drying Process

Many recycling operations in Uganda have to wash the dirty plastic flakes to clean them and then dry the flakes before storing, shipping, or processing. The drying process is resource intensive. In industrial plastic recycling operations, dewatering machines and thermal dryers are used, but these require a lot of electricity. In Uganda, power can be unreliable, expensive for small-scale recycling operations, and it consumes resources. Instead, many recyclers opt to dry the plastic utilizing Uganda's intense solar irradiation for free. Often, the wet flakes are spread on a tarpaulin and exposed to sunlight for hours until the flakes are dry.

We developed a mathematical heat transfer model to predict the drying time for this scenario and conducted experiments in Uganda to gather data and tune the model. The goal is to develop suggestions to improve the resource efficiency of the solar drying process.

4.1 Introduction

Motivation

Many plastic recyclers in Uganda wash dirty plastic flakes to clean them and then lay the wet plastic on tarpaulins in the sun to dry before shipping or processing. If the weather is rainy or cloudy, they cannot dry the plastic in the sun and either have to use machines and pay for additional electricity costs or wait until the weather is favorable, which can disrupt production.

To improve this solar drying process to increase production efficiency and save time and electricity, we studied the drying process from a fundamental heat transfer phase change perspective. We developed a heat transfer model and conducted experiments to gather data and refine the model. This work is still ongoing, but the goals are to understand the physical processes driving and the variables affecting solar drying of wet plastic flakes, develop a model to predict drying time based on input variables, conduct experiments to validate the model, and propose and test improvements to the current drying process.

4.2 Development of Mathematical Model

The problem is difficult to model because the layer is inhomogeneous. Wet plastic flakes are randomly spread in a flat layer on a tarpaulin. Water coats the flakes, and some water drips off and puddles on the bottom, but the majority of the layer is air (over 60% volumetrically). Initially, we tried to model the problem as porous media, but a porous media model is not appropriate for this scenario because the interstitial spaces are large compared to the medium and the holes are not consistent. We had to return to fundamentals, start with the heat equation, evaluate all the possible contributions, and try to develop a physically accurate model based on conservation of energy and mass.

In this drying problem, there are four possible heat transfer mechanisms. 1) Direct solar radiation transmitted through and absorbed by the layer. 2) Conduction from the flakes at the top of the layer to the flakes at the lower parts. 3) Convection at the top of the layer with the ambient surroundings. 4) Heat released from water vaporization.

In the experiments, the volume fraction of plastic flakes was on average 23.6% and the average volume fraction of water was 14.8% leaving air with a void fraction of 61.6%.

This analysis specifically examined drying PET plastic flakes from water and soda bottles in Uganda. PET has a contact angle of approximately 79 degrees [66], so it is slightly hydrophilic. PET also exhibits hygroscopic behavior, so it requires large inputs of energy to evaporate moisture.

Possible relevant variables for this problem include the thickness of the layer, the initial and final moisture content, void fraction of the layer, ambient temperature and humidity, the intensity of the incident solar irradiation, absorptivity, reflectivity, and transmisivitty of the layer, the interface temperature between the liquid and vapor phases, convection coefficient with the ambient, conduction path length through the liquid, temperature of the layer over time, and thermal properties of the materials.

Governing Equation

To develop a mathematical heat transfer model, a control volume was pictured on the plastic/water/air matrix as shown in Figure 4.1. Conservation of mass, species, and energy as well as Fourier's Law of conduction was then used to develop a governing equation and initial and boundary conditions.

In Figure 4.1, the depth of the layer is shown on the y axis with y_i being the total thickness. T_a is the ambient air temperature, T_0 is the temperature of the tarp at the bottom of the layer, and I_{Di} is the net solar irradiation (incident minus reflected) at the surface and entering the layer.

Starting with the heat equation,

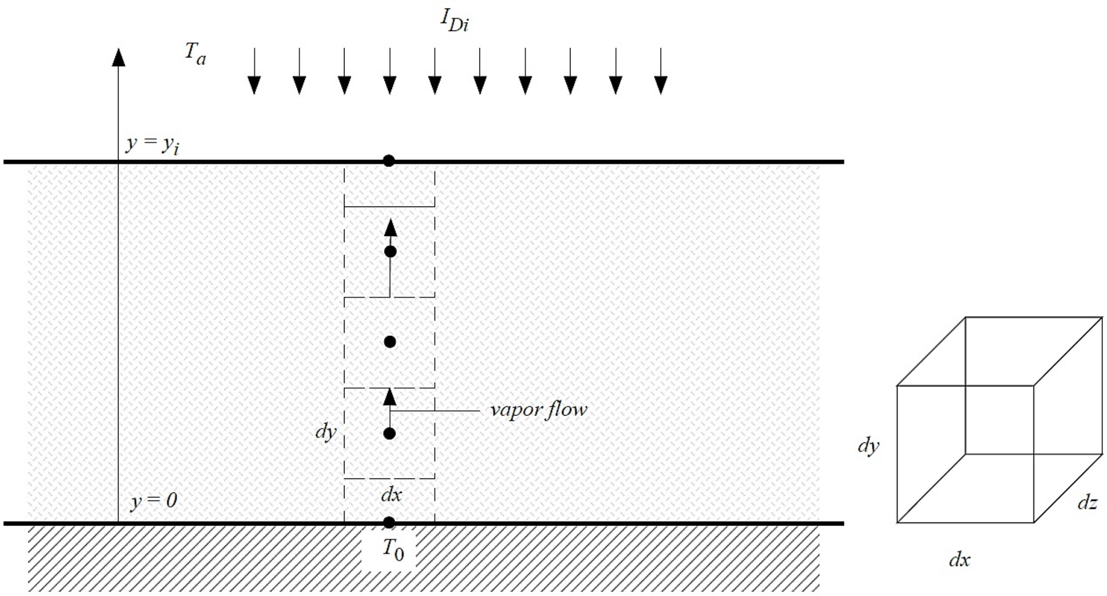


Figure 4.1: Control Volume Analysis of Layer

$$\rho C_p \frac{\partial T}{\partial t} = -\Delta \cdot \vec{q} + g \tag{4.1}$$

there is no generation, so the last term drops out. The q contributions come from absorption of incoming solar irradiation, net conduction within the layer, and energy removal due to evaporation.

$$\frac{\partial}{\partial t}(\rho_m C_{p_m} T_m) = q_s^{'''} + q_{cond}^{'''} - q_{evap}^{'''} \tag{4.2}$$

The left hand side of the equation represents the rate of accumulation/energy storage. The subscript $_{\mathrm{m}}$ represents the mean value of the plastic/water/air layer.

To find $q_s^{'''}$, the penetration of the solar irradiation into the layer was analyzed using Equation 4.3.

$$q_s^{'''} = \frac{dI_D}{dy} = \alpha(1-\epsilon)I_D \tag{4.3}$$

where I_D is the net solar irradiation (incident minus reflected) within the layer. α is the volumetric absorbed fraction of radiation and $(1-\epsilon)$ is the volume fraction of plastic.

Rearranging Equation 4.3 and integrating over the depth of the layer gives

$$\int_{I_{D_i}}^{I_D} \frac{dI_D}{I_D} = \int_{y_i}^{y} \alpha(1-\epsilon)dy \tag{4.4}$$

$$ln\left(\frac{I_D}{I_{D_i}}\right) = \alpha(1-\epsilon)(y-y_i) \tag{4.5}$$

$$I_D = I_{D_i}\ e^{\alpha(1-\epsilon)(y-y_i)} \tag{4.6}$$

Plugging equation 4.6 back into the previous equations gives

$$q_s^{'''} = \alpha(1-\epsilon)\ I_{D_i}\ e^{\alpha(1-\epsilon)(y-y_i)} \tag{4.7}$$

where $q_s^{'''}$ is the volumetric heat generation in the layer from absorption of solar irradiation. The units of $q_s^{'''}$ are $[W/m^3]$.

Returning to equation 4.2, $q_{cond}^{'''}$ is the net conduction within the layer, which can be evaluated as

$$q_{cond}^{'''} = k_m \frac{\partial^2 T_m}{\partial y^2} \tag{4.8}$$

For $q_{evap}^{'''}$, the water that evaporates was modeled as hemispherical droplets sitting on the surface of the plastic flakes as depicted in Figure 4.2.

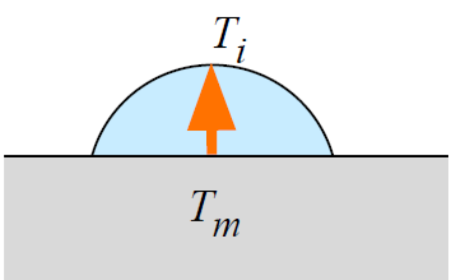


Figure 4.2: Modeling of Hemispherical Water Droplet on Plastic Flake

T_m is the mean plastic temperature, T_i is the liquid/vapor interface temperature, and δ_e is the mean effective conduction path length through the liquid to the interface. For T_i, the dew point temperature was used since that is the temperature at which the air above the droplet would become saturated with water vapor at a given pressure and relative humidity. For each set of experiment data, the dew point was calculated based on the ambient relative humidity and temperature for that day.

Therefore, $q_{evap}^{'''}$ can be modelled as

$$q_{evap}^{'''} = A_i^{'''} \frac{(T_m - T_i)k_l}{\delta_e} \tag{4.9}$$

where k_l is the thermal conductivity of the liquid water.

By definition,

$$A_i^{'''} = \frac{A_i^{'''}}{V_l^{'''}} V_l^{'''} \tag{4.10}$$

and for hemispherical droplets,

$$\frac{A_i^{'''}}{V_i^{'''}} \sim \frac{\delta_e^2}{\delta_e^3} = \frac{1}{\delta_e} \tag{4.11}$$

Equation 4.9 can then be written as

$$q_{evap}^{'''} = \frac{(T_m - T_i)k_l}{\delta_e^2} V_l^{'''} \tag{4.12}$$

Finally, the full governing equation becomes

$$\rho_m C_{p_m} \frac{\partial T_m}{\partial t} = \alpha(1-\epsilon)\ I_{D_i}\ e^{\alpha(1-\epsilon)(y-y_i)} + k_m \frac{\partial^2 T_m}{\partial y^2} - \frac{(T_m - T_i)k_l}{\delta_e^2} V_l^{'''} \tag{4.13}$$

Nondimensionalization

To nondimensionalize the governing equation, the following character scales were defined:

$$\tau_m = \frac{y_i^2 \rho_m C_{p_m}}{k_m} \tag{4.14}$$

$$\Delta T_C = \frac{y_i I_{D_i}}{k_m} \tag{4.15}$$

$$\alpha_m = \frac{k_m}{\rho_m C_{p_m}} \tag{4.16}$$

Then dimensionless parameters were defined as

$$\hat{t} = \frac{t}{\tau_m} \tag{4.17}$$

$$\eta = \frac{y}{y_i} \tag{4.18}$$

$$\Phi = \frac{T_m - T_i}{\Delta T_C} \tag{4.19}$$

Φ is the dimensionless local temperature where T_m is the mean temperature of the layer and T_i is the temperature of the liquid-vapor interface of the water.

The governing equation 4.13 can be written with the nondimensional parameters as:

$$\frac{\partial \Phi}{\partial \hat{t}} = \frac{\partial^2 \Phi}{\partial \eta^2} + \alpha y_i (1-\epsilon) e^{-\alpha y_i (1-\epsilon)(1-\eta)} - \left(\frac{k_l}{k_m}\right)\left(\frac{y_i}{\delta_e}\right)^2 V_l^{'''} \Phi \tag{4.20}$$

The initial conditions are:

$$Temperature\ IC : \Phi(\eta, 0) = \Phi_0 = 0 \tag{4.21}$$

$$MC\ IC : V_l^{'''}(\eta, 0) = V_{l,0}^{'''} \tag{4.22}$$

because at $t = 0$, $T = T_0$ for all y (and η,) and it is assumed that the whole matrix starts at the same initial moisture content.

For the boundary condition at the bottom, where $y = 0$ and $\eta = 0$, an adiabatic BC is used, and at the top surface, a convection BC with the ambient air is used.

$$Bottom\ BC : \frac{\partial \Phi}{\partial \eta}(0, \hat{t}) = 0 \tag{4.23}$$

$$Top\ BC : -\frac{\partial \Phi}{\partial \eta}(1, \hat{t}) = Bi[\Phi(1, \hat{t}) - \Phi_a], where\ Bi = hy_i/k_m \tag{4.24}$$

Idealizations

The model described above is based on a number of idealizations.

First, it is assumed that solar energy is the dominant energy input, so that in this first approximation, combined evaporation and diffusion effects are treated as negligible. The basis for this is the theory that as the solar energy raises the temperature of the layer and the water evaporates, the air in the interstitial pores and immediately above the layer becomes saturated. The moist air rises to the top of the layer due to buoyancy effects and wind over the surface carries the saturated air away from the layer enabling more liquid within the layer to evaporate and follow the same process.

Second, the water to be dried is modeled as hemispherical droplets sitting on the plastic, and the energy required for evaporation is found from conduction through the droplet with the liquid-vapor interface temperature equal to the dew point temperature of the ambient environment. Based on parametric analysis for typical droplets, the conduction path length, δ_e was set to 7 mm.

Third, α, the volumetric absorbed fraction of radiation, is treated as constant. Since obtaining accurate irradiation data was challenging due to clouds and weather conditions, the α values were tuned until the model matched well with the experiment data, and then the mean of those α values was used. The mean value used in the nondimensionalized governing equation was 68.2 1/m.

For the initial condition, it is assumed that the entire layer starts at the ambient temperature of its surroundings. For the boundary conditions, it is assumed that the tarp at the bottom is adiabatic and that there is a constant rate of convection at the top surface of the layer.

The model is 1D analyzing the energy transfer in just the thickness of the layer and assumes that the width and length are very large compared to the height of the layer.

Additionally, constant properties at average temperatures are used. For density, specific heat, and thermal conductivity, mean values for the matrix are used calculated from volumetric averages of the respective properties for plastic, water, and air.

Further simplifications for solving the governing equation at short and long time scales were made and are described in the following section.

Solving the Governing Equation

The solution to the governing equation 4.20 can be broken into a short-time scale and a long-time scale solution.

At short times, the thermal capacitance and solar input terms dominate because Φ is small and gradients in Φ are small. (T_m is still approximately equal to T_i.)

Therefore, at short time scales, the governing equation reduces to

$$\frac{\partial \Phi}{\partial \hat{t}} = \alpha y_i (1-\epsilon) e^{-\alpha y_i (1-\epsilon)(1-\eta)} \tag{4.25}$$

which can be solved analytically through integration.

$$\Phi = \Phi_0 + \hat{t} \alpha y_i (1-\epsilon) e^{-\alpha y_i (1-\epsilon)(1-\eta)} \tag{4.26}$$

At longer time scales, the vaporization and input solar energy terms dominate because the matrix reaches a high enough temperature that the thermal capacitance and conduction terms become secondary. Therefore, at long time scales, the dominant terms become

$$0 = \alpha y_i (1-\epsilon) e^{-\alpha y_i (1-\epsilon)(1-\eta)} - \left(\frac{k_l}{k_m}\right) \left(\frac{y_i}{\delta_e}\right)^2 V_l^{'''} \Phi \tag{4.27}$$

which can be rearranged to

$$\Phi = \left(\frac{k_m \alpha (1-\epsilon) \delta_e^2}{k_l y_i V_l^{'''}}\right) e^{-\alpha y_i (1-\epsilon)(1-\eta)} \tag{4.28}$$

assuming that at least some solar irradiation reaches the bottom of the layer.

Conservation of energy and water vapor mass dictate that

$$h_{lv} \frac{\partial m_l^{'''}}{\partial t} = h_{lv} \rho_l \frac{\partial V_l^{'''}}{\partial t} = -q_{evap} = -\frac{(T_m - T_i) k_l V_l^{'''}}{\delta_e^2} \tag{4.29}$$

Integration reveals that

$$V_l^{'''} = V_{l,0}^{'''} e^{-\frac{(T_m - T_i) k_l}{h_{lv} \rho_l \delta_e^2} t} \tag{4.30}$$

These equations can be solved numerically. A Dufort-Frankel finite difference numerical method was used starting at the third timestep. The short-time scale analytical solution was used to find solutions for the first and second timesteps, which was fed into the Dufort-Frankel scheme. The Dufort-Frankel method can then march forward in dimensionless time, $\hat{t}$ to find the drying time.

At each timestep, for successive y values going down from y_i to $y = 0$, find a new Φ value, compute $T_m - T_i$ at y, find $V_l^{'''}$ at y, and repeat for successive timesteps until $V_l^{'''}/V_{l,0}^{'''}$ is negligible throughout the layer or $V_l^{'''}$ reaches the final desired moisture content. The corresponding time when this point is reached is the drying time.

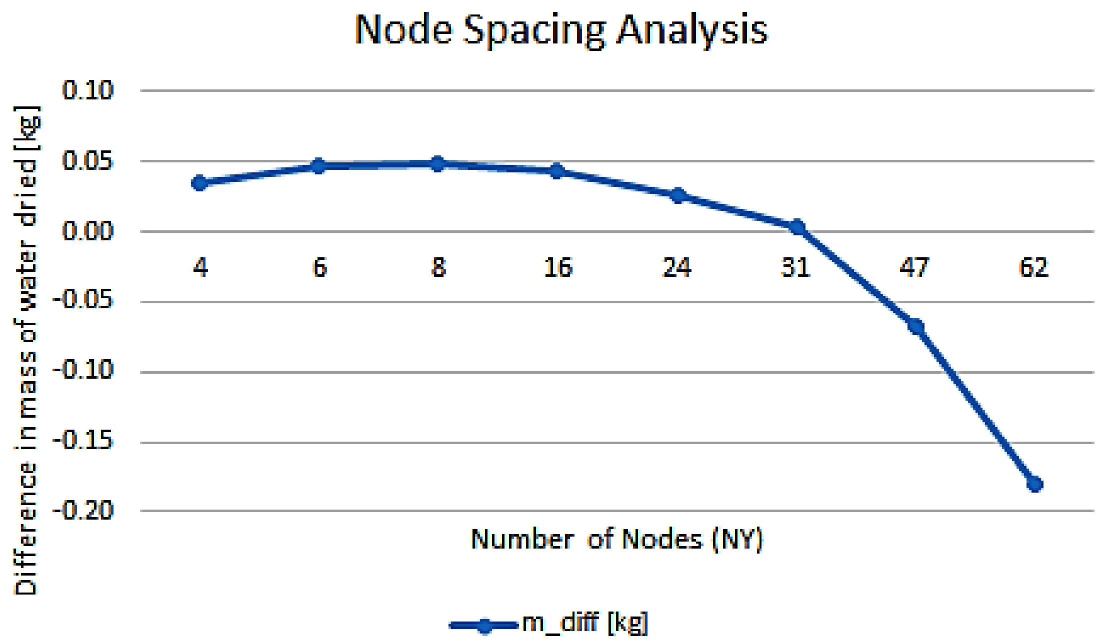


Figure 4.3: Node Spacing Analysis

Node Spacing Analysis

A node spacing analysis was conducted to find the number of nodes that should be used to increase model accuracy. As shown in Figure 4.3, the asymptotic limit of the model was reached when 8 nodes were used. The horizontal axis shows the number of nodes, and the vertical axis shows the difference between the model's prediction and the experimental data final results for the mass of water dried.

Additionally, the dimensionless time step was set to 0.01364.

4.3 Experiments

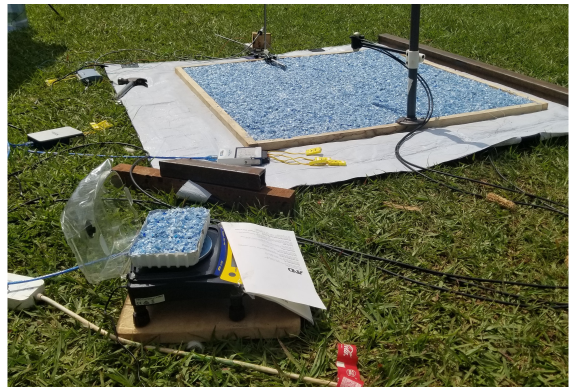
To collect data to input into and validate the model, experiments were conducted in Gulu, Uganda at the premises of Takataka Plastics. A variety of experiments were conducted during August 2021 and January 2022. Figure 4.4 shows the general experiment setup.

Figure 4.4: Setup of Drying Experiments

To measure solar irradiation, three Apogee SP-510 pyranometers were used. (output 0 to 100mV) One was mounted facing up and level with the plastic flakes to measure the incident irradiation, one was mounted facing down above the flakes at the recommended height of 20cm above the surface to measure the reflected irradiation, and the last pyranometer was buried under the tarp, facing up and positioned so that the top surface of the sensor dome was level with the bottom of the plastic flakes (a hole was cut in the tarp for the sensor to peak through.) This bottom pyranometer measured the amount of irradiation that was transmitted through the layer.

To measure moisture content of the plastic, a CY1050W halogen moisture meter was used (110 g capacity/5 mg readability) (Figure 4.5a). An A&D EJ-303 EJ Series Compact Balance was used to log the mass over time of a small tray of wet plastic adjacent to the larger tarp setup (Figure 4.5b). This allowed the mass of water evaporating to be logged through the whole experiment duration. An ATOM SF-400A compact weighing scale was used to measure the initial and final mass of the plastic flakes and water.

(a) CY1050W Moisture Meter



(b) EJ-303 EJ Compact Balance Adjacent to Larger Flake Setup

Ten Type K thermocouples from Omega (wire gauge 40 AWG, 5TC-TT-K-40-36) were strategically positioned to measure the temperature at the top, middle, and bottom of the layer in two locations, the air above the flakes, and the ambient air away from the experiment.

Humidity directly above the flakes and in the ambient away from the flakes was measured using two Omega HX71-V1 probes (Figure 4.6). Wind speed was measured with an Omega FMA904A-V1 air velocity transmitter. The humidity probes and air velocity transmitter were powered by an Omega 24 Vdc regulated power supply.

All of the data was logged with four DAQs: one NI-USB 6008 8 AI, two NI 9211 4 TC, and one OM-USB-TC-AI 4 TC/4 AI data acquisition devices. A LabVIEW program was written to read, manipulate, and save the data.

Figure 4.6: HX71-V1 Probe Measuring Relative Humidity Above the Flakes

Experiment Procedure

The general procedure for the experiments was to first obtain shredded PET flakes, weigh the dry plastic (enough to reach the desired layer thickness– a one inch thick layer required approximately 8 kg of dry PET flakes to fill a one square meter frame.) The plastic was washed and allowed to soak in water. While the flakes were soaking, the experiment equipment was setup. The tarp(s) were laid out in an area with ample sunshine, sensors were setup, and computers were connected for logging.

Once the equipment was setup, excess water was drained from the flakes, and the wet flakes were weighed. The mass of the water added was obtained by subtracting the wet weight from the original dry weight of the plastic. After mixing the wet flakes to ensure the water is evenly distributed, several moisture content samples were taken–this was considered the initial moisture content. Immediately, the flakes were spread on the tarp(s). A frame was used to ensure the flakes were spread in a one square meter area and that the desired thickness was evenly achieved across the layer.

The thermocouple sensors were placed within the layer on two opposite sides–at the bottom, middle, and top of the plastic, and a humidity probe was positioned over the surface of the flakes. Additional wet flakes were placed in a small tray (lined with a piece of tarpaulin) on the small adjacent weighing scale.

The LabVIEW program was started, and the data from all the sensors was logged. Every 30 minutes, moisture content samples were taken of the top, bottom, and a mixed section of the wet flakes. The experiment was allowed to run for 4-5.5 hours, weather permitting. Finally, after stopping logging the data, the final mass of the flakes was measured. The initial mass of the dry flakes was subtracted from this final mass to find the amount of water left in the layer. The mass of water that evaporated and diffused into the air was this mass of water left subtracted from the initial mass of water added.

Most of the experiments were conducted for a one inch thick layer either on a white or black tarpaulin, but a few additional experiments were conducted with 0.5 inch thick layers, 1.5 inch thick layers, and simultaneous experiments on both tarps for a side-by-side comparison (Figure 4.13). In all of the experiments, the wet PET plastic flakes were spread over a one square meter area.

4.4 Results and Discussion

For a one inch thick plastic layer, the model can accurately predict the drying time and amount of water lost when certain variables are tuned. Taking experiment data for a one inch thick layer on a black tarpaulin as an example, as shown in Figure 4.7, the model predicts the drying time to within 0.03 minutes of the experiment time and within -0.046 kg of the experimentally measured mass of water left.

To reach this level of model accuracy, the values for α and δ_e were tuned. Figure 4.8 shows how a parametric analysis was conducted to find values for these variables which would yield an accurate drying time. The ambient temperature value was taken from weather data, and the dew point temperature was used for the interface temperature, T_i.

The model predictions for average moisture content in the layer over time also align decently well with experimentally measured values. As shown in Figure 4.9, the model predictions for the average moisture content of the layer generally match the trend of the experimentally measured mixed MC values. The model also appropriately predicts the moisture content in the top layer should be less than the average moisture content, which is less than the moisture content at the bottom of the layer. For the top of the layer, the experi-

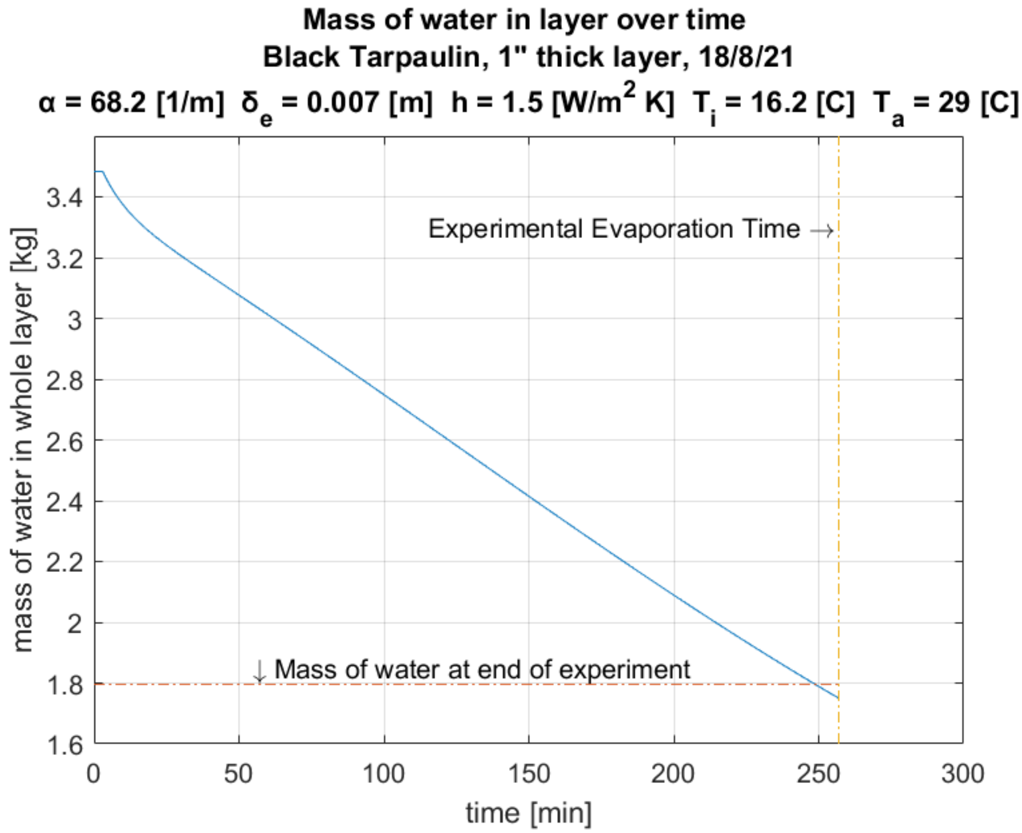
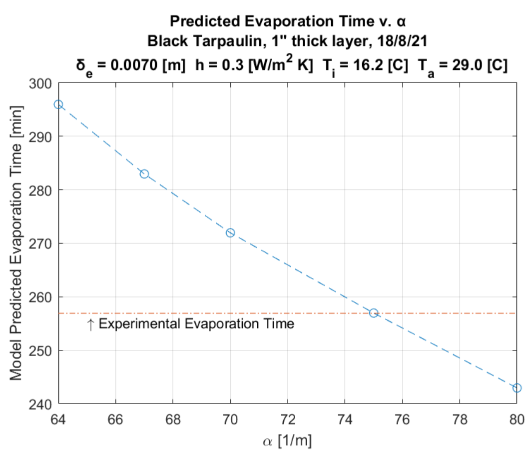
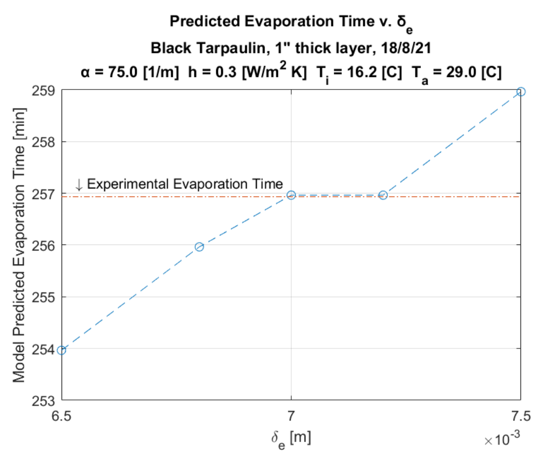


Figure 4.7: Model Prediction of Drying Over Time



(a) Varying α



(b) Varying δ_e

Figure 4.8: Parametric Study of Model Parameters

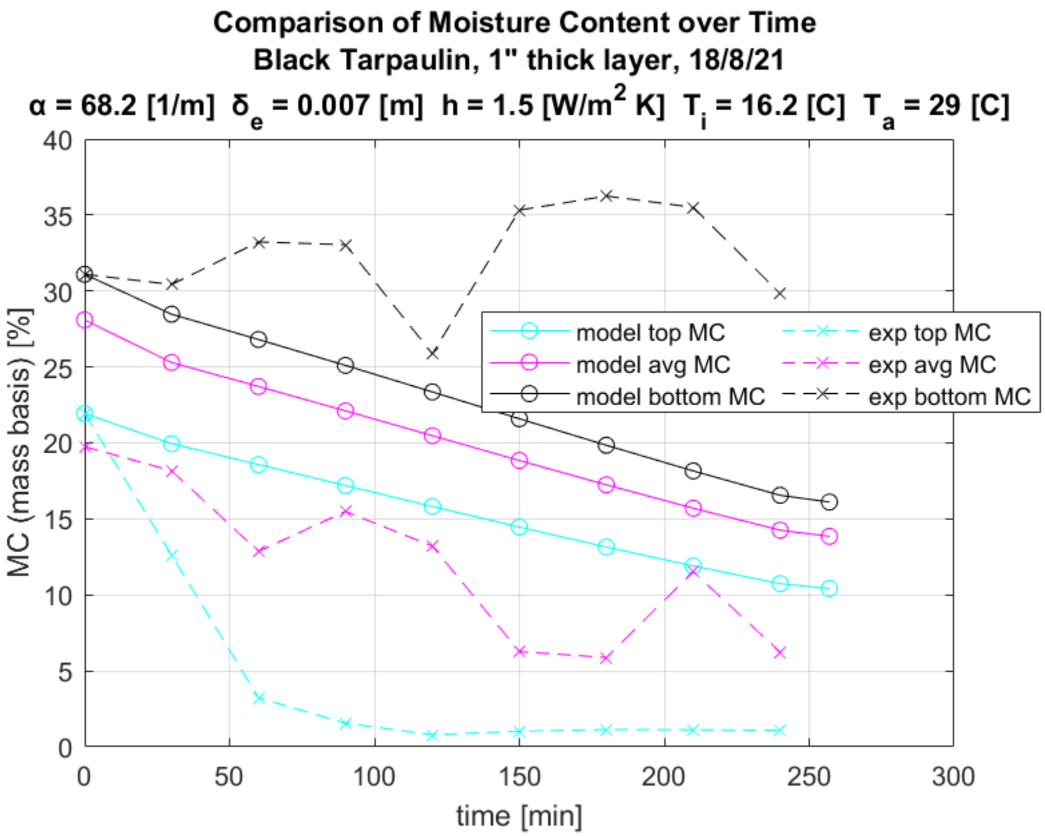


Figure 4.9: Comparison of Model Prediction and Experimentally Measured Moisture Content Over Time

ment results show a sharp decrease in moisture content in the first 60 minutes followed by a more gradual reduction and then plateau. The model did not predict this trend well. For the bottom of the layer, the experimental results do not show a clear trend–this is because water puddles in some areas on the tarp, so sometimes a sample is taken from flakes sitting in a puddle while other times, the bottom sample is more dry. Since the experiment data is not clear, it's difficult to verify the accuracy of the model for the bottom moisture content.

Figure 4.9 shows results for one experiment on a black tarpaulin for a one inch thick plastic layer. Data from other days of experiments reveals similar results.

Dewpoint

In the drying process, water is diffusing into the ambient air, so the ambient humidity and temperature significantly affect drying rate. To study this, the dewpoint temperature during multiple experiments was analyzed. Figure 4.10 shows the dryness ratio versus dewpoint for multiple experiments. For the one inch and half inch thick layers, the plot shows a general

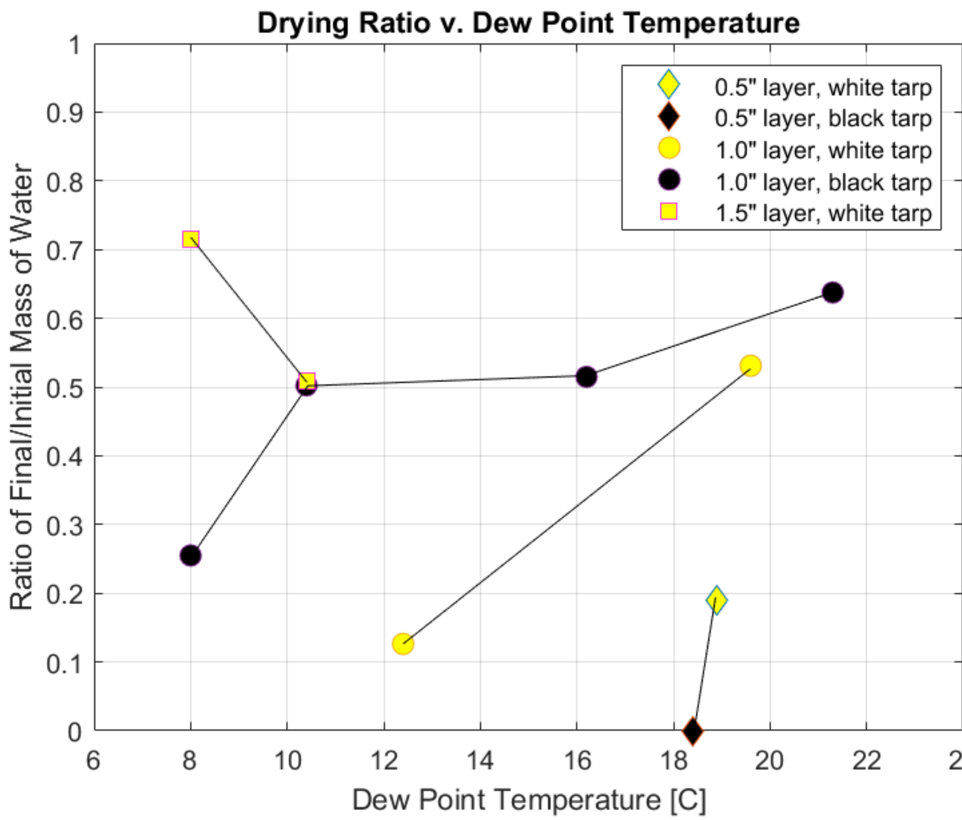


Figure 4.10: Comparison of Drying Ratio v. Dew Point for Multiple Experiments

trend of less drying at higher dewpoint temperatures. This is consistent with mass transfer theory since at higher dewpoints, the ambient air already contains more moisture, so it's more difficult for the water on the plastic to diffuse into and add additional moisture to the ambient air. For the 1.5 inch thick layer, it was too thick for the solar irradiation to completely reach the bottom, so other factors other than the dewpoint affected the drying rate.

Solar Irradiation Data Analysis

Figure 4.11 shows the solar irradiation data experimentally measured with the pyranometers. Smoothed polynomial curve fits were found for the incident and reflected irradiation data at the surface of the layer, and their difference was used for the model input, I_{D_i}.

To verify that the model results are physically accurate, an analysis of the absorptivity and transmissivity of the layer was conducted. The fraction of irradiation that reaches the bottom of the layer can be calculated using the equation below.

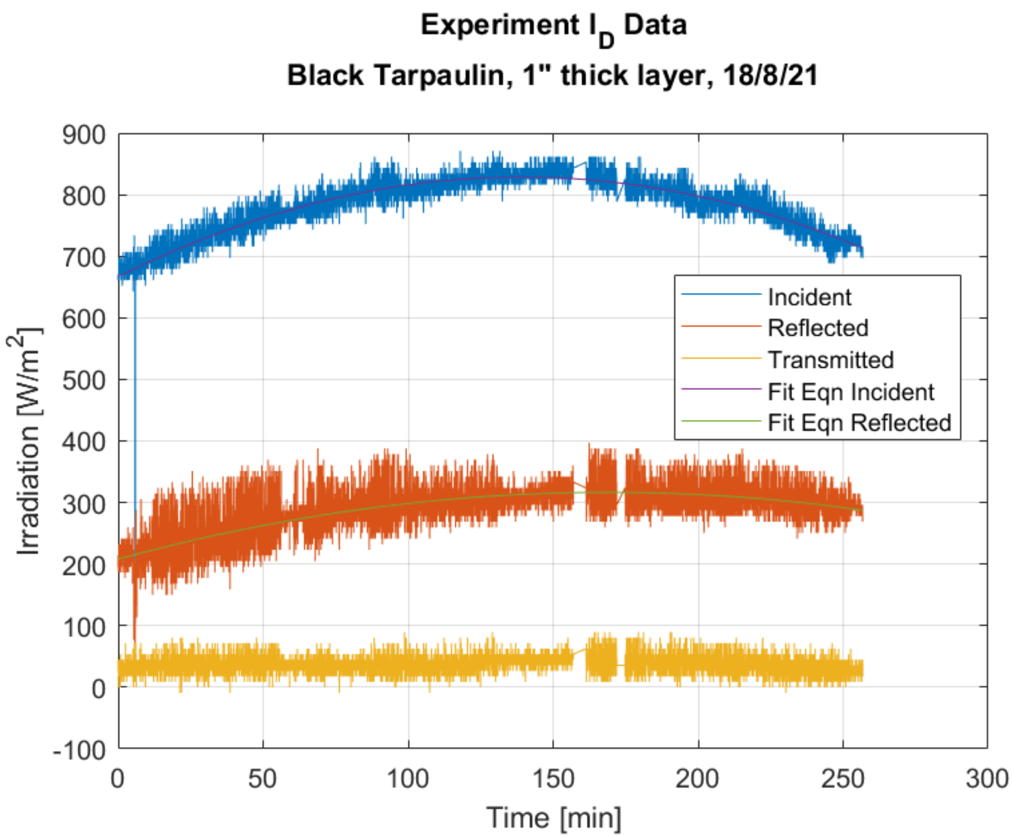


Figure 4.11: Experimentally Measured Solar Irradiation

$$\frac{I_{D_i} - I_{D_B}}{I_{D_i}} \tag{4.31}$$

where I_{D_i} is the net irradiation hitting the top of the layer and I_{D_B} is the irradiation that passes through the layer and reaches the bottom. Replacing I_{D_B} with equation 4.6 gives

$$\frac{I_{D_i} - I_{D_B}}{I_{D_i}} = \frac{I_{D_i} - I_{D_i} e^{\alpha(1-\epsilon)(y-y_i)}}{I_{D_i}} \tag{4.32}$$

evaluating this term at $y = 0$ for the irradiation at the bottom of the layer gives

$$\frac{I_{D_i} - I_{D_B}}{I_{D_i}} = \frac{I_{D_i} - I_{D_i} e^{-\alpha(1-\epsilon)y_i}}{I_{D_i}} \tag{4.33}$$

The I_{D_i} terms cancel each other, leaving

$$\frac{I_{D_i} - I_{D_B}}{I_{D_i}} = 1 - e^{-\alpha(1-\epsilon)y_i} \tag{4.34}$$

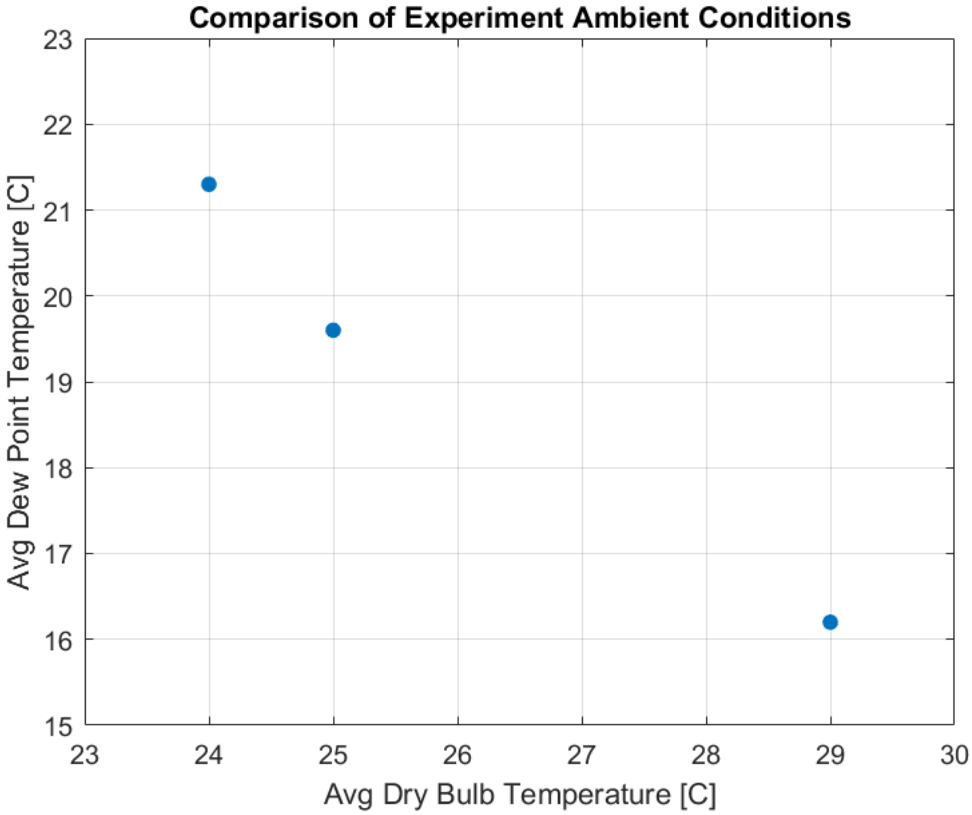


Figure 4.12: Comparison of Ambient Conditions for Experiments Conducted on 1 Inch Thick Layers in August 2021

Evaluating the right hand side with the average α value used in the model of 68.2 1/m and the average volume fraction of plastic of 22.9% measured in the experiments reveals that for the one inch thick layers, 32.7% of the irradiation entering the layer at the surface reaches the bottom. This is physically plausible and therefore corroborates that the model could be a reasonable approximation.

These average values were calculated from experiments on one inch thick layers in August 2021. Figure 4.12 shows the ambient air dry bulb and dew point temperatures. Since these values vary, it shows that the model results are applicable for a range of weather conditions.

Black v. White Tarpaulin

The effect of drying the plastic on a white versus black tarpaulin was identified as an interesting variable to study. It was thought that the black tarp would cause the plastic to dry faster because the black tarp would absorb more solar irradiation and become hotter than the white tarp. The hotter bottom surface would help dry the plastic faster through conduction and even some radiation off the tarp itself.

However, there was also an argument that the white tarp would reflect more irradiation which could facilitate faster drying. Any solar irradiation that was transmitted through the layer and reached the tarp (plus the irradiation directly hitting the areas of the tarp on the sides exposed to the sun) would be reflected back into the wet plastic and have another chance to be absorbed.

To test the two theories, simultaneous experiments were conducted on black and white tarpaulins side-by-side. The same mass of wet plastic flakes was spread in 0.5 inch thick layers on the two tarps. A thickness of 0.5 inches was chosen to ensure that sufficient solar irradiation would be transmitted through the plastic layer and reach the tarpaulin surface to either be reflected or absorbed. Since the experiments were conducted side-by-side, both tarps experienced the same weather conditions, so variation in incoming irradiation and ambient wind speed, temperature, and humidity were not a factor.

Figure 4.13: Side-by-Side Experiments Comparing Drying Rates on Black v. White Tarpaulins

Surprisingly, there was no measurable difference between the drying rates on the black versus white tarpaulin. After exposing the plastic to the sun for four hours, all of the water in both experiments had evaporated.

Initially, for each tarp, 4 kg of dry PET flakes was mixed with 1.75 kg of water and spread in a 0.5 inch thick layer. At the end of the experiment, the final mass of the plastic/water mixture left on each tarp was 3,996 g for the white tarp and 3,993 g for the black tarp meaning that all 1.75 kg of water on both tarps had dried (within error bounds of the experiment procedure and weighing scale used.)

The mass of the small pans logging the amount of water evaporated was within 1% of each other throughout the experiment. The final average moisture content of the two experiments was within 0.5% of each other. Moisture content samples were also taken every 30 minutes throughout the experiment–these indicate that the flakes on the black tarpaulin could be drying faster than those on the white tarpaulin, but there was an insufficient number of samples to make conclusive determinations.

Model and Experiment Agreement

Table 4.1 summarizes a comparison between the model predictions and experiment data for three experiments conducted in August 2021 on one inch thick layers. These results were obtained using the average tuned α value of 68.2 1/m, δ_e of 0.007 m, convection coefficient h of 1.5 W/m^2K, interface temperature equal to the average ambient air dew point throughout the experiment, and ambient temperature equal to the average air temperature throughout the course of the experiment.

Table 4.1: Comparison of Model and Experiment Results

	Mass of Water Dried [% Diff]	Drying Time [% Diff]
Exp 1	2.57%	-0.01%
Exp 2	1.50%	0.12%
Exp 3	-2.50%	-0.07%
Avg	**0.52%**	**0.01%**

4.5 Conclusion

This research sought to understand the physical phenomena driving solar drying of wet plastic flakes in Uganda spread on a tarpaulin. An energy-based phase change mathematical model was developed to predict drying time and experiments were conducted to validate results. Obtaining accurate data in these drying experiments was challenging due to weather conditions and the complexity of variables. This proposed model is highly sensitive to solar irradiation variations, and the plastic is also highly variable–the size of the flakes, cleanness, color, absorptivity and reflectivity, the angle at which the flakes are aligned, and even their properties can vary depending on various additives and manufacturing processes of different bottle companies.

However, despite these challenges, for the one inch thick layer experiments conducted in August 2021, the model can match experiment data to within 0.5% when α and δ_e values are tuned. Further research should explore model accuracy under varying solar conditions, layer thicknesses, and irradiation and weather conditions at different times of year.

Acknowledgement

I sincerely thank Patrick Masembe, Jacob Wokorach, and Amba Moses for their assistance in conducting experiments for this research.

Chapter 5

Developing a Practical Solution

5.1 Exploration of Existing Solutions and Gaps

Before developing a new solution, I first needed to understand the existing solutions and the gaps in Uganda's plastic waste problem that they were failing to address. I spent a year reading about plastic waste recycling initiatives across the world; consulting experts, conducting over 200 interviews mostly in Uganda, and visiting businesses, community organizations, and institutions engaged in waste management across Uganda.

The current solutions can be categorized into five types:

I. Highly Industrialized Companies
II. Small Businesses
III. NGOs
IV. Student/Academic Projects
V. Hobbyists

I) Large, high-tech, imported recycling machines are difficult to maintain and repair and prohibitively expensive for Ugandan entrepreneurs. II) Small-scale projects often lack capital and use environmentally dangerous methods of melting plastic in oil drums over open fires releasing toxic fumes and greenhouse gases. Many of the small business in Uganda engaged in plastic recycling only collect and sort the waste because they can't afford the machines for further processing. Thus, the collectors make very little to no profits. They are at the mercy of middlemen and fluctuating prices dictated by the international plastic recycling and petroleum markets. Some of the small collector businesses I interviewed were actually making losses–negative profits–but didn't realize it because of lack of financial understanding capacity. III) NGOs engage in some collection efforts but are usually focused on education initiatives that upcycle waste into art or homemade products that are not durable or saleable. The initiatives rely on grant funding and are not self-sustainable. When the funding runs out, the projects die. IV) Student projects are also short-lived. They last for a semester, summer, or maybe a year or two until the students move on. Much of that time is spent getting the students up to speed to understand the problem. The students themselves are usually not experts in plastic recycling and usually don't understand the context of the community, so the students usually have very little to offer aside from some small project funds. They do some small experiments and encourage local efforts in recycling for a little while until the students move on. V) Hobbyist machines are low volume and usually not durable–they can't process enough to support a sustainable business or address the magnitude of the plastic waste problem.

Below are some examples of the different types of solutions.

Figure 5.1: Resintile Manufacturing Process

Figure 5.2: Resintile Roof Tiles

Highly industrialized companies are characterized by high startup costs because they utilize imported large-scale machinery such as shredders, mixers, granulators, agglomerators, washing lines, extruders, hydraulic presses, and injection machines. These operations are energy intensive and employ a small number of people in a centralized factory. These companies are mainly focused on urban areas both in where they source their plastic and in their target customers because their prices are out of reach for villagers.

An example of this category is Resintile, a Kampala company that makes roofing tiles from recycled plastics. They estimate a startup cost of approximately 100,000 USD not including the land, building, taxes, and insurance. They employ 5 managers, 2 assistants, and 16 shift workers and sell between 90,000-120,000 tiles/year.

Kenya has a few industrial scale companies producing plastic lumber, WPC (wood plastic composite), and paving blocks from recycled plastic. One example is EcoPost in Nairobi making fence posts, sign posts, and benches from plastic lumber and WPC. [9] A newer company, Gjenge Makers, also in Nairobi, is making paving blocks by melting plastic waste and sand. [10] The company was founded by Nzambi Matee, a Kenyan female mechanical engineer.

Many small, startup companies are producing products from plastic waste around the developing world. In Mexico, a company called Eco Domum manufactures large panels for roofs and even walls from plastic waste.

A Columbian startup, Conceptos Plasticos, builds homes and schools from "bricks and blocks" made from plastic waste. The modular design makes shelters easy and quick to assemble. [11] They have attracted significant international attention and are scaling quickly.

In Burkina Faso, a startup called TECO^2 is creating thin roof tiles from used LDPE bags. They are working with labs in France to develop a process that fuses the plastic instead of

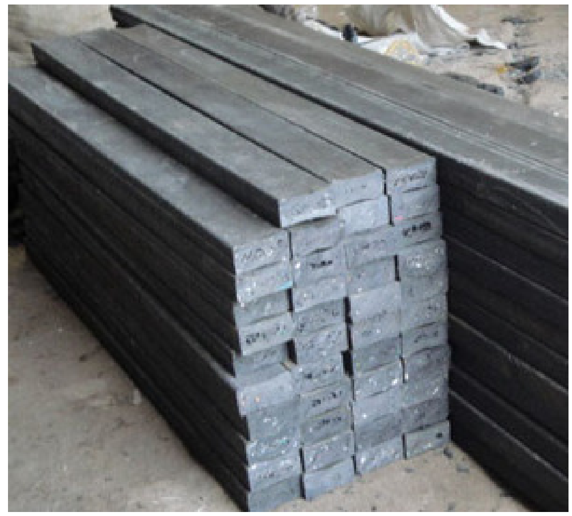


Figure 5.3: Fence Posts and Plastic Lumber made by EcoPost in Kenya

burning to reduce the release of fumes. Their tiles are 400x more insulating than the common iron sheet roofing, and one square meter of their tiles uses 10 kg of recycled plastic. [74]

Figure 5.4: Conceptos Plasticos Building

In Uganda, a small company in Kampala called EcoWays makes fence posts and lumber from plastic waste. Originally, they developed their own machines working with local workshops, but the output was slow and the machines were not always reliable. After partnering with an international plastics engineer and obtaining some funding, they were able to import larger machines. The company is growing quickly.

In Masaka, a district in southern central Uganda, an organization called Eco Brix collects plastic waste and makes a variety of products including plastic lumber. They also engage in lots of education and outreach efforts and seek to employ handicapped members in their community. One of their founders is from the UK and they receive funding and partnerships from Europe.

Wazi Recycling was a startup in Kampala trying to make pavers from plastic waste. Pavers are shaped bricks used for covering compounds in Uganda. Wazi Recycling reported that their prototype pavers were cheaper to produce and stronger than conventional cement

Figure 5.5: Gjenje Makers Pavers and Founder, Nzambi Matee

pavers, and they had received many orders. [93] However, they were limited by funding–they never secured the necessary equipment to produce pavers at scale, and have shifted to focus on making designer eyeglass frames from plastic waste. [94]

In Cape Verde and Angola, a Dutch design firm, Better Future Factory, is working with local entrepreneurs to make floor tiles from plastic waste. Called New Marble, the tiles are very attractive but expensive and mainly purchased only by ex-pats. The smallest manufacturing unit costs approximately $6,000-11,000, so Better Future Factory is working on improving their production efficiency. [26]

Since small businesses in developing countries are often run by a single entrepreneur with limited capital, these ventures often struggle to scale unless they find international partners.

NGOs often use simple technology, which is sometimes dangerous, and include education components to teach communities about recycling. But NGOs struggle to scale. Their techniques are often open-source, but without high revenue streams, it is difficult to move beyond a few communities where they have local partnerships.

Figure 5.6: WasteAid UK Paver Process

For example, WasteAid UK is working in the Gambia to make pavers from LDPE bags. They melt the bags in an oil drum over a fire, mix the melted plastic with sand, and shovel the mixture into molds. This method can produce 300-400 pavers a day with a 6 person team, but their process to melt the plastic can be hazardous to workers' health and the environment. WasteAid UK relies on local churches, non-denominational groups, and anyone who is interested in their work to move to new communities. There are several NGOs in Kampala that work with plastic waste. They are mainly focused on educating people about the dangers of plastic waste and how they can reuse the plastic, so they pe-

Figure 5.7: Ecoways Fence Post and Table from Plastic Lumber

riodically hold workshops teaching people how to build shelters, brooms, dustbins, or other products by cutting plastic water bottles. Local artists also make displays from waste plastic. These are great education campaigns, but they do not effectively address the magnitude of the plastic waste problem, and the NGOs are limited by funding.

There are also many student or academic research projects that are usually focused in one partner community and are often short-term projects. They serve more as a learning experience for the students than to improve the quality of life for the local people. For instance, an Engineers Without Borders team from Carnegie Mellon worked with an NGO in Ecuador to create machinery that could cut PET bottles and fuse them into strips for roofing sheets. However, their process is very time and labor intensive and the roof will not withstand UV rays well. [109]

An Engineers Without Borders team from MIT worked with plastic waste in Kampala, Uganda. They made small products and trinkets by melting waste plastic in heated cooking oil. [110]

A masters student from Australia partnered with an NGO called Waste for Life in Sri Lanka to develop a composite roof made from waste HDPE plastic reinforced with rice husks and banana fibres. While the product is aesthetically pleasing and of high quality, manufacturing it is a multi-step, time-consuming process that uses labor and power intensive

(a) Eco Domum Panel

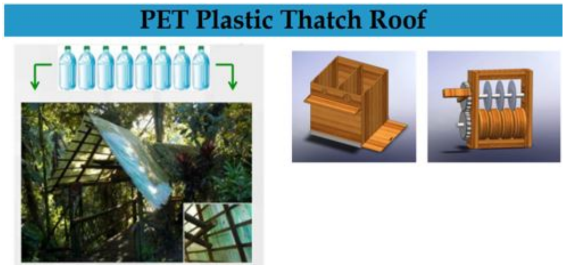
(b) TECO^2 Entrepreneur, Calvin Tiam

(c) Better Future Factory New Marble Floor Tiles

machinery. [128]

An interesting low-tech solution in rural Kenya was developed by Stefan van der Heijden, a masters student of Integrated Product Design at Delft University of Technology, in collaboration with a Dutch NGO, the Grow and Flourish Foundation. They developed ways for rural Kenyans to make their own pipes, flat sheets, and rope from discarded plastic bottles. The base construction materials can be used to make gutters, windows, or other products. The products are very affordable because they are made by cutting the bottles or shaping them around a wooden mold over a fire, but they are not durable or aesthetically pleasing enough to be sold at a market. [79] [80]

Additionally, researchers have shown the potential of using pyrolysis to recover high calorific value fuel gas from plastics. [81, 102, 150] Although pyrolysis of plastics is not yet implemented at an industrial scale in Uganda, it has been proven in laboratory experiments [126] and small scale community experiments. [124] Researchers at Makerere University in Kampala partnered with a team at the University of Kentucky to develop a small-scale

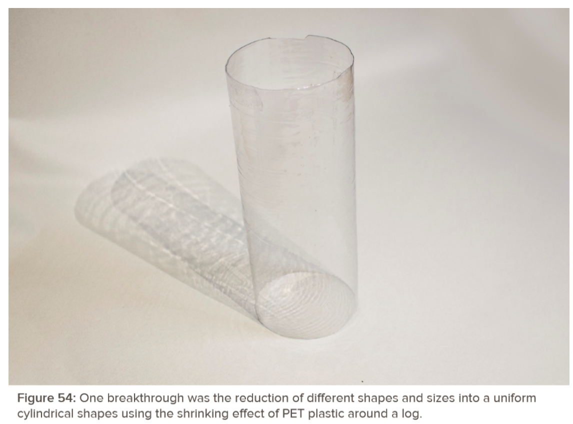


(a) EWB PET Roof Project

(b) Waste for Life Composite Roof

Figure 5.9: Student Projects for Plastic Roofs

(a) Molding Plastic Bottle Over Flame



(b) Fused Plastic Tube

Figure 5.10: Low Tech Fusing of Plastic Bottles

pyrolysis reactor. [89] They used the fuel oil generated to run a tractor. However, PET plastic cannot be used in pyrolysis.

Hobbyists around the world also engage extensively in making products from plastic waste. Youtube videos, blogs, and forums abound of people making personal trinkets or small products for sale in online bazaars. Many use their kitchen ovens or toaster ovens, but one popular site, Precious Plastics, based in the Netherlands has developed open-source, low-cost, small-scale plastic processing machines such as a shredder, extruder, sheet press, and injection molding machine. [77] The global open-source movement is building machines for small-scale, non-PET recycling, but they are not durable enough for continued use, their slow output can't handle the vast amounts of plastic waste, and they can't use PET. Additionally, the products are mostly designer-focused (e.g. eye glass frames), so they use only a small amount of plastic waste, and it is time consuming to get the colors and shape perfect. Another solution, 3D printing, is not yet widely used in developing countries, and time-consuming printing is not fast enough to recycle the magnitude of plastic waste.

To summarize, most of these existing solutions are either too small scale to support a profitable business that could provide meaningful local economic development, or they are so industrialized that the start-up capital costs put these solutions out of reach of most Ugandans. Some are also hazardous, and most do not have the capability of processing PET. The industrialized solutions are also highly energy-intensive and centralized in capital cities, leaving cities and towns far from the capitals with no recycling options. None of these solutions offer a safe, economically practical means of disposing of the plastic waste in large towns far from recycling plants–especially not PET.

Exploration of Problem in Gulu, Uganda

To better understand the problem, when starting my research, I conducted an assessment of plastic waste and people's perception of waste and recycled products in Uganda. The assessment was conducted in summer 2018 and primarily focused on Gulu–a town in northern Uganda that was recently upgraded to city status.

Gulu does not sort its waste and has no recycling options. We confirmed that plastic bottles and bags are the most common type of plastic waste and that they are generally thrown anywhere after use. [164] The Gulu Municipality has several skips throughout town and hires cleaners to sweep the streets and dump waste in the skips. A truck is supposed to empty the skips in the landfill outside of town, but the skips are often left overflowing because trucks are broken or there is a shortage of fuel. At the dumpsite, the waste is eventually burned or buried. It is burned to create new space in the landfill and to combat flies. [80] There are a few companies that businesses hire to transport their waste to the landfill. These companies are technically illegal since all waste is supposed to be managed by the municipality, but the private companies are less expensive than the town pickup, so businesses still engage them. Many street kids in Gulu pick bottles and sell them to people for carrying kerosene or filling with local juice. However, this is a small number of bottles and only those in good condition can be used.

Many individuals dispose of their waste in their private homes. Burning is the most common means of disposal.

Although there are no detailed records tracking the amount of different types of plastic waste in Gulu, I estimated that Gulu generates approximately 2.5-2.9 tons of plastic bottle PET waste per week and 330 kg of LDPE bag waste per week. (These numbers are from my assessment in 2018, but Gulu's population and amount of plastic waste has significantly increased since then.) The lower PET estimate is based on the number of cartons of soda sold by the Pepsi soda depot in Gulu and extrapolated for the number of other depots. The upper PET estimate is derived from assuming that on average, each person in Gulu drinks one plastic bottle of soda per week. The LDPE estimate is based on the amount of thin film waste that one municipal street gang was able to collect for me from one of the four divisions in Gulu.

I interviewed over 200 business owners, government officials, professors, construction workers, NGO organizers, and general consumers. The majority of the interviews were in Gulu, but some were also conducted in Kampala and Mbale, a district far from Gulu and different in climate, industry, and politics. The surveys from Mbale corroborated those in Gulu proving that Gulu is an archetype of many districts across Uganda. If our solution works in Gulu, we can replicate it throughout Uganda.

(a) Surveying Men Gathered at Village Center in Gulu, Uganda

(b) Interview with Lecturers at Gulu University

Figure 5.11: Interviews

Of the 200 interviews, 123 were surveys of the general public. Most were done in focus groups, and we were careful to survey a wide distribution of age groups, genders, and socioeconomic levels of rural and townspeople. The survey revealed the following results:

- 73% of interviewees burned their plastic waste or threw it in pits (trash thrown in pits is ultimately burned usually).
- 46% of interviewees were most interested in buying plastic roofs, but they also expressed interest in flooring tiles, gutters, and pavers. People wanted to feel and use the products before giving accurate willingness to pay information, so we will conduct further studies.
- 47% liked plastic roofing, 38% were unsure, and only 15% said no. Interviewees most desired durability, price, and beauty in a roof. 62% were not satisfied with their current roofs. 59% said they paid more than they expected for their roof. User survey and competitor pricing analysis confirmed there is a need for affordable, quality roofing in Uganda. Roofing would provide higher margins than other products, but roofing is complicated to manufacture because it must meet durability and aesthetic requirements.

- 75% preferred extruded over same-form plastic products. NGOs in Uganda teach people how to cut plastic bottles to make useful products, so I added questions about melted versus same-form plastic products to our survey. 70% wanted to buy recycled plastic gutters rather than make gutters themselves.

Major Unresolved Issues

After reflecting on my waste assessment in Gulu and on all of the existing solutions for recycling in developing countries, as described in Section 1, I believe the gaps they fail to address in Uganda's plastic waste problem are:

1) No PET recycling plant in East Africa

PET water and soda bottles are one of the most prevalent types of plastic waste in Uganda, but there is no way to recycle the bottles anywhere in East Africa.

Current PET recycling technology used in Western nations requires massive industrial scale. One study found that a PET recycling facility for East Africa would require a $20-44 million USD investment to set up and need to source bottles from Uganda, Kenya, Rwanda, and Tanzania combined to reach a large enough scale to be profitable [47]. This is logistically and politically not feasible. Even in the most economically developed East African nation of Kenya, which has more bottles than Uganda, Chinese investors set up a $44 million PET recycling plant, but it soon closed because it was operating at only 1/3 capacity because it could not collect enough plastic bottles to make operating the plant profitable [116]. Although not enough to warrant an industrialized recycling plant, there is still massive amounts of PET in Uganda, and none of the existing solutions can recycle it. A top government official told me Uganda is "desperate for a solution to PET."

But processing PET is difficult due to its chemical properties. Melting and reshaping PET is challenging due to its hygroscopic nature, narrow melting temperature range, low viscosity, and semi-crystalline nature. Across the world, there is currently no scalable, non-industrial solution to recycle pure PET waste directly into a valuable end-product.

2) Long distance transportation of low-value plastic waste is not economical

In Uganda, the only recyclers/exporters are in the capital of Kampala, but there are many large population centers with lots of plastic. This means that other cities, and even villages, either have to transport their waste to Kampala or they have no recycling option. But plastic is high in volume and low in value–transporting it is not economical, especially not on Uganda's poor road network.

For example, Gulu is the second largest population center in Uganda with approximately 150,000 residents–it has a lot of plastic waste. But Gulu is a 6 hour drive from Kampala. And different types of plastic waste in Uganda have varying levels of value–jerricans and other HDPE plastic has the highest value because there are some companies in Kampala that can recycle the HDPE directly into conduits or other products. LDPE has little recycling applications in Uganda and it's very difficult to collect a full kilogram of lightweight plastic bags, so most recyclers are not interested in LDPE. PET plastic waste in Uganda has the lowest value because there is no way to recycle it in the country. So scrap dealers in Gulu are mostly only interested in HDPE–although they often have to wait and struggle to find a truck that is already heading to Kampala but with no cargo so transport costs will be a little cheaper. And even then, they often have to mix the plastic waste with higher value aluminum scrap to make a profit. Some don't even cover the costs and actually lose money but don't realize it because of lack of financial skills and training. The only way PET can possibly be profitable to transport is if the bottles can be compacted by a baling machine or reduced to flakes in a crusher. Most scrap dealers cannot afford these machines, and even with them, the profit margins on transporting PET are very very low.

So most of the plastic waste in Gulu is stuck with nowhere to go. To describe this, I coined the term "waste sinks"—areas where waste is burned and littered because it cannot be disposed of or recycled properly. Sadly, there are hundreds of thousands of other waste sinks like Gulu across the developing world.

3) Lack of awareness among community members about a) the *dangers* to their health from burning and littering plastic and b) the *value* of plastic waste

Most community members do not realize that burning their plastic waste is detrimental to their health and the environment around them. In Uganda, many schoolchildren are taught that the responsible way of disposing of their waste at home is to burn it–burning your waste pile removes the unsightly heap from neighbors' views and reduces flies which can cause diseases. However, since plastic has become a major part of Ugandans' waste stream in the last few years, people have not been taught that burning plastic releases carcinogens, PAHs, other toxins, particulate matter, and greenhouse gases that are harmful to their health. Many women even use the plastic bags to light their fires and charcoal stoves for cooking. The women and children near the stoves inhale the toxic fumes from this burning plastic every day.

Additionally, people don't realize that their plastic waste has value. They don't know that plastic is comprised of highly calorific hydrocarbons–a high density energy source, that if utilized properly, can generate electricity and fuel. People also don't realize that new, beautiful products can be made from their plastic waste that can be sold for good profits.

Because people have not been taught the value of and the dangers posed by their plastic waste, they burn, litter, and discard it anyhow.

4) The value in plastic waste is extracted from communities and the majority of the profits are exported. This leaves waste pickers, who do the most dangerous and laborious work in the plastic waste value chain, with the smallest share of profits.

In the plastic waste value chain, the majority of the profits are in the final, end product made from the recycled plastic. The people who collect, sort, and sometimes wash the dirty plastic waste receive very little compensation for their work because it's unskilled labor (although it's dangerous work) and there are many middle-men along the process who take a cut of the profits. Dealers buy from collectors, the dealers sell to exporters in Kampala, the exporters sell to international buyers, who sometimes process the plastic themselves or sometimes sell to other companies to process into new products, who finally sell to consumers. With all of these players, the people who originally owned the waste receive very little to zero value for their plastic. And the informal waste pickers, who face the dangers of disease, sickness, sometimes police, and the denigration and mockery by public opinion for collecting waste, receive very little for their hazardous and laborious work.

5.2 Model for Addressing Gaps

To address these gaps, I developed a model for local, distributed recycling and co-founded a social enterprise in Uganda based on the ideas. I partnered with Peter Okwoko, a Ugandan lecturer and community activist passionate about the environment and creating opportunities for youth. In 2020, we launched Takataka Plastics in Gulu, Uganda with the vision of transforming waste and empowering communities.

Through implementation, observation, and reflection, I generated and refined hypotheses on how to address Uganda's plastic waste challenge. I present the ideas here for others to learn from and build upon.

Our model is built on the following foundations:

- Local, Decentralized, Distributed Recycling

  To reduce long-distance transportation and emissions costs, we locally transform plastic waste into saleable products to create a circular economy and keep the economic benefits of value addition in the community. Plastic waste is collected, processed, and sold as new products all within the same community so the jobs and value of the end-products benefit those who originally owned the waste. To accomplish this local circular economy model, we needed small-medium scale recycling machines.

  We decided to build the recycling machines locally and make them manually operated to support more jobs. Rather than paying for automation and additional electricity, we can hire more youth as production staff. Although it's taken us several years to figure out how to build small-scale recycling machines using local fabrication techniques and primarily local materials, our machines are approximately $1/4^{\text{th}}$ the cost of importing similar machines from Europe (when price, shipping, and import taxes are factored in). Plus, our machines are more durable and they're easier to maintain and repair because the parts are available. Building the machines locally also supports local fabrication shops and advances the capacity of local engineers. Because our machines are so much cheaper than importing equipment, our model can be more easily replicated in other cities, making scaling faster.

- Focus on PET

  I knew we needed to find a local recycling solution for PET water and soda bottle waste–it was the most prevalent type of plastic waste and had the lowest value because

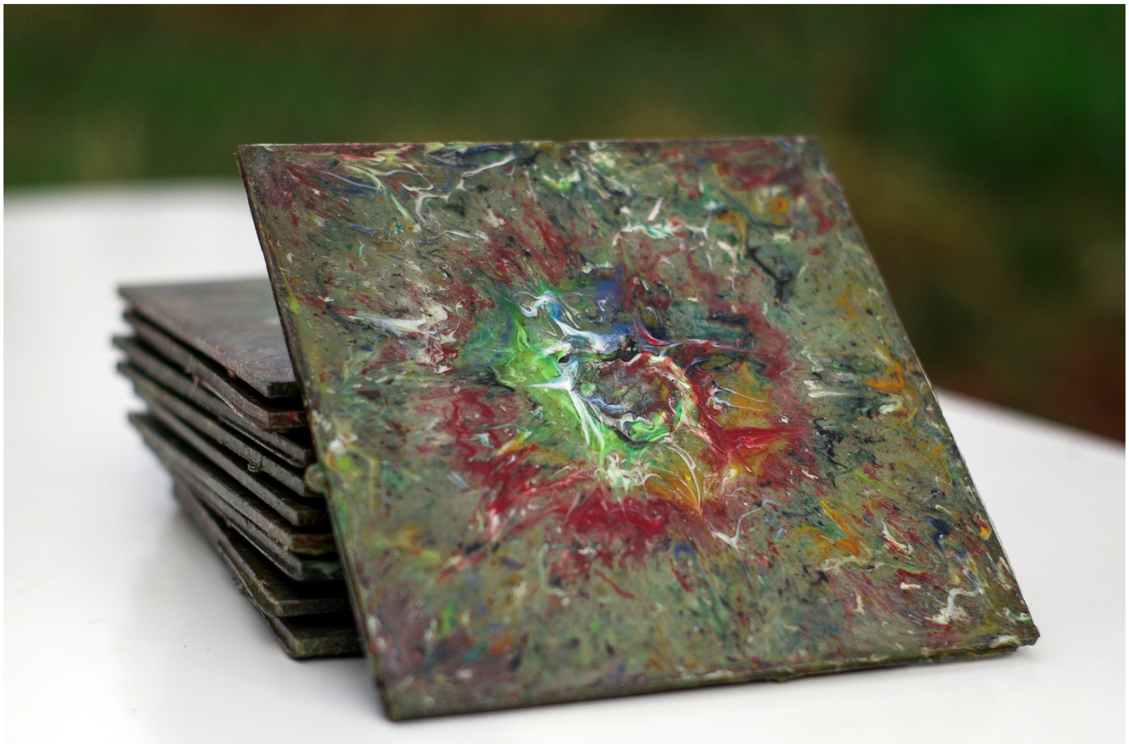


Figure 5.12: Takataka Plastics Wall Tiles from Recycled PET

there was no solution for it in Uganda. But melting and making strong products from PET is difficult–all of my first PET prototypes completely failed—cracking and crumbling under the slightest load—but the samples made from other plastics were strong. Although it was tempting to stay with the easier route of transforming non-PET plastic waste, we kept pressing for a solution for PET.

I devised a process and collaborated with Ugandan engineers to locally build machines to alter the chemical structure of PET just enough to prevent brittleness and make a strong product. The experienced plastic engineers I talked with in the U.S. were skeptical that our process could work. They thought we could not achieve industry standards for melting PET with our local machines, and even if we could, the products would be a dangerous fire hazard in people's homes.

Despite this, I persevered in testing my hypotheses and after many, many experiments, we successfully made durable, attractive wall tiles from PET waste with locally built, small-scale machines. To test the flammability of our PET tiles, we built an experiment setup to perform a corner burn test (similar to the UL 1715 Fire Test of Interior Finish Material international standard), and our plastic tiles passed! They are safe for use in people's homes and businesses.
Each square meter of our tiles recycles 6 kg of PET and prevents the emission of 13.2 kg of CO_2 from burning plastic.

Figure 5.13: Takataka Plastics Recycled PET Wall Tiles undergoing a Flammability Test

- Carefully consider product-market fit
  The versatility of plastic and recycling machines means many different products can be made from plastic waste. They key is to identify a product that can bring in enough revenue to support a self-sustainable business. The product must fill a need that customers have, the scale of the need and the scale of the production process must match with the scale of the supply of plastic waste, and the product application must be compatible with the material properties of the type of plastic waste needing to be recycled. We devoted significant effort to finding this right product-waste fit.

  We identified the construction market as our initial target market because a) Uganda has a large, growing construction market that could provide enough demand for all of the products we could make, and b) construction materials require large volumes of material—the scale of material needed could address the magnitude of the plastic waste problem. Smaller products, even if sold for high margins like in designer goods, tourist trinkets, or even medical devices, could be profitable, but they wouldn't be able to recycle the massive amounts of plastic waste in developing countries.

  Uganda's construction market is booming driven by rapid urbanization and development leading to commercial expansion and an increase in personal disposable income. The country's construction market is estimated to be $3 billion USD [17] and projected to grow at 8.1% over the next ten years. [155] The Ugandan government reports an 8 million unit housing shortage by 2030 and an estimated need for 200,000 housing units annually. [157]

  I conducted extensive market research to strategically pick a product. From my initial survey, I realized people would buy products made from waste only if they were durable and attractive–if the bottles were still in their same form and looked like waste, even if the product functioned well and solved a need, most Ugandans would not pay money for something that looked like trash. I realized we would need to melt the plastic and re-form it into strong, beautiful products to support a sustainable business. I explored alternative heat sources, such as biomass or a parabolic solar dish, but the precise temperature control needed to safely melt plastic led me to electric heating. Thankfully, 78% of Uganda's electricity is generated from hydropower, a renewable resource.

Initially, I focused on trying to make roof tiles but pivoted to wall tiles after realizing that the type of your roof is a status symbol in Uganda—convincing people to buy a novel product for something as socially important and expensive as a roof would be difficult. Additionally, wall tiles have a high profit margin, their indoor application means they don't have to withstand UV degradation and weathering effects and microplastic pollution is less of an issue, and their thinness is amenable to PET.

Since nearly all washrooms and kitchens in both commercial and urban residential buildings in Uganda are tiled, the ceramic tile industry is expanding rapidly. While it is difficult to find market data specifically for Uganda, "In 2017, total tile consumption in Africa reached 920 million sq.m following uninterrupted growth with volumes more than doubling over the previous nine years (CAGR +8.9% 2017/2008). While local production also more than doubled, it was still insufficient to fully meet demand. As a result, the African continent continues to be the third largest macro-region for world ceramic tile imports." [165] Domestic ceramic tile production in Uganda is at least 10 to 30 million sq. m/year. [165]

Focusing on Gulu where Takataka Plastics currently operates, I conducted surveys in 2019 of all the shops selling ceramic tiles and determined that the number of ceramic wall tiles currently sold in Gulu is greater than our production target of 1,500 sq m per month, meaning that there is enough potential demand for all our tiles, assuming 100% market capture. We can also sell to nearby cities such as Lira, Kitgum, and Arua to increase our potential market. My survey also revealed that three hardware shops in Gulu had recently started stocking ceramic tiles within the last few months because more customers were asking for tiles and the shops saw potential for a profitable market.

Our PET tiles affix to walls with cement and grout, the same technique used with ceramic tiles, so we don't have to train contractors and masons how to install our tiles. At the end of their life, our tiles are recyclable again because they're pure PET with only non-toxic colorings. We've experimented with many different coatings, pigments, and additives to achieve various colors and patterns. As we developed prototypes, we sought lots of feedback from potential customers and masons on our tile size, color, shape, finish, and ease of mounting.

If we scaled to all developing nations, the global market size for our PET wall tiles is 3.6 billion consumers. We'd create over 700,000 production jobs for vulnerable youth, and recycle 2 billion kg of plastic waste annually. Plus, the myriad of other product opportunities both from Ugandan companies requesting customized products and new Takataka products from our own market research gives us ample demand to close the loop in creating a circular economy.

Additionally, we can generate additional revenue and impact by selling our small-scale recycling machines to other organizations. Many aid agencies, NGOs, and even local entrepreneurs want to start community recycling projects, but they don't have the knowledge to develop it themselves or the resources to import machines. Takataka Plastic's locally made, more affordable machines have attracted significant interest, and we've already sold two machines to an organization working in a refugee camp in Western Uganda. Our machines can empower more communities to create jobs and improve their environment by transforming plastic waste into valuable products. Additionally, the versatility of plastic allows different products to be made with the same machine simply by changing the mold. So we collaborate with the organizations to develop molds for products their community wants–putting the power of design into the hands of the community.

- Operate as a social enterprise
  - for financial sustainability

    For long-term sustainability, the solution should have revenue streams and at least break-even financially. We don't want to be solely an NGO that has to rely on donations and grants to keep operations going. At the same time, the focus of the business should be to make social and environmental impacts in the community–not to make economic profits. The solution should seek to create as many local jobs as possible, especially for vulnerable youth, and help protect the environment.

    Takataka Plastics has a triple bottom line–we operate on the People, Profits, Planet model, and all three elements are of equal importance to us. So sometimes we consciously decide to take a particular approach that might not be the most efficient financially, but if it creates more jobs or helps change more people's mindsets about recycling, then it fulfills our mission and is the right approach.
  - to create jobs

    Because offering someone a job is crucial to community development and healing after trauma, creating jobs is one of, if not the most, effective forms of development. According to the World Bank, 43% of people in Sub-Saharan Africa live in extreme poverty. [139] A job gives a person the chance to work and provide for themselves and their family, a chance to learn and grow, and to gain self-esteem and respect from the community. Uganda has the world's fifth fastest population growth rate, and sadly, job opportunities are few. With nothing to fill their time and no money in their pockets, youths can quickly lose self-respect and be drawn into criminal activities. Northern Uganda is especially challenged because LRA soldiers ravaged the region for nearly 20 years. The brutal killings and abductions ended in 2006, but the Internally Displaced Persons camps and aid handouts continued for years. Now, the loss of a generation and the teachings and passing on of customs they would have offered, the decades of missed years of schooling, the tension of child soldiers now grown up trying to integrate back into their communities, the pain of remembering lost friends and loved ones, the lack of infrastructure, the tribalism remaining after civil war, the years of aid reinforcing handout mindsets and corruption, and the hidden scars of unaddressed trauma leave many youth with broken homes and few opportunities. Gulu alone has an estimated 600 youths living on the street [76], and the unemployment rate in Gulu is more than twice the national average [8, 97, 146]. Having a job, especially in a workplace community that understands the impacts of trauma, is crucial to healing. It gives a person a place to go when they wake up every morning, brings purpose in having something to do, and gives them a community that supports and cares about them.

Therefore, Takataka Plastics seeks to create as many jobs as possible for vulnerable youth and offers trauma counselling for all of our staff. They have an opportunity to go through an 11 week trauma counseling program, and we have a full-time counselor on staff building relationships and trust so team members feel comfortable opening up. Since we employ many street-connected youth, child mothers, and other vulnerable people who have experienced multiple levels of trauma, they have to process their past before they can build a future. Counselling often helps them become more productive, reliable employees and happier people who contribute to their families and communities.

It's also important for other staff members to understand the impacts of trauma so they can respect and work well with the more vulnerable team members. Plus, even educated, established staff have many family and economic stresses in their lives, and trauma counselling can help them personally too.

The self-respect and savings gained from steady work along with trauma counseling has transformed many of our staffs' lives. They've started side hustle small businesses, rented places to live, and re-united with family. People have commented that you can't tell that these young people formerly lived on the streets– they have now become productive members of society.

- for social impact

  A major component of Takataka Plastics work is outreach & education. We need to change community members' mindsets about waste (and the people working with waste). We have to help the community realize the dangers to their health caused by burning and littering their waste and help them see the value their waste has if it can be recycled. We do this through school outreach programs, monthly community cleanups, radio shows, social media marketing, partnering with local comedy groups and musicians to create comedy and music videos, and through being invested in the community. These outreach efforts cost money, but they are worth it because educating and developing the community is always right. Plus, it helps us collect more plastic waste and also helps our marketing efforts since people will be more appreciative of and willing to buy recycled plastic products.

We also try to change the way people view those who work with waste–from seeing it as a dirty, last option job for the lowest members of society to viewing recyclers as innovators and stewards safeguarding their city's environment and people's health. By making beautiful products from plastic waste and through excellent branding, in just a couple of years, we have changed people's mindsets in Gulu and helped them appreciate the innovation and beauty of recycling.

- Keep the community central

  From the beginning, we knew it was imperative for the solution to be developed and led by a local team for long-term sustainability and community acceptance. All of our staff are Ugandans and have lived in Gulu for years–they're invested in and know the community. (While working on my PhD, I am not yet full-time staff at Takataka Plastics). We constantly spend time in the community talking to people, understanding their needs, getting feedback on prototypes and ideas, and collaborating to find solutions. Our focus is not on making a profit, and not even primarily on recycling plastic waste–our focus is on empowering and developing the community.

After years of research and a couple more years of designing, building, and testing machines, we've developed and refined this local, holistic model that we believe is a solution to Uganda's plastic waste and unemployment challenges.

After being in operation for only two years and a few months, Takataka Plastics has 33 full-time staff who support on average 5 dependents. We've also created 421 indirect and induced jobs. We've prevented 20 tonnes of plastic waste from entering the environment and prevented 46,700 kg of CO_2 from entering the atmosphere. We've reached over 1 million people with our message of recycling and community development and directly engaged more than 50,000 people in our outreach efforts. Takataka Plastics has also supported 12 in-person university interns and more than 30 remote students. Additionally, all of our staff go through trauma counselling and have access to our company savings group. Street-connected youth have been reunited with their families, the streets are cleaner, and more people can provide for themselves and their families. By transforming waste, we are empowering a community.

In the coming years, Takataka Plastics looks forward to scaling to other cities across Uganda.

Figure 5.14: Most of the Takataka Plastics Team in Feb 2022

Chapter 6

Practical Lessons for Development Engineers

This chapter outlines some lessons I have learned during my 6 years of working in development engineering and running a social enterprise in Uganda. I compiled these reflections with the hope that others interested in venturing into cross-cultural development work will be able to learn from my experiences, avoid harmful mistakes, and create more just, sustainable development practices. The lessons here are written primarily for people educated in the Global North who wish to enter into projects in the Global South or any community that they are unfamiliar with.

It is well-known that the developing world is a junkyard of failed projects – good-hearted donors send equipment and supplies that are not needed or can't be supported; large, top-down agencies impose solutions; consultants and teams of volunteers jet in and out, the list of harm caused to communities under the guise of "helping the poor" goes on and on. These failures are usually not because of numerical or technical errors – the mistakes are because of a failure to understand context. Therefore, in this chapter, I do not present differential equations or numerical models; I propose the *mindset* needed to approach development work from a primarily qualitative perspective. Understanding how to ask questions, what questions to ask, and how to go about answering the questions is the most important, foundational (and often overlooked) part of development. Here, I attempt to offer lessons to guide this understanding.

The insights presented here are not restricted to plastic recycling – the lessons can be applied to a wide range of development projects with the caveat that these reflections are from my experiences in community-centered social entrepreneurship, and I come from a technical background. Many of the insights can apply to other sectors, but these lessons are especially pertinent to community-centered development. My insights are also from a Ugandan context, but they can apply to other geographic areas, even U.S. communities. The lessons are by no means comprehensive, and some will likely dispute the arguments presented here, but I hope that by taking the time to write my reflections on development work, others will be challenged to think critically and holistically and pause to self-examine before launching a project.

6.1 Humility

You don't have the answers

Whenever you enter a community (especially if you have not lived there for many years), enter with the mindset that *you don't have the answers*. Countless projects have failed because outsiders enter a community thinking they're the experts, they're well-educated or experienced, they've studied this problem, and they know the right solution. But theories developed outside of a community do not often work practically. You must listen to, respect, and collaborate with community members to develop sustainable, long-lasting solutions. Show humility by entering the community with a mindset to learn. A humble mindset, a respectful attitude, and an acknowledgment that you don't know all the answers are the foundations of sustainable development.

Outside consultants often don't have the answers and can even be harmful

Outside consultants are fast, but they are very expensive and give recommendations that often do not work long-term because they usually do not involve the local community enough. Oftentimes, outside "experts" are hired to make recommendations on how best to implement projects. They hold some meetings, scope out the area, talk to some community members, collect some data, then go back to their desks, do some research and calculations, and write long reports. But no one can learn the local community in a two week assessment – defining a project plan after such a short research phase and without giving local stakeholders a real chance to collaborate often leads to unsustainable, failed projects. Outside consultants usually suggest imported copy/paste recommendations from similar projects in other areas and generate long reports that usually only the funders read, not people in the local community.

Instead of wasting limited project funds on hiring expensive outside consultants, that money could instead have large impacts locally if used for project implementation or facilitating locals to do the research and develop recommendations. Local community members often have ideas on how to solve challenges–they often just lack the resources to do so. Additionally, with stable Internet now generally accessible across much of the developing world, bright community members can do research themselves to learn what similar projects have tried in other areas of the world. They can pick and choose what concepts will work in their community, merge those ideas with local resources and practices, and develop a customized solution that will resonate with local community members – a local solution that the community can be proud of and take ownership of. Community members involved in project formulation and implementation are invested in the project and suggest solutions they want to use, ensuring long-term project sustainability. People from outside the community can still be helpful if they stay within the community to build relationships, trust, and respect throughout the course of the project and experience the conditions and prototype solutions firsthand. It is also helpful if they are knowledgeable/have skills in the project area to share with the local community and collaboratively develop a customized solution.

Although there are many, many examples of consultants causing projects to fail and harming communities, I'll highlight a couple here.

One town I visited in Uganda during my field work received funding from a European development agency for a multi-year project to improve the town's solid waste management (SWM) system. Most of the town's waste wasn't collected, so residents burned or littered their waste. The little waste that was collected was dumped on the outskirts of town in an unofficial dumping ground (where it was eventually burned.) The project hired multiple (expensive) outside consultants, most with PhDs and masters degrees and decades of experience in the international consulting industry. The European consulting firm hired sub-contractors to get more local experience, but even the sub-contractors were from far-away Kampala, Uganda's capital, and not personally invested in the community. Although there is a university near the town with qualified professors and researchers, none of them were part of the project.

The European consultants visited the town for 2 weeks then returned a few months later for less than 1 week. An Australian "development expert" visited for less than 1 month for their assessment. The consultants worked with the local government and held a few meetings to get feedback from the community, but their stakeholder evaluation was insufficient and their baseline waste survey was incomplete. They could have gotten much more feedback from the townspeople if they utilized radio–going on community discussion shows and asking people to call in with their questions and comments–or collaborated with local environmental organizations to host a conference and round table discussion. Most people in the town didn't know a waste study was conducted or that a landfill was being proposed.

Additionally, the consultants' waste assessment lumped different types of plastic into the same category–they didn't collect baseline data or make estimates on the projected amounts of the different types of plastic. They proposed a recycling scheme, and the report presents calculations, pictures, financial estimates, etc. but in calculating the recyclable potential, they didn't account for different types of plastic waste having different values. In Uganda, scrap dealers buy plastic waste at varying prices according to type (HDPE, PP, LDPE, PET), cleanliness, and color (to some extent–color helps distinguish the type of plastic). The consultants' proposed recycling scheme doesn't even mention the most valuable type of plastic waste in Uganda. They just highlight the most visibly obvious types without digging deep enough to understand the real situation. Additionally, the report assumes that the town's "less prosperous areas" have no significant amounts of valuable recyclables based on the consultants' assessment of the waste from "high income areas." The consultants made assumptions to support convenient conclusions that made their work easier instead of taking the time to walk through the low-income areas (which is where the majority of the people live), talk to the residents, and study the amount and types of waste they generate.

Outside consultants may be experts in a technological or scientific area, but they are not experts in this community. It takes more than a few weeks-long assessment trip to understand the complexity of a community and develop long-term solutions.

The consultants generated two long reports (120 and 238 pages) that are not widely distributed and most stakeholders have never even seen. Local government officials and environmental organization leaders have never read the reports. The consultants recommended that the town's current unofficial dumping site be upgraded to a proper landfill, but the site is small, so it will only be able to operate for a predicted 10 years before it will be full. They recommended investing millions of euros in landfill construction and importing equipment, and after 10 years a totally new site will have to be developed. The consultants recommend using a clay liner in some areas (although the permeability calculations presented in the report are cringe-inducingly terrible) and an expensive, imported HDPE plastic liner to contain the leachate in other areas. But the report gives no justification for why the consultants chose an HDPE liner and no discussion of alternatives considered. Instead of researching for a more accessible, cheaper, local solution, the engineers recommend the default material used in European landfills without considering if it's the best option for Uganda. The report even admits, "in spite of the control measures, leaks of leachate through isolated defects in the liner installation and piercing of the liner by accidental damage are **inevitable**." (emphasis mine) Surely a local solution could be found that at least matches the effectiveness of an expensive liner where leaks are "inevitable."

The project imported expensive skips, trucks, and hundreds of containers for holding and sweeping waste. (Just 1 compactor truck costs 75,000 Euros, and skips for the initial phase were 116,000 Euros! Meanwhile, the street sweepers (most of them women) are paid only 25 Euros/month.) After just 6 months, some of the skips were already broken, and since they were imported, they couldn't be repaired locally. Additionally, the town had no money to fuel the trucks, repair the vehicles, or pay the drivers. So the trucks sat idle and the graveyard of broken, unused, imported, donated equipment in the town yard grew.

Understandably, some equipment must be imported, but think of the number of local fabrication jobs that could be supported if some of the equipment was made locally? Development agencies should consider how the beneficiary community can be supported throughout the project–not just receive the projected outcomes at the end.

The consultants' report extensively discussed how the town could support fueling and servicing the vehicles and paying the salaries of drivers and street sweepers through small service fees–the community's contribution to the project. The report gave financial projections and compared the suggested fee amount to other studies. But that didn't help implement the scheme. Plus, collecting fees from the community and relying on the local government to fuel and repair the vehicles (which they had failed to do with their existing fleet) was a pretty unreasonable solution from the beginning. When the project fails, the consultants blame the local government for not doing what they were responsible for or following the solution outlined in the reports (but the government officials never read the long reports.) And the local government just waits to be rescued by the donor agency sending more funds to make the project "work." Thus the cycle of excuses, wasted funds, and unsustainable projects continues.

The solution recommended is not sustainable because the outside consultants don't put enough effort into understanding the local community and finding local solutions, and the local government just wants the donor money which must be spent before the project expires even if the recommended solution is not what's best for the community or is not sustainable long-term.

To oversee project implementation, the European development agency pays for the consulting firm to rent an office in the town, buy vehicles, and send a few staff to live and work there. The staff are paid European salaries, issued work permits (a 3-year work permit for professionals in Uganda costs 7500 USD), and some firms give additional travel/living stipends.

Instead of spending millions of euros on expensive outside consultants and imported equipment, development agencies should hire local people and give them time to develop sustainable solutions. Local people know their community's problems, have relationships with the stakeholders, know who to consult as local experts, and are personally invested in the project success. If you experience the detriments of poor waste management every day where you're living, then you have incentive to make it better, and your neighbors and people around you will keep you accountable.

If the local people don't have all of the expertise needed for a project, hiring outside expert advice can be helpful, but the consultant collaborate with the locals–go back and forth suggesting ideas and exploring local solutions. The consultant should guide, teach, and build the knowledge and skills of the local staff and most importantly respect them and value their input. And instead of hiring European consultants, consultants from the capital could be hired, so that instead of contributing to the international development machine, even consultants' salaries goes towards developing the country the agency is supporting. But take care to do your due diligence before hiring a consultant–taking the time to vet and investing in the right consultant is worth it. A consultant should be humble, respectful of the community, and patient to find a long-term, sustainable solution.

The project in this example is still ongoing. However, it doesn't look hopeful. It's already over three years behind schedule, and imported equipment has already broken down. Land ownership issues delayed construction of the landfill for a while, and now the local contractor hired to build the facility doesn't have enough funds to finance the construction. Work is proceeding very slowly with few workers and they're struggling to import the recommended HDPE liner. (The donor agency and consultants only release a small amount of funds to the contractor up-front–most of the money is paid after completion. Contractors are supposed to be vetted to ensure they have enough capital to do a job, but sadly oftentimes, contractors are chosen because they're willing to give a kickback to government officials–not because they're qualified for the job.) Meanwhile, the people in the town are still suffering from poor waste management and the negative health implications caused by litter and burning trash.

Another example of outside consultants jeopardizing projects and wasting money is from a different European development agency. They send consultants to give trainings without prior warning to the organization they're working with and demand the staff to drop what they're doing and attend the training. Although the consultants are Ugandan, they're not from the region, so they don't speak the local language and most of the staff can't understand them. They give trainings in topics that the organization is already familiar with, so they're not helpful. Meetings are held just to check boxes in grant requirements and add numbers to impact statements. The consultants write their reports, collect their money, leave and forget because they're not invested in the community or interested in doing what actually helps the people long-term.

Some Kampala consultants forge data–they don't want to make the effort of going to the field and conducting surveys or they know what conclusions they want to have, so they sit at their desks and make up the numbers. In the offices of this development agency, young interns from this European country dictate over and usurp experienced, local experts. Oftentimes, interventions and projects are done just to spend the money before it expires and goes back to the donor agency.

The international development consulting industry is a major contributor to failed projects, junkyards of broken equipment, aid dependency, and underdevelopment. A new approach is needed. Outside consultants do not have the answers.

Big aid often stems from ulterior donor motives and rarely supports holistic community development

Countries that receive the most foreign aid have negative growth and development rates. In her book *Dead Aid*, Zambian Dambisa Moyo exquisitely summarizes this and argues that aid is in fact *why* Africa has failed to develop [111]. She states, "between 1970 and 1998, when aid flows to Africa were at their peak, poverty in Africa rose from 11% to a staggering 66%." After 6 decades and over $1 trillion USD in African aid, the continent is not better off – in fact, the most aid-dependent countries over a thirty year period had an average annual growth rate of *negative* 0.2%. Aid increases corruption and conflict and discourages entrepreneurship. Aid can even put local small businesses out of work when well-intentioned donors hand out imported, free goods or introduce new systems. Moyo shows that aid is not even benign – it is malignant. Aid is not the solution – aid is in fact, *the problem*.

Aid can also be detrimental to the benefactors by creating "Savior Complexes" and giving donors an inflated view of themselves. Aid creates power injustices.

While aid is often needed to support large infrastructure projects (which can benefit everyone in a community), aid is often a tool of statecraft that disguises ulterior donor agendas under the guise of humanitarian work. Western nations use aid to prop up corrupt, oppressive despots for their own political, economic, and military goals (this was especially true during the Cold War but still happens today.) Very little aid is truly for humanitarian purposes; most aid is meant to accomplish self-serving donor interests rather than solve recipients' underlying problems. Therefore, donors turn a blind eye when corrupt politicians divert millions of dollars because holistic community development is not the goal of most aid.

Additionally, aid is often distributed through a top-down approach where donors decide which projects their funds should be used for. Critiquing this model, William Easterly proposed the idea of Planners versus Searchers [57]. Planners think they are the experts who know the answers and dictate project plans. Easterly believed planners only increase bureaucracy, reinforce old, failed models of development, and waste billions in aid money without achieving real impacts. He argued poverty could be ended by decentralized ”searchers” discovering ways to meet individuals' needs. Searchers ”imitate the feedback and accountability of markets” to provide goods and services, solve problems, develop communities, and end poverty [58].

Searchers admit that poverty is complex and requires an understanding of the political, social, historical, institutional and technological factors. Easterly asserts that local knowledge, local skills and local circumstances are imperative for sustainable success [57, 80].

Contrasting Easterly's denunciation of planners, the rapid growth of China and the Asian Tigers was a result of strong central planning. However, China's rapid macro-economic growth was at the detriment of environmental and social factors. Even impressive decreases in poverty rates do not reflect successful holistic development across the three pillars of People, Profits, and Planet.

And China's central planning was internal–planning by aid agencies can be worse because usually the allegiance of aid agents' ultimately lies with their foreign governments. Therefore, the projects funded by aid must accomplish the foreign government's motives–which are not necessarily solving a community's problems holistically.

Development is ***complicated***

Development is multi-faceted, difficult, and takes time. I believe in the marathon (not the sprint) approach for sustainable, more just development.

Good development is much more than technical plans. Good development is about understanding people. And people are complicated. Take the time to build relationships, study stakeholders, and find the right partners. Consider all the angles of a project–technical, financial/business model, environmental, political, educational, community engagement and outreach, and power relations. Who is benefiting? Who is left out? There is always a danger of unintended consequences, but taking time to think through the entirety of a project can help mitigate harmful side effects.

To truly develop solutions with community buy-in takes time. Cultures in many developing countries do not operate on the fast-paced timescale of the Western world. Respect that. Ruminate on the problem, sit with the community, build relationships with partners, iterate through prototypes to collaboratively develop long-lasting, sustainable solutions that community members will want to use and be invested in maintaining.

6.2 Respect and Invest in the Local Community

The local community has many of the key answers

You, the project implementer, don't have all of the answers. Outside consultants don't have the answers. The people who are impacted by the project have many of the key answers.

The people who will be using the product or service, the people who experience the problem you're trying to solve everyday, the people whose lives the project will change–they're the ones with many of the key answers. No matter what their level of education is–even if they can't read or write–no matter what they look like or what they wear, regardless of if they speak your language or understand your customs–respect them. Listen to these people and involve them in the project from the very beginning all the way to the end. They're the ones who will live with the project after you leave, so if you want the project not to be forgotten, if you want these people to incorporate your changes into their lives, then they need to be part of the entire process in a respected, valued, even deferential role. The people whose lives are being changed should have the final say.

Creating local jobs is very important, if not the best, form of development

Giving people a chance to provide for themselves has a huge impact on their self-esteem, their children/siblings' development, and the local economy. Having a job to wake up to every morning gives people a purpose, especially for those who have experienced trauma, this is extremely important to helping them be productive and not fall into unhealthy methods of running away from the trauma such as through drinking alcohol, smoking weed, stealing, chasing women/men, abusing family and friends, and engaging in other practices harmful to themselves and society. Simply being able to provide for themselves and dependents brings a person much respect from their family, their community, and even themselves.

Since steady jobs are so difficult to get in many developing countries, a person with a job often is expected to support many relatives and friends. Taking Takataka Plastics as an example, each of our staff supports on average 5 dependents. That means one job is providing food, housing, schooling, or medical care, etc. to six people. Even our production team members who get paid $3.34 per day support their family and friends. One of Takataka Plastic's best employees is a former street youth who has worked his way up to Night Shift Production Manager through his hard work ethic, dedication, and resourcefulness. He invests nearly all of the money he earns in helping his family develop. In less than two years, he's bought 3 cows, 6 goats, and 2 pigs. He's also purchased 25 metal roofing sheets and made 20,000 construction bricks to build a permanent house for his mother and father. He expects by the end of the year, he'll have saved enough money to finish building the house. He inspires other staff with his saving and investing. For a youth who never finished primary school and was living on the streets less than three years ago to have accomplished all of that is truly remarkable.

Obviously, job creation also trickles down to support the whole local economy. If someone is earning a salary, they spend money to rent a room, buy food, purchase new clothes and shoes, etc. They often start their own side hustle businesses creating more jobs and buy merchandise from wholesalers to stock their businesses. Or they invest in farming and buy pigs, goats, chickens and other animals or seeds and fertilizers and hire people to weed and harvest and sell the grown animals and crops at the local market.

According to GIZ, every new job creates an additional 5.49 indirect jobs (jobs created in the supply chain) and 2.32 induced jobs (jobs resulting from direct and indirect employees spending more and increasing consumption) are created for each direct and indirect job [106]. Therefore, 1 job actually creates 12.76 jobs. For X direct jobs created, the total number of jobs is actually $((X * 5.5) * 2.32)$.

Support Local Innovation Competitions

Local innovation competitions to fund local solutions have potential for sustainable, more just development, but need strong mentoring and follow-on funding opportunities.

Innovation competitions inspire and encourage people, especially youth, to solve challenges that are impacting their lives. Many even already have ideas but lack the resources to prototype and try them. Even at universities in Uganda, engineering students often have to fund their own final year projects. Building something and presenting results is a requirement to obtain the degree, but universities lack the funds to provide even minimal project support, so students (many of whom are already struggling to pay tuition, fees, and house and feed themselves) have to buy materials, sensors, equipment, and sometimes pay for lab tests. It's no wonder that students' projects are small and limited in impact. Supporting projects with even $500 USD can go a long way in initial prototype development.

More small innovation competitions have started to spring up in Uganda in recent years. They have great potential to find and empower locally-led projects rather than ideas brought by outside organizations, but many of the competitions lack follow-up support. Winning a few hundred dollars and receiving a short Facebook post of recognition is a great start, but it doesn't last for long. There needs to be clearly articulated stages of follow-on funding to push projects through iterations and weed out and select the ones with potential to succeed.

The competitions also need to offer participants more local mentorship and guidance. As discussed previously, developing sustainable solutions is multi-faceted–no one has all the skills to make it happen. Oftentimes, a bright, passionate engineer has a great idea but no clue how to grow and scale it. Or a committed community organizer or savvy business person has sees an opportunity but has no idea how to build or test a solution. They have the will and the energy, but they need guidance. Oftentimes, US or European professionals are willing to volunteer time to mentor such projects, but these coaches rarely understand the local context, so their advice is not useful. There needs to be more knowledge-sharing, mentoring, and support from successful local professionals. However, in some cultures, knowledge and networks are highly valued, and after fighting hard to get it, some people don't want to share them with others. But budding projects can grow exponentially if experienced, successful entrepreneurs, engineers, etc. working in the region take the nascent developers under their wing and commit to advise them, connect them to powerful people, and advocate for them. This is what local innovation competitions in Uganda are lacking.

Education opportunities (especially abroad) are another impactful form of development

Education has big long-term, sustainable impacts. There's no dispute that education empowers a person, improves the skills of a country's workforce, and grows the local economy. But sadly public schools in many developing countries are not well-funded. Those who can afford it send their children to private schools, creating a widening wealth gap similar to trends currently seen in the U.S.

Education abroad is especially impactful when the students return to their own communities to share their knowledge and implement what they've learned. Seeing new cultures and learning how things are done in other countries is eye-opening and useful to everyone. You can pick which ideas resonate with you, adapt them, and incorporate them into your life and inspire those around you to do the same.

Large-scale infrastructure projects benefit everyone

Access to reliable power, Internet, good roads, clean water and sanitation, adequate buildings, and excellent schools are the tools any community needs to grow. Adequate infrastructure enables local enterprises to succeed and allows new ones to start. It also attracts new investment. For example, for many years, the power in Gulu has been unstable so there is very few industrial operations. Even some of the few companies left and shifted to Lira, an adjacent town, because even though Lira is smaller, the power is more reliable there. Without the industries, there's fewer jobs, fewer opportunities for post-harvest processing of crops, and less money in the local economy. At a smaller scale, restaurants and supermarkets struggle because when the power goes off, they have to run generators to power refrigerators to preserve food or lose their stock. Or they lose customers when people ask for items that are not available. Many struggle to make a profit when having to buy fuel to run generators and some restaurants are forced to close.

The only caveat with large infrastructure project investments is beware of corruption and negative environmental impacts. It's common for contractors, politicians, project developers, and other players to skim funds and to not do proper environmental assessments. When assessing projects and how they get practically implemented, consider who is the project supposed to be for? Who are all of the winners and losers?

Consider the *appropriate scale* There's an appropriate scale for different types of projects. Infrastructure projects and establishing universities costs millions of dollars. However, addressing a community's specific challenges sometimes requires small-scale, local solutions. Some concepts can carry over and work in similar projects in other communities, even other countries, but don't assume that just because another community has the same problem, you can copy/paste the solution and it will work elsewhere. Each community will have its own nuances needed for sustainable implementation. Before scaling up or replicating your project, ask "does this solution really solve *this* community's needs? What modifications are needed to make it relevant to and accepted by people here?"

There is collateral damage for everything–and the damages are magnified in bigger projects. A classic example is buildings hydropower dams and reservoirs, but even the Green Revolution in India, and China's rapid development achieved their big goals of bringing stable electricity and water, increasing agricultural productivity, and growing the economy but at the expense of the environment, displacing people, desolating culture and heritage, destroying the livelihoods of smallholder farmers, and ruining the air and harming people's health with pollution. Regardless of the scale of your project, even if it's "successful," ask yourself what harm is caused by side effects and unintended consequences? And beware that the bigger the project, the bigger harm collateral damage will cause. So start small and take the time to test the pilot adequately.

Invest the time to listen to community members before planning projects

Sustainable development takes a looong time–accept and embrace that fact in planning projects rather than using it as an excuse for projects behind schedule. Set reasonable timelines that give space for community dialogue, rumination, and developing a collaborative solution with all stakeholders. Then commit the time and focus to use the listening and planning months well–interviewing, holding meetings, reading, conducting surveys, prototyping, etc. takes a lot of work. If this foundational initial process is rushed or left to the last minute, the whole project is jeopardized.

This can especially be an issue with student projects. Many students in the Global North want to work on projects in the Global South because they feel like they're helping people and doing something meaningful. But students are very busy and when projects are forced into timelines to meet a 16 week class schedule, it's difficult to properly understand the community, experience the problem, research and iterate through solutions. To do a development project in a semester takes proper scoping by the teacher and partner organization in advance, students committed to investing meaningful amounts of time, and a hands-on project implementer from the partner organization regularly checking in with the students. I've seen and even participated in many student projects and volunteer groups that have good intentions but end up doing nothing or harming the community they're trying to help. Students and volunteers get busy, don't devote enough time to the project, throw something together without adequate research just before the deadline, don't communicate often or well with the partner/host organization staff on the ground, attempt to do projects in areas they are not knowledgeable in, etc. You can't design a solution from a desk or lab thousands of miles away from where it's being implemented without understanding what the situation is on the ground, what materials and equipment are available, how people relate to the problem, what power is available and how reliable it is, etc. And a short assessment trip isn't enough time to understand all those things (except potentially if you're already an expert in the project area and have worked and lived in similar communities before–but even then, your understanding of this community will be incomplete. You'll have to listen to and rely heavily on insights from the local partner organization staff.)

Even my first trip to Uganda as a 19-year old college sophomore, looking back now, was a development disaster. Although our team checked all the boxes–we partnered with a local host organization, had an experienced advisor who had traveled to this community multiple times, our plans had been checked and approved by our national organization committee, we underwent pre-trip orientation to understand cultural differences, emailed our plans to the host organization staff, brought our test kit equipment, and did some research–in the long-run, we hurt the community. Our host organization hadn't read our plan (that we developed without their consultation) that we emailed them–we didn't know that email is not the most effective or preferred means of communication in Uganda. The driver/guide bringing us around didn't speak the local language (he was from a different tribe and lived in a different part of the country near the airport). Many people in villages don't speak English, and we certainly didn't speak Acholi, so communicating with the community was challenging. During the time that we chose to travel (which was convenient for our schedules), we didn't realize that schools in Uganda were on holiday, so many of the teachers and staff we had planned to interview weren't around.

We thought we were culturally sensitive because we slept in a hut (a very nice one–not a typical village hut), ate local food (again, not typical village food and I sadly vomited up my special goat dinner in the night), knew enough to call a meeting with the local water committee and attempt to ask them about the status of their boreholes (but we still couldn't communicate well because we didn't have a proper translator), and got "community ownership" of the project by getting them to donate their labor and a few wooden posts. We were a bunch of clueless, naive college students driving around Ugandan villages with no business trying to implement a project–we didn't even know engineering yet and we certainly didn't understand this community. We labeled our 2 week trip a success–we collected our samples, talked with community members, assessed the problem, constructed a few fences (that fell down or were stolen/scavenged for the barbed wire and nails shortly after we left), signed an MOU, and took a happy picture with community members. But we didn't have any long-term positive impacts, and we made promises that we didn't keep. We spent thousands of dollars on a trip that only benefited us–not the community. Even donating the funds we raised for our plane tickets to our host organization would have done a lot more good for the community. We put our volunteer experience on our resumes, posted our pictures on social media, and only perpetuated the harmful expectations of foreigners swooping in, giving handouts and promising development, but failing to understand the community or work with them to build anything that addresses the root of their problems long-term. Our team didn't mean to cause harm–we simply didn't know better and were blind to the real impacts of our actions.

Although in hindsight, my first trip to Uganda was a mess, and I regret the unintentional harm we did, I'm grateful that it introduced me to the Ugandan people and led to the opportunity for me to go back on a Fulbright research grant and live in a village for 10 months, which led to doing my graduate research there, which led to co-founding a social enterprise that now employs 33 Ugandans. I'll never know everything about Ugandan culture or how to implement engineering projects in an under-resourced setting, but after 8 years of working in Uganda, I know a bit more about how to listen to the local community and know enough to defer to trusted Ugandan colleagues when I'm unsure.

There are rare cases when a short humanitarian trip can help a community (when the foreigners approach with a humble mindset, commit to the community long-term, build relationships, and communicate realistic expectations of the project timeline–if you're going back and forth for short trips and have to raise funds, it usually takes years.) But beware that when volunteers and outside consultants only have time to jet in, conduct a 2 week assessment, and jet out, insufficient time listening to and designing with the community are major issues that can cause long-term harm.

Beware that people often tell you what they think you want to hear

When doing interviews/surveys, some people might not be completely honest. If they think your project will give them something or benefit them, they could exaggerate answers. Or they could say they need whatever project xxx you're proposing when in actuality, a yyy project is what they really need. This scenario is especially prone to happen when a team of Westerners is asking the questions. Decades of aid and NGO projects have made many people in developing countries accustomed to handouts. They fear that if they're honest, the project will be taken elsewhere, and they'd rather have something (even if it's not really what they need) rather than nothing.

To try to avoid such scenarios, have local partners ask the questions. Experienced local community development workers understand the context and can better tease out real answers. It's still useful for your own understanding to attend at least some of the interviews, but don't overwhelm the community with a whole team of mzungus. Split up and pair one or two of the outsiders with a couple of local partners. And instruct the local team to push for honest answers and get to understand the root of the community's challenges.

Don't overcomplicate solutions

The best solutions are simple. They don't even have to be technical. Business models, education/outreach for behavior change, policies, etc. are often important solutions too. Sometimes something as simple as placing a sign, conducting a training session with follow-ups, or shifting an existing solution to a new location can solve the problem. Usually a combination of many of the approaches is the most successful. Engineers especially like to over-design. They want to add this feature, use that gadget, and make it perfect. It's easy to get excited and lost in the details until your solution has grown into a monstrous, complicated thing. The old adage of KISS (Keep It Simple Silly) is very true. Think about the root of the problem you're trying to solve.

Value local knowledge

There is a lot of local knowledge that is not verified by "experts" or published in peer-reviewed journals, but it's extremely valuable. Local herbs and medicines are classic examples, but building and fabrication techniques, community organizing methods, farming, and other local practices are also treasure troves of indigenous knowledge. Even simply knowing where to find materials or what to use as local substitutes is incredibly helpful. Search for, value, and credit local knowledge. And the credit is key–add your local collaborators as co-authors on papers, split fellowship money, give them a percentage of businesses you start, etc. Projects can't succeed without local knowledge, and those who share their knowledge with you should be acknowledged and compensated.

Build local capacity rather than importing machines

Do not contribute to the graveyard of imported equipment that's sitting idle and useless because it broke and can't be fixed. There are many machines scattered across Uganda and developing countries that were sent by good-hearted donors but are not used or are just scrapped for parts because the technology is too complicated and local staff are not trained how to use and maintain them. A part breaks, and there's no local replacement. Or a sensor malfunctions, but no one is trained how to diagnose and fix such a simple problem. Or the machine doesn't work on the voltage rating of the beneficiary country. (However, local fabricators, engineers, and electricians can often find ways to jury-rig something to make a machine work if the machine would actually be useful, and if there's money to fix it, and if the leaders in charge care enough to make the extra effort to make it work. The jury-rigged solution usually won't last for that long or won't work great, but if the machine would be really beneficial to someone, they can usually find a way to make it work–although it will cost money to fix it.)

I've even seen university labs with equipment sent by development banks that's never used because the equipment sent wasn't what was really needed and the university staff were not adequately trained in how to run the machines. The development bank sends a consultant to deliver and install the machines, give a brief training, and leave. But it's not sufficient training for the staff to learn how to actually operate such machines themselves. And often the cutting tools or blades are not included, so the university has to find funds to buy the tools to use the machines. Although it would be a lot of work, a committed, bright university staff member could scrape together funds to buy tools and could teach themselves how to operate the machines using the Internet and trial and error, but if the machines are not what the university needs, no one is going to put in this effort. Thus, tens of thousands of dollars of aid sits idle–wasted.

Instead, find local solutions and invest in building up local capacity–both people and workshops. It's very possible to build many machines locally. It might take more time to design, develop, test, and build iterations of a new machine rather than importing a ready-made one, but it's much cheaper to build a machine locally rather than buy a new one abroad and pay shipping and import taxes. Plus, a locally built machine can be maintained and repaired when it breaks, and it builds the capacity of the local engineers and fabricators. Scalability is also vastly improved compared to importing–once you've figured out how to build a durable, operational machine well, it's easy to replicate and build many more that can be sold. Such a method is much cheaper than importing many machines and gives local fabricators and/or your project a revenue stream.

The time needed to design and build a machine locally can be greatly reduced if blueprints of similar machines are available (perhaps online from an open source platform or from a partner organization) or if an old machine has been imported and can be studied. Many new industries in a country get started by studying, copying, and adapting similar machines that have been built in other countries.

The exception to this limited import guideline is for makerspace and workshop equipment. Uganda needs more lathes, milling machines, routers, CNC machines, and even 3D printers and training for more Ugandans to learn how to operate such equipment. These machines are extremely helpful in building local machines and open doors to innovation. Importing these maker tools, some of which are not very expensive, opens a plethora of opportunities for projects to develop local, custom solutions to specific challenges.

Obtaining materials, such as 3D printer filament and aluminum blocks, to use on these machines can often be a challenge and should be considered before importing the equipment, but many times a local solution for the material can be found.

Scaling depends more on the people implementing it than on the technology

You can have proven tech in one location, but to make it work in another place, it needs to be run by a passionate, honest, qualified, committed, connected local community member. When something breaks, they need to know how to fix it or know who to call. They need to forge partnerships with the local government, community groups, businesses, neighbors, etc. They know best how to market the solution to the community to get buy-in and make sales. They know how to manage and motivate staff according to local culture and context. Someone who knows what communities to reach out to, what connections to make, and what procedures to follow to do so. Do you need a letter of introduction before approaching the town clerk or university lab? Without a knowledgeable, committed, connected, honest community member leading the project, it can easily fail.

Ideally, partner with a local community member who is already doing something in the project area. If they're already working on something on their own—even if it's small—they've shown they're willing to invest their time, energy, and money to find a solution to this problem. If their vision and goals align with the project aims, they will be an excellent project manager and the project will have strong community ties. Even if the person is not exactly qualified with the required skills, they can learn those. Passion and honesty are more important than educational background. Sometimes, someone who hasn't been trained in an area even brings new ideas and insights because they're not blinded by preconceived ideas and theories that something won't work. They can imagine new, creative ideas.

Having the right local team will make or break a project

This point is similar to the previous one, but it extends beyond just the project leader to the whole team. The right leader can inspire and push a team, but having committed, talented, honest team members pushes a project to a new level. From sales people to engineers to community engagement officers to counsellors to drivers to cooks—investing in the right team pays off in the long run. While this is true of any business or project in any country, this point seems to often be overlooked in development work.

Passionate team members or volunteers or interns might be willing to take a smaller salary or work for free for a while, but they'll eventually have family and life pressures and need financial security. It's common in Uganda and other developing countries for people to have side hustles—jobs are often unstable and there's many entrepreneurial opportunities, so people often have multiple income streams. If you want employees to be fully focused on their work, you need to pay them enough to not be distracted by side hustles. Additionally, having the organization support additional education or trainings for the staff boosts employee retention and moral.

6.3 Respect Culture

Live in a village

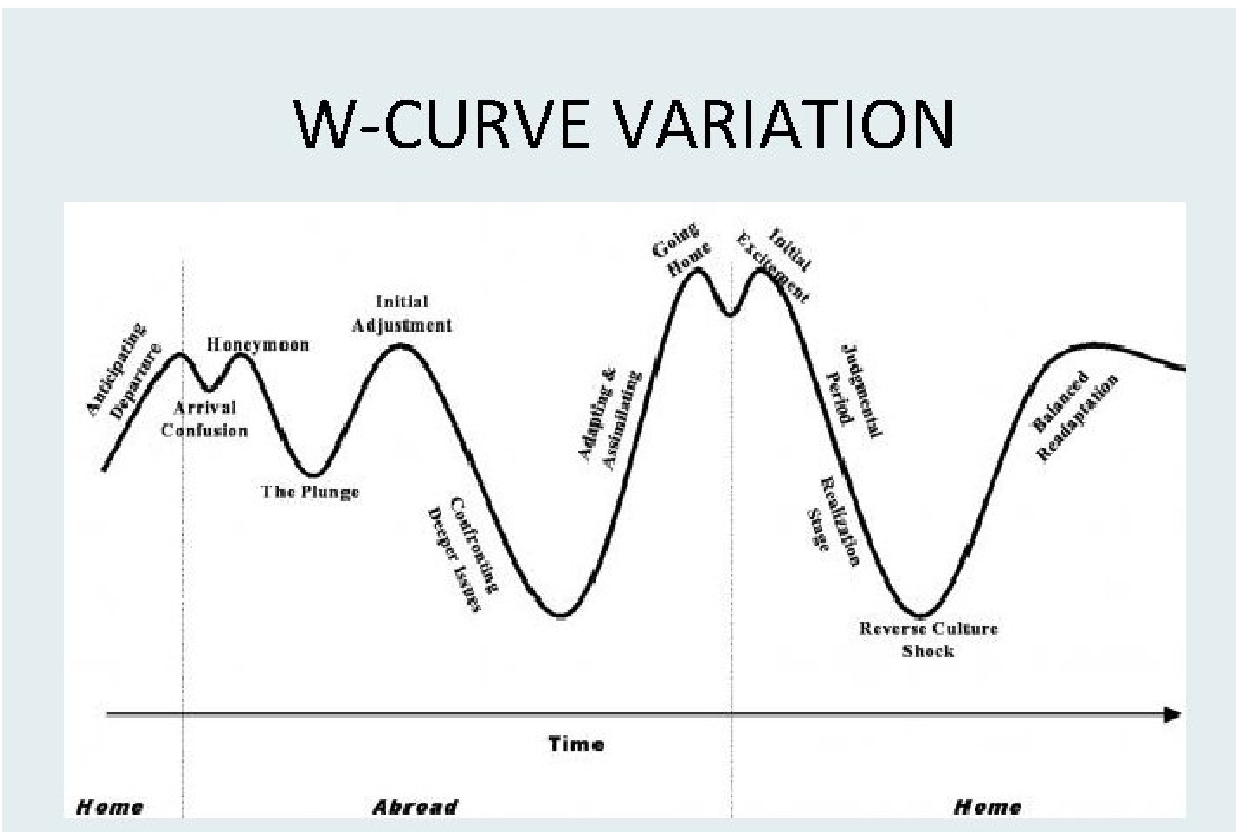
I firmly believe that everyone interested in development work should start with living 6+ months in a village. Listen before you act.

No matter where and at what level of the development system you end up working in—whether it's Director of the World Bank, a Program Manager at USAID, or a community organizer at a small NGO—it is imperatively important for you to viscerally understand what daily life is like for the millions of people living in poverty. You need to appreciate and experience the hardships as well as the joys of the majority of the world who live in villages and slums–fetching water from a borehole every day; washing clothes by hand; growing, harvesting, and processing your own food; depending on the weather for your survival; the struggle to access basic health care and education, but also the joys of living in community–working together at tasks; the excitement of eating chicken and drinking soda on Christmas after eating only beans and cassava every day; worshiping in prayer together; experiencing the richness of culture–traditional weddings, burials, ceremonies; celebrating & mourning with dancing, drums, and singing–and just appreciating the joys of simple living and doing it together.

Because the decisions you make in your work will impact these people's lives. So before you go sit behind a desk or don your labcoat, go spend time living with the people you are trying to work with. Understand how they do things and the reasons why they do them. Build relationships and don't judge. See them as people, not as numbers in a report. So years later when you are sitting at your desk contemplating which project to fund or analyzing your test tube sample for a new drug or writing code for the next crop monitoring system, you'll still see the faces of the people you're working for and the millions more like them.

Take time to process

Give yourself space and time to adjust to culture shock and reverse-culture shock. When immersing yourself in a new culture, you'll experience many challenges and low points, but also much richness. Embrace it all. Dive in–cry, laugh, learn, and grow. Many scholars have debated the "W" Curve model of adjustment proposed by Gullahorn and Gullahorn in 1963 [75] (an extension of Lysgaard's 1955 U-curve [105]). Although everyone's experience is unique and the models don't accurately portray the phases of transition for everyone, the W-curve is a helpful visual and starting place to understand the emotional and psychological stages of adapting to a new culture.



W-Curve Variation Model (Adapted from Gullahorn and Gullahorn, 1963, modified from http://www.iesabroad.org).

Figure 6.1: W-Curve Model

I found reverse culture shock (adjusting back to American life after spending 10 months in a Ugandan village) much harder than I anticipated–more difficult than adjusting to Ugandan culture initially. It's necessary to take time to process and reflect. There are positive and negative aspects of every culture–how has what you've seen changed your thinking and challenged your belief system? What ideas or practices do you want to incorporate into your life now even back in your home country? What customs and ideas are you grateful for from your culture and what do you want to change?

Development work (and life) is a marathon, not a sprint. Don't burn out. Sustainable projects take years to develop and implement. Give yourself opportunities to re-energize, so you can see your projects through to completion well.

Excessive Reporting Requirements and Inflexible Budgets Hurt Development

Many government and multilateral organizations and even some NGOs that fund development projects require excessive reporting requirements and meetings that are burdensome and take time away from project implementation that actually impacts the community. Funders should do their due diligence and vet fundees then trust them to implement their project as they see fit. The downfall of so many development projects stems from program managers sitting in distant offices dictating to the people on the ground how to run a program or constantly asking for updates and pictures to know what's going on and correct it because the distant manager thinks they know better because they're educated, they have experience, they've studied the issue and read the reports and literature, etc. If you're not on the ground, you have no right to be taking copious amounts of time away from project implementation. Don't micromanage. Trust the local team to know how best to implement the project according to their culture to help their own community. It's helpful to all parties for funders to check-in periodically, assess progress towards project goals, and offer suggestions, but don't make such requirements burdensome.

Similarly, inflexible budgets/requisition procedures lessens community impact. The world is dynamic. Needs change—especially for a fast-growing social enterprise. When we apply for a grant that takes months to be approved and then even longer for funds to be released, by the time we actually get the money, sometimes we no longer need the piece of equipment we requested for—we now need a different one. Or the outreach campaign we want to implement has changed because the community's needs has changed. But inflexible budgets from some large organizations don't allow us to spend the money differently from what we outlined in the grant. And they release funds to buy equipment for the amounts listed in the grant quotations. If we find what we need for cheaper, we can't keep the extra money and use it for other project needs. There's no freedom to adapt to changing organization and community needs and no incentive to stretch project funds for maximum impact. Funders claim their procedures are needed for accountability reasons, but strict procedures are not effective at preventing corruption—someone who is bent on cheating can and will find ways around procedures. It is very common in Uganda for dishonest program implementers to get inflated quotations and receipts from friends or whoever they're buying from and keep the extra money for themselves. It has happened to Takataka Plastics several times (we refused and lost the sale—they bought from someone else who would agree to go along with their scheme).

Restrictive budgets and requisition procedures, excessive reporting requirements, and burdensome check-ins reinforce the old, unjust development models where distant funders hold power over and dictate to local implementers. Do your due diligence, pick fundees and employees based on character, and trust them to do what's best for their community. A few times, Takataka Plastics has received large amounts of funds from foundations, companies, and even individual people without onerous applications or reporting requirements—they read online about what we've done, have a few calls with us, sometimes ask us to fill out simple program plans, and then send us unrestricted funds. We'll send updates periodically and sometimes have calls where they offer suggestions and guidance, but they trust us to do what we see fit to best meet the project goals. Such processes are so much better than the restrictive, slow procedures of large traditional development organizations.

6.4 Flexibility

When working in other cultures, it's crucial to be flexible. There will be different concepts of time, ownership/sharing of personal things and money, different business practices and appropriate ways of interacting with different groups of people, even different greetings, dress, food, and climate.

Someone could show up hours late for a meeting—it doesn't mean they don't respect you—it's just a different concept of time. You can push them to keep time, and because you're from a different culture or you're in a business setting, they'll understand, but be aware that if you push them when they're not ready, they could do a rushed, poor job. Patience pays. In Ugandan culture, people don't like to say "no" and disappoint others by admitting they're too busy or they don't know how to do something. So they say they'll do it, but never get around to it. Or start it but never finish it. (The same thing happens in the US.) It helps to have a relationship with the person and be able to talk frankly to them about what they're really able to deliver.

Uganda and many other cultures from the Global South are much more community-centric than individual-focused American culture that values independence. Uganda is starting to adopt more Western mindsets towards goods and saving (which frankly is not good because the earth doesn't have enough resources to support the whole world adopting Western consumerist lifestyles. Plus, it's well-documented that the consumerist, individualistic, Western lifestyle doesn't make people happy–it often leaves them unsatisfied and depressed), but traditionally, Ugandans are very free with sharing their resources and even their money. A friend might pick your sweater or power bank and never give it back. It's not that they stole it—it's just that they needed it and ownership of goods and the idea of personal property is not as strong. People are willing to share. You're free to pick from your friends things if you have need of them too. People are also expected to and willing to share their own money more than in Western societies. Older siblings help support sending younger ones to school. When a relative or friend is sick, they can ask for help with medical bills (most people don't have insurance—the community/social network is the insurance. If you get injured, I help you, and I can expect support from you if I fall ill). When there's a wedding, burial, or sometimes even a birthday party, friends contribute money. Even workplaces (both individual people and the company) contribute if an employee loses a close family member.

In Uganda, respect for elders is important. Whether it's older relatives, teachers, government officials, or business connections, showing proper respect by listening to them, approaching with a quiet, humble attitude, and even serving them something helps build relationships.

Focus on the problem, not the solution

Don't grow too attached to a particular solution. Focus on the problem you're trying to solve and be open to approaching it in different ways. Be willing to completely give up your original ideas if feedback from the community and experiments suggest a different solution is needed.

For example, I originally wanted to make roof tiles from plastic waste. I saw a lot of structures in Uganda with unfinished or poor roofs. Roofing was expensive and thatch was a fire hazard. I researched how other scholars and organizations around the world were making roofing panels and tiles from plastic waste. I studied the roofing market in Uganda, made prototypes, and surveyed over 200 people. After talking with all these people, I realized that Ugandans were interested in products made from plastic waste, but roofing would be hard to sell. In Uganda, the type of roof you have is a status symbol—the poorest people have thin grass thatch roofs, the next tier is metal sheets (with all different gauges, coatings, and styles depending on what you can afford), and the best roofs are clay tiles. People save for years to buy a good roof—it's expensive and a reflection of their societal status. It would be difficult to convince someone to buy a completely new type of product for something that's so important as a roof. This cultural realization combined with the technical difficulty of developing a roof that could withstand UV rays and weathering, support loads, resist fire, avoid microplastics, etc. made me realize that roofing tiles might not be the best product. The core problems we were trying to solve were plastic pollution (especially PET waste) and lack of jobs in Uganda—the exact products we make are just the means to support a self-sustaining business model to solve the two core problems. So after a year and a half of research, I gave up the idea of plastic roofs and switched to wall tiles. It required an entirely different manufacturing process, so it was back to the drawing board, but the market for wall tiles was large, the selling price was high enough to allow for reasonable profit margins, and the indoor application meant fewer technical criteria. As Takataka has grown, there have been other times where I had to give up my initial ideas. Although it's hard to let go of something you've worked hard on and believed in, it's crucial to listen to feedback from the community, be flexible, and focus on the core problem you're trying to solve. Don't hold your plans and ideas too closely.

Just try

If you have an idea, just try to build it. Theories only get you so far. Especially in the context of developing countries with limited infrastructure and access to materials and equipment, you need to physically try things because what's available doesn't fit perfectly into textbook property tables and theoretical models. Rather than making a lot of assumptions to come up with a theoretical prediction, do a simple experiment. See how a material or process behaves in the real environment.

When I wanted to make wall tiles from PET plastic waste in Uganda, all the U.S. plastics engineers I talked to said it wouldn't work—they'd list a bunch of polymer characteristics of PET that make it difficult to melt and say we wouldn't be able to reach the stringent material property requirements with the equipment I wanted to build in Uganda. Despite this dejecting feedback, we kept trying. We did experiments with PET in Uganda. We read articles and polymer textbooks. We developed new ideas to try and built small machines. And eventually, it worked! Late one hot sweaty night after struggling all day, we finally made a strong, small tile from PET.

Countless other times as we've developed processes and built machines at Takataka Plastics, we've learned the most from just trying something. Many times it fails, but physically interacting with your work builds intuition—seeing how the plastic melts, feeling the texture, playing around with different mixtures—that's how you understand what's really happening and come up with new ideas. And you can't learn those things from theories. Researching what others have done, understanding high level theories, making calculations, and drawing up designs are important and helpful to an extent, but don't wait too long to leave your desk and just try something. I made my very first plastic tile in my apartment oven—it wasn't pretty, but I learned a lot in just a couple hours. I had read about melting temperatures and polymer properties and even watched YouTube videos of melting plastic, but it wasn't the same as physically doing it myself and building that intuition. (Plus, photos of our "first prototypes" helped in applying to social entrepreneurship competitions.)

Iterate

Iterate over and over—build prototypes, fail, try again, get feedback, adjust, repeat. Use Human-Centered Design (HCD) and Co-Design concepts. You can't deliver a product that customers will buy or that the community will want to use if you don't get their input on what they want. And you can't just do an assessment, talk to your users once, go back to your desk, and expect to design a perfect solution. You have to iterate. Build a few prototypes. Let your intended users physically touch, handle, and use them. Even if the prototypes are not perfect. Ask people to compare what features they like and dislike about different designs? When developing our TakaChairs, people liked even the first chairs we built, but after they sat in them for a few hours, they could offer suggestions to improve them: the angle of the back didn't allow for relaxing, the seat was too small, after sitting in the Ugandan heat for hours, people's legs became sweaty, etc. We used this feedback to make even better chairs with stronger marketing points.

And no matter how good your design is, it won't work perfectly the first time. There will always be something you didn't anticipate—a part comes loose after multiple uses, an angle is awkward to use, an element heats up too much, etc. You have to build your design and let people physically try it for a while (not just for a few minutes or hours, but for a whole day or more) to discover the design flaws and how to improve it.

For example, at Takataka Plastics, we built more than 4 injection machine prototypes and many more iterations of specific components before making a machine that we're happy with. With each design, our engineers built, we'd have the production team members use it and get their feedback on what they liked and didn't like. Is the machine comfortable to operate? What parts of the process take the most time? What parts fail most often? The production team uses the machines the most, so even though most of them haven't even finished primary school, they can often make even better suggestions than the engineers. The production team knows the feel of the machines; they've developed tricks to ensure the quality of the products they make and speed up the production process. Listen to the people who will use what you're designing.

Pivot to adjust to changing community needs

A community's needs change over time, and to serve them well, you need to change with them. A solution that was working well and filling a need may become obsolete or unnecessary after a few years. New problems emerge. A prime example is the COVID-19 global pandemic. The whole world's needs suddenly and drastically changed. And nothing is going back to the way it exactly once was.

Takataka Plastics was only in its third month when Uganda announced its first case of COVID-19. Our business wasn't even officially registered yet and we didn't even have a product—we were still trying to figure out how to make tiles from PET. But we decided we wanted to help our community fight the pandemic. When we heard that doctors and nurses in the COVID ward of our local hospital didn't have face shields, we realized what we could do to help. Face shields are made from plastic, and that's what we do. We paused our efforts of wall tile research, and threw all of our energies into making face shields. We iterated through dozens of designs getting feedback from nurses on different prototypes until we had an effective, comfortable, affordable face shield. Eventually, we partnered with an Austrian company to get a mold for the frame and small machine to increase production. We produced and distributed over 20,000 reusable face shields to 27 districts across Uganda, recycled over 1,200 kg of plastic waste, and created 14 jobs. (See our April 2020 blog, UC Berkeley article, and IIE magazine article for the full story). After the need for face shields reduced, we returned to focusing on wall tiles, but pivoting to producing PPE helped our community in a time of need as well as helped our company grow and achieve our mission of recycling plastic waste and creating jobs for vulnerable youth.

Consider hidden trauma

Team members can have a lot of family/personal burdens and hidden trauma that can affect work performance—be understanding before jumping to judgment. This is also true in the U.S. but more common in developing countries where many people live in poverty, have experienced war, and struggle daily to support their family with basic life necessities. Stressful family situations, such as children falling sick, burials, supporting children's and relatives' school fees, etc., can cause employees to not show up or come late for work, be distracted, underperform, and act disrespectfully. Even lack of food and hunger can make employees too weak to focus at work. Before speaking harshly or punishing employees, first ask what's going on. Is there a reason for their behavior you don't know about? Can/should the organization support the employee in any way? If the unprofessional behavior continues, you'll have to give warnings and eventually let the employee go, but oftentimes, the stressful situation is temporary or hidden trauma can be addressed through counseling and the employee's behavior will improve.

At Takataka Plastics, we specifically seek to hire vulnerable, at-risk youth. Teens who live on the street. Girls who are already mothers. Some are orphaned by war. Many have fled abusive home situations. We know many of these youth we hire won't be as productive initially as people who haven't suffered such trauma and abuse, but that's part of our company's mission—to help people recover from trauma and restore them to their families and community by offering them a job, a supportive workplace environment, and an opportunity to provide for themselves. We have a full-time counselor that does group and individual counseling and is always available when someone wants to talk. For some, the counselling really makes a difference. Processing the trauma buried deep inside changes their whole attitude and demeanor—they become much happier, productive, and a joy to be around. For one particular girl, she was an ok worker at first, but would often take breaks and get distracted at work. After going through trauma counseling with our counselor, she totally changed! Her neighbors and even her mom asked, "What have you done to Akello (name changed)? She's so active and jolly now!" Takataka Plastics also has a collective saving group to encourage staff to save and invest their money in farming, livestock, and side hustle businesses. Sometimes all our efforts don't work, and we've suspended many youth and even fired several. But for those who embrace the opportunities, it changes their lives. Through their salary and savings they also change their families' and friends' lives.

Before jumping to conclusions or harshly criticizing someone, first seek to understand their situation, especially if your organization/project has a social mission. Extend grace to those who have suffered trauma.

Try different methods of communication

When communicating cross-culturally, even if everyone understands English, try different modes of communication (verbal, written, different platforms). I've found Ugandans are more comfortable and can better articulate their thoughts when speaking rather than writing. But for them to understand me, it helps if I summarize what we've talked about in a short written form. It helps clarify next steps and avoid misunderstandings. Sometimes communication issues can be solved simply by using a different platform. Americans tend to send emails and schedule meetings in work environments and text in informal/personal settings. Often, it's very difficult to communicate with Ugandans well over email. They call on the phone or use WhatsApp. You can schedule a time for a meeting or a video call, but if it's a quick query, just call or send a WhatsApp message. Email is reserved primarily for formal communication. So if you're working with someone from a different culture and are frustrated with the lack of communication, misunderstandings, or a language barrier, try giving them a call or sending a WhatsApp message. You might be surprised by the improved response.

6.5 Commitment

Commit to a community

For a project to be sustainable, you must live with the people you work alongside in the community the project is impacting. No matter how good the intentions or the ideas are on paper, if you're not invested in the community, the project won't last for long or grow. The most sustainable, impactful projects are community-driven. If you want to be a project implementer, you have to be part of the community to make that happen. Learn the local language, wear the clothes—even a little goes a long way in developing connections and trust. In Uganda and many developing country cultures, business is very relational—we make sales, form partnerships, and make things happen best with the people we know. You need to live in a community long-term to build those relationships and develop that trust with community members.

Starting projects is easy, growing them is hard

It's easy to start projects but very difficult to follow through and maintain and grow them. People's initial excitement quickly wanes, and it takes commitment, perseverance, and living where you're implementing the project to keep it going. Someone needs to encourage everyone who initially signed on to keep participating and invite more people to join. You need to constantly iterate to meet the needs of the community, and you can only know what those changing needs are if you're there and actively listening and observing.

Starting a social enterprise is a LOT of work

I underestimated how much time and effort it takes to start a social enterprise, especially in a different culture. The practical logistics alone takes months—registering a name, choosing what type of entity to be, drafting legal documents and officially registering a business, setting up a bank account, creating a website, buying domain names, obtaining startup capital, getting a trading license, obtaining a PO Box, setting up an official email account, finding an office space, setting up Internet, connecting to power and water, creating vision and mission statements, hiring employees, creating company policies, etc. Then it takes time and investment for the community to get to know you—marketing, advertising, outreach programs, inviting people to visit and giving tours of your office. Forming partnerships with local leaders, government departments, other businesses and community organizations, etc. also takes time. Coming up with the idea is actually the easy part. Even testing, validating, building prototypes, and getting feedback at a research-scale is fairly straightforward. But implementing and scaling up the idea as a real business takes a lot of work. It's exciting, challenging, often rewarding, and you learn a lot, but if you're thinking of starting a social enterprise, first weigh the commitment and cost it takes.

Sales is HARD

Convincing someone to part with their hard-earned money and buy whatever product or service you're offering them amidst a sea of competitors is HARD. (And similarly, education/outreach—convincing people to change their mindsets and modify their behaviors—is HARD.) As an engineer, I thought developing the technology would be the hardest part—once we had a working product, it'd be easy and we'd grow quickly. But actually, sales is the hardest. Sales is easier if you design the product well—if you do the work of getting feedback from potential customers and incorporating their suggestions as you're developing the technology, your final product is designed to better meet their needs and it's easier to convince them to buy it.

I've also seen that people respect your idea and buy into it more if you win awards and competitions and publicize it. Media perception also matters—it's worth investing some money and time in developing a professional, good-looking media presence—but it should still resonate with the local community. Invest money or your own time in developing and maintaining a good website. Write blogs and social media posts. Give interviews. Host community events. Talk on the radio. Sponsor local sports teams. Network at local bars. Hire a PA truck. Create music videos and comedy skits with local groups. Go to schools and talk to students. Invite interns to work with your company. Work with local influencers to promote your products. Be creative in how you share your message, especially to the local community—merge modern marketing with traditional, cultural practices. For example, we built Takataka Plastic's first collection bin in the shape of an elephant because elephants are the traditional cultural symbol of the Acholi people. The community members liked the elephant—it made them smile, and they were encouraged to place their plastic bottles in the elephant to protect their environment rather than throwing the bottles on the ground. Both local and online media is important—local media helps drive sales and community acceptance while our online presence also helps reach an international audience and brings more funding and partnerships.

Partner with local community members If you have an idea and are committed to making it happen, don't implement it alone. Partner with a local community member who is already doing something similar. If they're already working in that space of their accord, especially if they're investing their own time and resources, then they likely have the passion, zeal, and commitment needed to implement and grow a project well. Listen to what they've already done and what their dreams are. Share your ideas and motivation. Discuss and set a shared vision. Then empower, trust, and respect them.

When I was doing my research on plastic waste and started developing ideas that would lay the foundations for what became Takataka Plastics, I met Peter Okwoko. At the time, he was lecturing in IT at Gulu University (I was working with the engineering department) while doing outreach in primary schools and the community around sustainable waste management. He was inspired by his masters study in Denmark—he learned about the circular economy; studied the People, Profits, Plant model for social entrepreneurship; and was impressed with how the Danes managed their waste. When Peter returned to Gulu, he started an organization called AfriGreen Sustain to teach Ugandans about sustainable environmental practices. He went to primary schools and taught students how to make pencil holders from plastic bottles and scraps of kitenge fabric. He funded a couple local innovator friends to do small experiments trying to recycle plastic waste into various products and coordinated a few local conferences/roundtable discussions to push the conversation on environmental issues in Gulu. Peter also had helped co-found a community-based organization called Hashtag Gulu to help the youths who live and work on the streets of Gulu and try to restore the lost trust between them and the community. Peter and I worked together on our research and community-scale recycling projects for a few months and realized we had a lot of the same goals of using waste as a resource to create jobs for vulnerable youth and improve the environment and public health. So we decided to partner together, applied for a grant, won funding, and launched Takataka Plastics.

When you partner with someone, whether it's when drafting official legal documents or simply an implicit understanding between you, realize that the extra 1% in a 51/49 partnership means more than the whole other 50%.

That last 1% determines who gets to make the final decisions. Who holds the power?

When we were starting Takataka Plastics, many people warned us against setting it up as a 50/50 partnership because there's no tie-breaker. The whole company can stop if the founders come to an impasse. Many encouraged me to take the extra 1% because I have to protect and defend my ideas, I'm the engineer, I'm more educated, I can bring more funding and connections, I'm from America, I'm getting a PhD at UC Berkeley, etc. None of these reasons seemed valid to me because ultimately, I will never understand the local community as well as my Ugandan Co-founder. If my desire is truly to make the most impact in the community, then I need to trust my partner's decisions. Holding an extra 1% doesn't convey that level of trust and respect. Peter and I formed Takataka Plastics as a 50/50 partnership.

How foreigners can be helpful

If you're from a developed country, the sad reality of this unjust world we live in is that you have more access to resources and more power than most people in the developing world. People will listen to you more. You're likely better educated. You can apply for more funding opportunities. The communities you can fundraise in have the capacity to give more. Simply because of where you were born and the passport you hold. With a humble attitude, you can use that power and access to also bring opportunities to people in developing countries.

Your role can be to:

- Bring funding. Initially, all of Takataka Plastic's funding came from U.S.-based grants and social entrepreneurship competitions. We've since received some African-focused funding, but there are a lot more funding opportunities in the U.S.

- Build the capacity of the local team. Help the local team get access to equipment, receive training, and advance their education. Give them the resources and skills to do more.

- Ask questions—help the local team think through problems critically and holistically. The Ugandan education system doesn't teach much critical thinking or creative problem solving, so sometimes in my role at Takataka Plastics, I find the most helpful thing I can do is simply to ask questions to help our engineers see the problem in a way they haven't considered it before. I ask questions and make them explain more and more until we get to the root of the problem. Oftentimes, along the way, we uncover a simple solution or a new approach to try. I encourage our staff to search for creative local solutions. Rather than wanting to build pristine-looking, complicated machines they see pictures of online, I push them to think of how can we use cheaper, local materials and simpler processes?

- Make connections and amplify local voices. Introduce your local team to your networks. Use your background to help bring opportunities for them to be heard by a wider audience. If you have an interview opportunity, invite one of the local staff to join you and make sure they have opportunities to speak. Even help the local team apply for fellowships and funding opportunities. Even if they speak good English, oftentimes, many of our staff at Takataka Plastics struggle to write in English since it's not their first language and Uganda is much more of an oral than a written-based culture. Our staff have great ideas and can share them eloquently when speaking, but writing them down and pulling out only the key points to fit in a limited word count answer on an application is difficult. If they haven't had much experience writing applications, especially for Western funding agencies, our staff often don't know what the funders are looking for or how to express their ideas in a way the funders understand. So my role is often to help edit and write succinctly the ideas I've heard our staff say, explain what prompts are looking for, and ask questions to tease out answers in the direction the application wants. (Also, funding agencies should make their application processes more suited to local people by allowing video submissions or interviews/pitches instead of written proposals, reducing the number of questions and making applications shorter, being forgiving with grammar and English mistakes, and investing in an applicant for their character and passion and ability to make things happen even if their ideas are not expressed as well as applicants versed in the terminology and style of the evaluator's educated world would. Currently, local people are excluded from many funding opportunities because they don't write in the way the international funders expect.)

- Translate cultural nuances between the local team and outside partners. When we have a call with our Ugandan staff and international partners, even if everyone on the call speaks English, many times there's still miscommunication and disconnect because of use of different terms; lack of understanding of local culture, context, available materials and resources; and different implicit ways of thinking because of different backgrounds. My role is to translate the differences and help the parties clearly understand each other. Many times they don't even realize that the other party is not understanding what they're meaning. Someone who has lived in and understands both cultures is key to helping international partnerships be effective.

Train the local team, expose them to all kinds of ideas, and let them choose what they think can work in their community, then let them implement it in their own way that will resonate with and work for their people.

However, beware that even if you understand the pitfalls of development and strive to enter into projects with an informed mindset, it's very easy to slip into the traps you knowingly wanted to avoid and end up repeating old development mistakes. Nieusma and Riley [118] brilliantly describe how despite their best intentions, even development practitioners who are aware of past failures and initially commit to approaching projects with a mindset towards long-term viability across socio-cultural, technical, financial, and ecological realms, can easily fail and end up extending social injustices. They outline two case studies where pressures from timelines, funding and academic systems, communication challenges, power relations, deep-rooted beliefs in outsiders as "experts", and traditional, deeply established views regarding the importance and value of technical skills over holistic community development led to the project leaders doing exactly what they initially committed not to do. They ended up focusing on product over process, and success became having something to show instead of building capacity. The projects "worked" if the technical components functioned as the project managers intended, not necessarily that the technology solved the community members' stated need."

It's easy to fall into the traps of the development system. So check yourself often–throughout a project, step back and assess your mindset and the project direction. Don't be afraid to turn down funding, make apologies, and pivot or even stop a project entirely if you realize that it's hurting more than helping the community.

6.6 Conclusion

In conclusion, development is complicated but the mindset with which to approach it is actually quite simple–just *focus on the people.* If you focus on the people you're working with and their needs, all the other aspects of the mindset needed for sustainable development fall into place.

Be humble and respect the community–they have the answers. Weigh your commitment to development work seriously. Don't set false expectations or make promises you won't keep. Understand the power you hold and use it well. Respect, invest in, and build up local community members. Honor and embrace culture. Hold your plans loosely and be flexible. I believe these ideas and mindsets can form the steps to sustainable, more equitable development projects.

If done well, development work is often painful, hard, and thankless. But it's also fulfilling and purposeful because you're directly impact people's lives.

And there is a role for foreigners—working cross-culturally is hard and sometimes it can feel like no one understands you or you don't fit in—but global partnerships are stronger and can reach farther than just local initiatives. But make sure you shine the spotlight on the local team.

Figure 6.2: Proposed Steps for Sustainable Development

Chapter 7

Conclusion

In the next decade, about 165 million tonnes of plastics are expected to reach their end-of-life in African countries. [67] This dissertation has focused on the plastic waste problem in Uganda—a country where 600 tonnes of plastic waste is generated daily [27] [86] and only 6% is collected. [29] The rest is burned, dumped in waterways, and littered in fields and streets with serious negative consequences to the environment and people's health. Sub-Saharan Africa has the worst solid waste management (SWM) of any region in the world [36]. In Uganda, 74% of uncollected waste is burned in open fires [36] releasing lethal carcinogens, toxins, and greenhouse gases not accounted for in global inventories.

Additionally, unemployment is an equally large problem in Uganda. Youth unemployment in Uganda stands between 64-70%. [48] "About 400,000 youths are released annually into the job market to compete for approximately 9,000 available jobs." [48] Uganda has the world's fifth fastest population growth rate, and there are simply not enough jobs. 78% of Ugandans are under the age of thirty. With nothing to fill their time and no money in their pockets, youths can quickly lose self-respect and be drawn into criminal activities. According to the World Bank, 43% of people in Sub-Saharan Africa live in extreme poverty, [139] and the region accounts for two-thirds of the global extreme poor population. While other regions of the world have made significant progress in reducing poverty, the number of people living in extreme poverty in Africa has increased from 284 million in 1990 to 433 million in 2018. [139]In Gulu, the area where my research is focused, the unemployment rate is more than twice the national average, [97] [156] and there are an estimated 600 youths living on the street–some as young as ten years old. [76]

This research analyzed and proposed a solution for Uganda's plastic waste challenge through technical exergy resource analysis, phase change modeling and experiments, and extensive fieldwork leading to the founding of a social enterprise with a local, circular economy solution for Uganda's plastic waste and unemployment challenges. Little comprehensive research exists on the plastic waste problem in developing countries–through a technical, social, and business approach, I attempted to present a holistic analysis.

This research is useful to recyclers in the Global South, policy makers, multilateral organizations, foundations, businesses, and NGOs making decisions about solid waste management practices in less-industrialized nations. The last chapter is also especially relevant to Development Engineering students and practitioners and more broadly to anyone who seeks to work or live in a community with which they are unfamiliar, especially in an under-resourced context.

This dissertation started with a more detailed introduction of the plastic waste problem in Uganda. Drawing from extensive fieldwork, interviews, and desk research, a description of what currently happens to plastic waste in Uganda and some of the stakeholders involved was presented. The large problem of plastic waste was broken down and summarized into 4 core unaddressed issues. Additional background on Uganda's unemployment challenge and an introduction to Development Engineering was also presented.

An Extended Exergy Analysis (EEA) of seven disposal and recycling options for plastic waste in Uganda was conducted to quantify and compare the resource use and environmental impacts of the different processes. Using exergy as a single metric, we were able to compare these very different processes to find the most resource-efficient (including environmental remediation of all pollutatns, by-products, and material inputs.) Some of the processes are currently used in Uganda, while others were proposed as new methods that could be feasible with Uganda's limited infrastructure. We analyzed disposal of waste plastic/sand roof tiles through open burning, burying, landfilling, pyrolyzing, incinerating in cement kilns, mixing into asphalt to pave roads, and recycling into plastic pavers. With a net exergy avoided of 16,462 MJ/tonne of tiles, mixing the waste plastic/sand tiles into asphalt roads proved to be the best option followed by pyrolysis with 11,303 MJ/tonne of net exergy avoided (including remediation). Recycling the tiles into pavers also saved net exergy showing that inputting some energy resources to recycle waste can add value and save net resources. Conversely, burying, landfilling, and incinerating all had negative net exergy values. We determined it is not practically feasible to bring all of the pollutants from open burning to an environmentally acceptable end state with the limited technology available in Uganda. These results are valid for HDPE, LDPE, and PP plastics but not for PET or PVC. For PET plastic waste, the EEA showed that recycling into a new product is the most resource-efficient end-of-life option. Such an empirical resource-use study focusing specifically on plastic products and disposal options feasible in developing countries has not been done before, so our results can be useful to policy makers, multilateral organizations, and NGOs making decisions about solid waste management practices in less-industrialized nations.

Chapter 3 presented an exergy analysis of a manufacturing process of a typical method in Sub-Saharan Africa for recycling plastic waste into new products. The goal was to identify the inefficiencies and suggest potential improvements. A company in Kampala, Uganda that manufactures roof tiles by melting and compressing plastic waste with sand was analyzed as a case study. Using an industrialized extruder and press, they produce recycled plastic/sand roof tiles that look like the clay roofing tiles popular in Sub-Saharan Africa. A summary and analysis of the Ugandan roofing market was also presented to complement the technical exergy analysis. The exergy analysis revealed that potentially recoverable exergy in the production process is 8% of consumed exergy, and the realistically recoverable exergy is 2% of consumed exergy.

Chapter 4 then dove into a fundamental phase change heat transfer analysis of a process commonly used by Ugandan recyclers. After washing the dirty plastic, many recyclers spread the wet plastic on tarpaulins to dry in the sun. We developed a mathematical heat transfer model to predict the drying time for this setup and conducted experiments in Uganda to gather data and tune the model. The model could achieve agreement with experimental data to within 0.5%, but further work is needed to verify the model under varying conditions.

Shifting towards the Development Engineering lens, Chapter 5 presented a description of existing recycling solutions in Uganda and other developing countries, a summary of the gaps they fail to address, and a hypothesis of how to solve the major unresolved issues. Based on this hypothesis of a local, decentralized, holistic approach to recycling, I co-founded a social enterprise called Takataka Plastics in Gulu, Uganda. We developed a process to transform water and soda bottles into durable, beautiful wall tiles making us the only recyclers of PET in Uganda. Through the founding and growth of the social enterprise, I refined and expanded my hypothesis, but so far, it seems very successful at addressing Uganda's plastic waste and unemployment challenges. After being in operation for only two years and a few months and surviving the global COVID-19 pandemic, Takataka Plastics has 33 full-time staff who support on average 5 dependents. We've also created 421 indirect and induced jobs. We've prevented 20 tonnes of plastic waste from entering the environment and kept 46,700 kg of CO_2 from entering the atmosphere. We've reached over 1 million people with our message of recycling and community development and directly engaged more than 50,000 people in our outreach efforts. All of our staff go through trauma counselling and can participate in our company savings group. Street-connected youth have been reunited with their families, the streets are cleaner, and more people can provide for themselves and their families. By transforming waste, we are empowering communities.

Finally, Chapter 6 outlined some lessons for Development Engineers that I have learned through my years of field work and running a social enterprise in Uganda. The lessons can be applied to a wide range of development projects–not just plastic recycling–but they're focused on community-centered development. The theoretical framework is supported by real-life examples from my field work. I propose the *mindset* needed to approach development work, because understanding how to ask questions, what questions to ask, and how to go about answering the questions is the most important, foundational (and often overlooked) part of development. I propose that the steps to sustainable, just development are to enter with humility, build up the local community, respect culture, be flexible, and commit long-term.

In October 2021, the Ellen Macarthur Foundation released a report corroborating the previous hypotheses and conclusions of this research. The report stated that ”the current take-make-waste linear plastics economy” is a serious environmental, socio-economic, and development challenge and that low-income and vulnerable communities often feel the serious negative impacts most heavily. The report concluded, ”a comprehensive circular economy approach to plastics is the only solution that can match the scale of the problem.” [67]

Plastic waste and joblessness are major issues affecting our world. I am grateful to have had this opportunity to pursue a PhD and dedicate my research to helping solve these impactful problems. Much work is still needed–many more careers and much funding will need to be devoted to finding and implementing solutions for these global issues.

And the engineers, business people, policy makers, educators, or whoever is working on the problem, need to be in the community where the project is being implemented. Whether you're working in Uganda, Oakland, Silicon Valley, or anywhere else, you have to be there listening to the people to develop collaborative, sustainable, just, and equitable solutions.

Bibliography

[1] personal interview with S.Otai of Resintile EA Ltd. Kampala, Uganda. 2015.

[2] personal interview with A. Nankabirwa, Limnologist, National Fisheries Resources Research Institute. 6 November 2019. 2019.

[3] interview with Dr. J. Seay, Chemical Engineering, University of Kentucky. 2019.

[4] Conducted interview with E. Bateham of Kijani Forestry on October 21, 2019. 2019.

[5] personal interview with road construction staff 20 February 2020. 2020.

[6] personal interview with Hima Cement employee Caroline 27 July 2020. 2020.

[7] personal interview with R.A. Latong, Supervisor, Latong Sons. 4 March 2020. 2020.

[8] Personal interview with Gulu City Town Clerk, Uganda. 2022.

[9] URL: https://www.ecopost.co.ke/index.php?page=main.

[10] URL: https://www.gjenge.co.ke/.

[11] URL: https://conceptosplasticos.com/.

[12] R. L. Jaén A. M. González and E. E. S. Lora. "Thermodynamic assessment of the integrated gasification-power plant operating in the sawmill industry: An energy and exergy analysis". In: *Renewable Energy* 147.1 (2020), pp. 1151–1163.

[13] H. I. Abdel-Shafy and M. S. Mansour. "A review on polycyclic aromatic hydrocarbons: Source, environmental impact, effect on human health and remediation". In: *Egyptian Journal of Petroleum* 25.1 (2016), pp. 107–123.

[14] United States Environmnetal Protection Agency. *NAAQS Table*. https://www.epa.gov/criteria-air-pollutants/naaqs-table.

[15] United States Environmnetal Protection Agency. *Plastics, WARM Version 13*. https://www.epa.gov/warm/versions-waste-reduction-model-warm#13. 2015.

[16] Laurent Lebreton Anthony Andrady. "Future scenarios of global plastic waste generation and disposal". In: *Palgrave Communications* 5.6 (2019). DOI: https://doi.org/10.1057/s41599-018-0212-7. URL: https://www.nature.com/articles/s41599-018-0212-7#citeas.

[17] Anita Anyango. *Top construction companies in Uganda*. Accessed: 2018-11-28. 2018. URL: https://constructionreviewonline.com/2018/07/top-construction-companies-in-uganda/.

[18] Kampala Capital City Authority. *Project Teaser Kampala Waste Treatment and Disposal PPP*. 2017.

[19] National Environment Management Authority. *National State of the Environment Report 2016/17*. 2017.

[20] Paige Balcom, Juliana Mora Cabrera, and Van P. Carey. "Extended exergy sustainability analysis comparing environmental impacts of disposal methods for waste plastic roof tiles in Uganda". In: *Development Engineering* 6 (2021), p. 100068. ISSN: 2352-7285. DOI: https://doi.org/10.1016/j.deveng.2021.100068. URL: https://www.sciencedirect.com/science/article/pii/S2352728521000105.

[21] Paige Balcom, Juliana Mora Cabrera, and Van P. Carey. "Extended exergy sustainability analysis comparing environmental impacts of disposal methods for waste plastic roof tiles in Uganda". In: *Development Engineering* 6 (2021), p. 100068. DOI: https://doi.org/10.1016/j.deveng.2021.100068. URL: https://www.sciencedirect.com/science/article/pii/S2352728521000105.

[22] World Bank. *Population growth (annual %)*. https://data.worldbank.org/indicator/SP.POP.GROW. Accessed: 2022-05-11. 2021.

[23] A. Bejan. *Convection Heat Transfer*. 4th ed. Hoboken, New Jersey: John Wiley & Sons, Inc., 2013.

[24] R. Berthiaume and C. Bouchard. "Exergy Analysis of the Environmental Impact of Paving Material Manufacture". In: *Transactions of the CSME* 23.18 (1999).

[25] Terrie K. Boguski. *Understanding Units of Measurement*. https://engg.k-state.edu/CHSR/outreach/resources/docs/2UnitsofMeasure022508.pdf. Oct. 2006.

[26] C. Boonekamp. *Discussion of plastic waste in the circular economy*. Personal interview via Skype. C. Boonekamp is an architect and social entrepreneur at Better Future Factory, a company making tiles from plastic waste in Africa. 2018.

[27] Yunus Social Business. *Plastic waste collection and recycling in uganda*. http://www.yunussb.com/blog/plastic-wastecollection. 2017.

[28] F. Bux and Y. Chisti. *Algae Biotechnology Products and Processes*. Springer, 2016.

[29] Planet Buyback. *Plastic Buyback: A Plastic Recycling Plant in Lira, Uganda*. https://www.planetbuyback.com/project/plastic-buyback/.

[30] V. Sata C. Jaturapitakkul K. Kiattikomol and T. Leekeeratikul. "Use of ground coarse fly ash as a replacement of condensed silica fume in producing high-strength concrete". In: *Cement and Concrete Research* 34.4 (2004), pp. 549–555.

[31] Geneva: Care. *Invitation to Innovation Challenge on: Plastic Waste Recycling and Local Manufacturing of Products Made from the Recycled Plastic in Ugandan Refugee Settlement*. 2019.

[32] Health & Justice Center for Environment. *Cement Kilns*. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwjSyuX_zLD3AhWbg4kEHRoQCUAQFnoECAIQAQ&url=http%3A%2F%2Fchej.org%2Fwp-content%2Fuploads%2FCement-Kilns-PUB-0401.pdf&usg=AOvVaw3eEPD1wUid14W9DyvTTUBA. July 2015.

[33] Forest Central Pollution Control Board Ministry of Environment and Government of India Climate Change. *Guidelines for Co-processing of Plastic Waste in Cement Kilns*. 2017.

[34] N. Chatziaras, C. S. Psomopoulos, and N. J. Themelis. "Use of waste derived fuels in cement industry: a review". In: *Management of Environmental Quality* 27.2 (2016), pp. 178–193.

[35] A. J. Chavan. *Use of Plastic Waste in Flexible Pavements*. 2013.

[36] R20 Regions of Climate Action. *Open Burning of Waste: A Global Health Disaster*. 2019.

[37] Harry Cockburn. *India bans imports of waste plastic to tackle environmental crisis*. https://www.independent.co.uk/climate-change/news/india-plastic-waste-ban-recycling-uk-china-a8811696.html. 2019.

[38] R. L. Cornelissen. "Thermodynamics and Sustainable Development; the Use of Exergy Analysis and the Reduction of Irreversibility". MA thesis. Twente University Enschede, Netherlands, 1997.

[39] United States Environmental Protection Agency Center for Corporate Climate Leadership. *Emission Factors for Greenhouse Gas Inventories*. 2018.

[40] A. Corrado, P. Fiorini, and E. Sciubba. "Environmental assessment and extended exergy analysis of a "zero CO2 emission", high-efficiency steam power plant". In: *Energy* 31.15 (2006). ECOS 2004 - 17th International Conference on Efficiency, Costs, Optimization, Simulation, and Environmental Impact of Energy on Process Systems, pp. 3186–3198. ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2006.03.025. URL: https://www.sciencedirect.com/science/article/pii/S0360544206000739.

[41] Kampala City Council. *Environmental Impact Assessment for Proposed Landfill Gas Flaring CDM Project at Mpererwe Landfill Site, Kiteezi*. 2008.

[42] Bonnie Courtemanche and Yiannis A. Levendis. "A laboratory study on the NO, NO2, SO2, CO and CO2 emissions from the combustion of pulverized coal, municipal waste plastics and tires". In: *Fuel* 77.3 (1998), pp. 183–196. ISSN: 0016-2361. DOI: https://doi.org/10.1016/S0016-2361(97)00191-9. URL: https://www.sciencedirect.com/science/article/pii/S0016236197001919.

[43] R. J. Crawford. *Plastics Engineering*. 3rd ed. Butterworth-Heinemann, 1998.

[44] J C Creyts and V P Carey. "Use of extended exergy analysis to evaluate the environmental performance of machining processes". In: *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering* 213.4 (1999), pp. 247–264. DOI: 10.1243/0954408991529861. eprint: https://doi.org/10.1243/0954408991529861. URL: https://doi.org/10.1243/0954408991529861.

[45] R. David. *CRC Handbook of Chemistry and Physics*. 90th ed. Boca Raton, FL: CRC Press, 2009.

[46] Martha Lesniewski David Levine Alice Agogino. *Design for Impact: A Development Engineering Graduate Program at UC Berkeley*. 2015. URL: http://best.berkeley.edu/wp-content/uploads/2015/07/DE_Mudd_v16_AMA.pdf.

[47] B. Davies et al. *DU Social Good Project – Africa Recycling Feasibility*. University of Denver. 2020.

[48] Advocates Coalition for Development and Environment. *Youth Unemployment and Job Creation in Uganda: Opportunities and Challenges*. https://www.acode-u.org/uploadedFiles/infosheet26.pdf. 2014.

[49] J. Dewulf and H. Van Langenhove. "Thermodynamic optimization of the life cycle of plastics by exergy analysis". In: *International Journal of Energy Research* 28.11 (2004), pp. 969–976. DOI: https://doi.org/10.1002/er.1007. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/er.1007. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/er.1007.

[50] J. Dewulf et al. "Illustrations towards quantifying the sustainability of technology". In: *Green Chem.* 2 (3 2000), pp. 108–114. DOI: 10.1039/B000015I. URL: http://dx.doi.org/10.1039/B000015I.

[51] J. Dewulf et al. "Quantification of the impact of the end-of-life scenario on the overall resource consumption for a dwelling house". In: *Resources, Conservation and Recycling* 53.4 (2009), pp. 231–236. ISSN: 0921-3449. DOI: https://doi.org/10.1016/j.resconrec.2008.12.002. URL: https://www.sciencedirect.com/science/article/pii/S0921344908002073.

[52] Jo P. Dewulf and Herman R. Van Langenhove. "Quantitative Assessment of Solid Waste Treatment Systems in the Industrial Ecology Perspective by Exergy Analysis". In: *Environmental Science & Technology* 36.5 (2002). PMID: 11918001, pp. 1130–1135. DOI: 10.1021/es010140o. eprint: https://doi.org/10.1021/es010140o. URL: https://doi.org/10.1021/es010140o.

[53] R. Dincer and M. Rosen. *Exergy: Energy, Environment, and Sustainable Development*. Elsevier, 2007.

[54] Rosen Dincer. *Exergy: Energy, Environmnet, and Sustainable Development*. ISBN: 9780080445298. Elsevier, 2007.

[55] Rachel Dzombak. *Development Engineering: A Critical Overview*. 2017. URL: http://berkeleysciencereview.com/development-engineering-critical-overview/.

[56] Easterly. *The White Man's Burden*. Oxford University Press, 2006.

[57] Easterly. *The White Man's Burden*. London, England: Oxford University Press, 2007.

[58] William Easterly. "Planners versus Searchers in Foreign Aid". In: *Asian Development Review* 23.2 (2006), pp. 1–35.

[59] EIA. *Carbon Dioxide Emissions Coefficients*. https://www.eia.gov/environment/emissions/co2_vol_mass.php. 2016.

[60] EPA. *NAAQS Table*. https://www.epa.gov/criteria-air-pollutants/naaqs-table. N.D.

[61] WHO Regional Office for Europe. "Air Quality Guidelines". In: Second Edition. Copenhagen, Denmark: WHO Regional Office for Europe, 2000. Chap. 5.9.

[62] WHO Regional Office for Europe. "PAHs". In: Copenhagen, Denmark: WHO Regional Office for Europe, 2000. Chap. 5.9, pp. 1–24.

[63] World Health Organization Office for Europe. "Chapter 5.9 Polycyclic aromatic hydrocarbons (PAHs)". In: *Air Quality Guidelines - Second Edition*. WHO Regional Publications, 2000, pp. 1–24.

[64] Export.gov. *Uganda Construction*. Tech. rep. www.export.gov/article?id=Uganda-Construction. Export.gov, 2017.

[65] The World Factbook. *Africa: Uganda*. https://www.cia.gov/library/publications/the-world-factbook/geos/ug.html. Nov. 2019.

[66] S.L. Fávaro et al. "Surface modification of HDPE, PP, and PET films with KMnO4/HCl solutions". In: *Polymer Degradation and Stability* 92.7 (2007), pp. 1219–1226. ISSN: 0141-3910. DOI: https://doi.org/10.1016/j.polymdegradstab.2007.04.005. URL: https://www.sciencedirect.com/science/article/pii/S014139100700136X.

[67] Ellen Macarthur Foundation. *Circular Economy in Africa: Plastics*. https://ellenmacarthurfoundation.org/circular-economy-in-africa-plastics.

[68] D. Selvam G. Pandi S. Raghav and K. Udhaya ku mar. *Utilization of Plastic Waste in Construction of Roads*. 2017.

[69] J. Dewulf G. Van der Vorst and H. Van Langenhove. "Thermodynamics and the destruction of resources". In: ninth Dover printing, tenth GPO printing. Cambridge: Cambridge University Press, 2011. Chap. Developing sustainable technology: metrics from thermodynamics.

[70] National Geographic. *How China's plastic waste ban forced a global recycling reckoning*. https://www.nationalgeographic.com/magazine/article/china-plastic-waste-ban-impacting-countries-worldwide. 2019.

[71] R. Geyer, J. Jambeck, and K. Law. "Production, Use, and Fate of All Plastics Ever Made". In: *Science Advances* 3 (2017).

[72] Google. *Benefits of Experiments*. Accessed: 2018-11-28. ???? URL: https://support.google.com/analytics/answer/1745147?hl=en.

[73] Pierce Gordon et al. *Building 21st Century Skills through Development Engineering*. 2017. URL: http://best.berkeley.edu/wp-content/uploads/2017/09/Harvey-Mudd-Building-21st-Century-Skills-through-Development-Engineering-1.pdf.

[74] C. Grellier. *Turning plastic waste into roofs in Burkina Faso*. Makery. http://www.makery.info/en/2016/11/08/transformer-les-dechets-plastiques-en-toits-au-burkina/ Accessed: 2018-11-28. 2016.

[75] J. T. Gullahorn and J. E. Gullahorn. "An extension of the U-curve hypothesis". In: *Journal of Social Issues* 19.3 (1963), pp. 33–47. DOI: 10.1111/j.1540-4560.1963.tb00447.x.

[76] *Gulu District Task Force Resettles Street Children*. The Independent. https://www.independent.co.ug/gulu-district-task-force-resettles-street-children/.

[77] Dave Hakkens. *Precious Plastics*. https://preciousplastic.com/. Accessed: 2018-11-28. N.D.

[78] *Lifetime Exergy Consumption as a Sustainability Metric for Enterprise Servers*. Vol. ASME 2008 2nd International Conference on Energy Sustainability, Volume 1. Energy Sustainability. Aug. 2008, pp. 35–42. DOI: 10.1115/ES2008-54181. eprint: https://asmedigitalcollection.asme.org/ES/proceedings-pdf/ES2008/43192/35/2685593/35_1.pdf. URL: https://doi.org/10.1115/ES2008-54181.

[79] S. van der Heijden. *Discussion of plastic waste and interventions in low-resource, rural villages of Kenya*. Personal interview via WhatsApp. S. van der Heijden completed his masters dissertation on solutions for plastic waste recycling in rural Kenya. 2018.

[80] Stefan van der Heijden. "Product design for effective development aid". MA thesis. TU Delft, 2018.

[81] M. Igarashi et al. "Pyrolysis of Municipal Solid Waste in Japan". In: *Journal of Energy Resources Technology* 106.3 (Sept. 1984), pp. 377–382. ISSN: 0195-0738. DOI: 10.1115/1.3231068. eprint: https://asmedigitalcollection.asme.org/energyresources/article-pdf/106/3/377/5513188/377_1.pdf. URL: https://doi.org/10.1115/1.3231068.

[82] MTE Consultants Inc. *Results of the Definitive Phase Assessment of the Leaching Potential of a Roofing Product*. 2012.

[83] *Increased roads building pushes up bitumen demand*. Kenya Bitumen. http://kenyabitumen.com/blog/6-from-hole-to-whole-%E2%80%93-why-it%E2%80%99s-smart-to-fix-driveway-potholes-fast Accessed 22 July 2020. 2019.

[84] Sustainable Recycling Industries. *Co-processing of non-recyclable hazardous plastic waste in cement kiln*. 2016.

[85] *Integrated Programme to Improve the Living Conditions in Gulu and Small Towns en Route in the Victoria Nile Catchment (IPILC) – Engineering and Institutional Development Consultancy (EIDC) Services: Solid Waste Management Concept*. Fitchner Water Transportation and GOPA Infra, Gulu, Uganda. 2018.

[86] Care International. *Invitation to Innovation Challenge on: Plastic Waste Recycling and Local Manufacturing of Products Made from the Recycled Plastic in Ugandan Refugee Settlement*. 2019.

[87] A. T. Alemu J. B. Aune and K. P. Gautam. "Carbon Sequestration in Rural Communities". In: *Journal of Sustainable Forestry* 21.1 (2005), pp. 69–79.

[88] H. V. Langenhove J. Dewulf and J. Dirckx. "Exergy analysis in the assessment of the sustainability of waste gas treatment systems". In: *The Science of the Total Environment* 273 (2001), pp. 41–52.

[89] C. Joshi and J. Seay. "An Appropriate Technology Based Solution to Convert Waste Plastic into Fuel Oil in Underdeveloped Regions". In: *Journal of Sustainable Development* 9.4 (2016).

[90] Chandni Joshi and Jeffrey Seay. "Total generation and combustion emissions of plastic derived fuels: A trash to tank approach". In: *Environmental Progress Sustainable Energy* 39 (Jan. 2019). DOI: 10.1002/ep.13151.

[91] S. Kaheru. *Discussion of plastic recycling in Uganda*. Personal interview at Mr. Kaheru's workplace in Kampala. S. Kaheru is Public Affairs Communications Director at Coca-Cola's recycling plant in Uganda. 2018.

[92] E. Kativu. "Carbon Dioxide Absorption Using Fresh Water Algae and Identifying Potential Uses of Algal Biomass". MA thesis. University of the Witwatersrand, 2011.

[93] B. Katwesigye. Personal interview at Ms. Katwesigye's workplace in Kampala. She is founder and CEO of Wazi Industries, a company making compound pavers from plastic waste. 2018.

[94] B. Katwesigye. *Wazi Recycling*. http://wazirecycling.com/ Accessed: 2018-11-28. 2018.

[95] Cheryl Katz. *Piling Up: How China's Ban on Importing Waste Has Stalled Global Recycling*. https://e360.yale.edu/features/piling-up-how-chinas-ban-on-importing-waste-has-stalled-global-recycling. 2019.

[96] Kaza et al. *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*. 2018.

[97] Jessica Kempner. *Youth Unemployment in Uganda Has Been Misdiagnosed*. The Palladium Group. https://thepalladiumgroup.com/news/Youth-Unemployment-in-Uganda-Has-Been-Misdiagnosed-.

[98] Bullock Khanna Palepu. "Winning in Emerging Markets: A Road Map for Strategy and Execution". In: *Harvard Business Review Press* (2010).

[99] Kinobe et al. "Reverse logistics system and recycling potential at a landfill: A case study from Kampala City". In: *Waste Management* 42 (2015).

[100] Allan Komakech et al. "Characterization of municipal waste in Kampala, Uganda". In: *Journal of the Air & Waste Management Association (1995)* 64 (Mar. 2014), pp. 340–8. DOI: 10.1080/10962247.2013.861373.

[101] Charita S. Kwan and Hideshige Takada. "Release of Additives and Monomers from Plastic Wastes". In: *Hazardous Chemicals Associated with Plastics in the Marine Environment*. Ed. by Hideshige Takada and Hrissi K. Karapanagioti. Cham: Springer International Publishing, 2019, pp. 51–70. ISBN: 978-3-319-95568-1. DOI: 10.1007/698_2016_122. URL: https://doi.org/10.1007/698_2016_122.

[102] Yeuh-Hui Lin et al. "Postconsumer Plastic Waste Over Post-Use Cracking Catalysts for Producing Hydrocarbon Fuels". In: *Journal of Energy Resources Technology* 135.1 (Nov. 2012). 011701. ISSN: 0195-0738. DOI: 10.1115/1.4007661. eprint: https://asmedigitalcollection.asme.org/energyresources/article-pdf/135/1/011701/6049661/jert_135_1_011701.pdf. URL: https://doi.org/10.1115/1.4007661.

[103] Hongfang Lu et al. "Emergy synthesis of an agro-forest restoration system in lower subtropical China". In: *Ecological Engineering* 27 (Oct. 2006), pp. 175–192. DOI: 10.1016/j.ecoleng.2005.12.002.

[104] Hongfang Lu et al. "Emergy synthesis of an agro-forest restoration system in lower subtropical China". In: *Ecological Engineering* 27 (Oct. 2006), pp. 175–192. DOI: 10.1016/j.ecoleng.2005.12.002.

[105] Sverre Lysgaard. "Adjustment in a foreign society: Norwegian Fulbright grantees visiting the United States". In: *International Social Science Bulletin* 7.1 (1955), pp. 45–51.

[106] MacGillivray et al. *Measuring Total Employment Effects: a lean data methodology for a portfolio of investments in developing countries*. https://assets.cdcgroup.com/wp-content/uploads/2018/06/25150849/Methodology-for-measuring-total-employment-effects.pdf#page=6&zoom=100,417,121. Accessed: 2022-05-11. 2017.

[107] Aldemar Martínez González, René Lesme Jaén, and Electo Eduardo Silva Lora. "Thermodynamic assessment of the integrated gasification-power plant operating in the sawmill industry: An energy and exergy analysis". In: *Renewable Energy* 147 (2020), pp. 1151–1163. ISSN: 0960-1481. DOI: https://doi.org/10.1016/j.renene.2019.09.045. URL: https://www.sciencedirect.com/science/article/pii/S0960148119313758.

[108] T. McCartney. *Do microplastics from the road get washed off into the environment?*

[109] EWB Carnegie Mellon. *PET Thatch*. http://cmuewb.org/projects#pet. Accessed: 2017-11-15. N.D.

[110] EWB MIT. *Waste plastics recycling needs assessment and more Uganda*. https://d-lab.mit.edu/news/waste-plastics-recycling-needs-assessment-and-more-uganda. Accessed: 2017-11-15. N.D.

[111] Dambisa Moyo. *Dead Aid: Why Aid Is Not Working and How There Is a Better Way for Africa*. New York: Farrar, Straus and Giroux, 2009.

[112] *Mukono Residents Want Garbage Dumping at New KCCA Landfill Halted*. 2021. URL: https://ugandaradionetwork.net/story/mukono-residents-want-dumping-of-garbage-at-new-kcca-landfill-halted-.

[113] M Sebyala Nabukeera, Raja Noriza, and Ali Boerhannoeddin. "Experiences, associated capabilities and responsibilities of Landfill Management in Kampala Capital City authority Uganda". In: (2015).

[114] W. Namakajjo. *Resintile (EA) Ltd.* Product Overview Report. Kampala, Uganda: Resintile (EA) Ltd., Aug. 2018.

[115] D. Nampijja. *Plastic bags in Uganda. A threat to Human Health and the Environment.* Makerere University. http://cees.mak.ac.ug/sites/default/files/Series_Plastic_bags.pdf.

[116] John Ndiso. *Plastic, plastic everywhere but not for African recyclers*. Reuters. 2019.

[117] Forests Philanthropy Action Network. *Terrestrial carbon: emissions, sequestration and storage in tropical Africa.* ://www.forestsnetwork.org/. 2010.

[118] Dean Nieusma and Donna Riley. "Designs on development: engineering, globalization, and social justice, Engineering Studies". In: *Engineering Studies* 2.1 (2010), pp. 29–59. DOI: 10.1080/19378621003604748.

[119] Alexandros K. Nikolaidis and Dimitris S. Achilias. "Thermal Degradation Kinetics and Viscoelastic Behavior of Poly(Methyl Methacrylate)/Organomodified Montmorillonite Nanocomposites Prepared via In Situ Bulk Radical Polymerization". In: *Polymers* 10.5 (2018). ISSN: 2073-4360. DOI: 10.3390/polym10050491. URL: https://www.mdpi.com/2073-4360/10/5/491.

[120] Nkwachukwu et al. "Focus on potential environmental issues on plastic world towards a sustainable plastic recycling in developing countries". In: *International Journal of Industrial Chemistry* 4.34 (2013). DOI: 10.1177/0734242X10390730. URL: https://link.springer.com/article/10.1186/2228-5547-4-34#citeas.

[121] A. O. Ikenna O. I. Nkwachukwu C. H. Chima and L. Albert. "Focus on potential environmental issues on plastic world towards a sustainable plastic recycling in developing countries". In: *International Journal of Industrial Chemistry* 4.34 (2013).

[122] N.T. Kim Oanh. *Monitoring and Inventory of Hazardous Pollutants Emissions from Solid Waste Open Burning*. American Geophysical Union, Fall Meeting 2017. abstract A43A-2418. 2017.

[123] Oehlmann. "A critical analysis of the biological impacts of plasticizers on wildlife". In: *Philosophical Transactions of the Royal Society B: Biological Sciences* (2009). https://doi.org/10.1098/rstb.2008.0242.

[124] P. Okwoko. *We love plastics*. http://www.facebook.com/AfriGreenSustain/videos/307120393307377/.. Jan. 2019.

[125] International Hydropower Organization. *Uganda*. https://www.hydropower.org/country-profiles/uganda. June 2018.

[126] Prosper Achaw Owusu et al. "Reverse engineering of plastic waste into useful fuel products". In: *Journal of Analytical and Applied Pyrolysis* 130 (2018), pp. 285–293. ISSN: 0165-2370. DOI: https://doi.org/10.1016/j.jaap.2017.12.020. URL: http://www.sciencedirect.com/science/article/pii/S0165237017308628.

[127] L. Parker. *A Whopping 91% of Plastic Isnt Recycled*. National Geographic. https://news.nationalgeographic.com/2017/07/plastic-produced-recycling-waste-ocean-trash-debris-environment/. 2017.

[128] R. Pramath. Personal communication via Skype. Mr. Pramath completed his masters dissertation research with Waste for Life, an NGO making roofing tiles from platic waste in Sri Lanka. Waste for Life, 2018.

[129] Manickam Premalatha and Sudharshan K. "Energy Balance and Exergy analysis of large scale algal biomass production". In: Aug. 2012.

[130] Waste Resources Action Programme. *Environmental benefits of Recycling - 2010 Update*. ://wrap.org.uk/resources/report/environmental-benefits-recycling-2010-update.

[131] Hanne Lerche Raadal et al. "Life cycle greenhouse gas (GHG) emissions from the generation of wind and hydro power". In: *Renewable and Sustainable Energy Reviews* 15.7 (2011), pp. 3417–3422. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2011.05.001. URL: http://www.sciencedirect.com/science/article/pii/S1364032111001924.

[132] Wazi Recycling. *Products*. ://www.wazirecycling.com/products/.

[133] Reporter. *Recycling Business to Ease City's Plastic Waste Problem*. New Vision. https://www.newvision.co.ug/new_vision/news/1313667/recycling-business-ease-city-plastic-waste. 2013.

[134] J. L. Richardson and L. T. Jin. "Algal productivity of natural and artificially enriched fresh waters in Malaya". In: *SIL Proceedings* 19.2 (1975), pp. 1383–1389.

[135] M.V. Rocco, E. Colombo, and E. Sciubba. "Advances in exergy analysis: a novel assessment of the Extended Exergy Accounting method". In: *Applied Energy* 113 (2014), pp. 1405–1420. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2013.08.080. URL: https://www.sciencedirect.com/science/article/pii/S0306261913007241.

[136] Agogino Roschuni Kramer. "Design talking: How design practitioners talk About design research methods". In: *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. Vol. 3. ASME, 2015. DOI: 10.1115/DETC2015-47843.

[137] Marc A. Rosen and Ibrahim Dincer. "ON EXERGY AND ENVIRONMENTAL IMPACT". In: *International Journal of Energy Research* 21.7 (1997), pp. 643–654. DOI: https://doi.org/10.1002/(SICI)1099-114X(19970610)21:7⟨643::AID-ER284⟩3.0.CO;2-I. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/%28SICI%291099-114X%2819970610%2921%3A7%3C643%3A%3AAID-ER284%3E3.0.CO%3B2-I. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/%28SICI%291099-114X%2819970610%2921%3A7%3C643%3A%3AAID-ER284%3E3.0.CO%3B2-I.

[138] A. B. Pandit S. B. Jadhao S. G. Shingade and B. R. Bakshi. "Bury, burn, or gasify: assessing municipal solid waste management options in Indian megacities by exergy analysis". In: *Clean Technologies and Environmental Policy* 19 (2017), pp. 1403–1412.

[139] Marta Schoch and Christopher Lakner. *The Number of Poor People Continues to Rise in Sub-Saharan Africa Despite A Slow Decline in the Poverty Rate*. World Bank Blogs. https://blogs.worldbank.org/opendata/number-poor-people-continues-rise-sub-saharan-africa-despite-slow-decline-poverty-rate.

[140] *Exergy as a Direct Measure of Environmental Impact*. Vol. Advanced Energy Systems. ASME International Mechanical Engineering Congress and Exposition. Nov. 1999, pp. 573–581. DOI: 10.1115/IMECE1999-0870. eprint: https://asmedigitalcollection.asme.org/IMECE/proceedings-pdf/IMECE99/16509/573/6815215/573_1_imece1999-0870.pdf. URL: https://doi.org/10.1115/IMECE1999-0870.

[141] S. Selke et al. "Evaluation of Biodegradation-Promoting Additives for Plastics". In: *Environmental Science and Technology* 49.6 (2015), pp. 3769–3777.

[142] P. Singh and V. Sharma. "Integrated Plastic Waste Management: Environmental and Improved Health Approaches". In: *Procedia Environmental Sciences* 35 (2016), pp. 692–700.

[143] Philipp F. Sommerhuber et al. "Life cycle assessment of wood-plastic composites: Analysing alternative materials and identifying an environmental sound end-of-life option". In: *Resources Conservation and Recycling* 117 (2017), pp. 235–248.

[144] Sonntag, Borgnakke, and Van Wylen. *Fundamentals of Thermodynamics*. John Wiley & Sons, Inc., 2003.

[145] R.E. Sonntag, C. Borgnakke, and G.J. Wylen. *Fundamentals of Thermodynamics*. Jan. 2003. ISBN: 978-3-642-02855-7. DOI: 10.1007/978-3-642-02856-4_3.

[146] Uganda Bureau of Statistics. *2019 Statistical Abstract*. 2019.

[147] L. Stougie. "Exergy and Sustainability: Insights into the Value of Exergy Analysis in Sustainability Assessment of Technological Systems". PhD thesis. TU Delft, 2014.

[148] Lydia Stougie et al. "Environmental and exergetic sustainability assessment of power generation from biomass". English. In: *Renewable Energy* 128.Part B (2018), pp. 520–528. ISSN: 0960-1481. DOI: 10.1016/j.renene.2017.06.046.

[149] S. Subramanian. “Plastic roads: India’s radical plan to bury its garbage beneath the streets”. In: *The Guardian* (2016). June 30, 2016.

[150] K. Suresh Kumar Reddy et al. “Thermal Pyrolysis of Polyethylene in Fluidized Beds: Review of the Influence of Process Parameters on Product Distribution”. In: *Journal of Energy Resources Technology* 134.3 (June 2012). 034001. ISSN: 0195-0738. DOI: 10.1115/1.4006790. eprint: https://asmedigitalcollection.asme.org/energyresources/article-pdf/134/3/034001/5888808/034001_1.pdf. URL: https://doi.org/10.1115/1.4006790.

[151] L. D. Suriyani. *Plastic Fantastic? Indonesia plans to turn waste into road tar*. https://news.mongabay.com/2017/08/plastic-fantastic-indonesia-plans-to-turn-waste-into-road-tar/. 2017.

[152] J Szargut, D R Morris, and F R Steward. *Exergy analysis of thermal, chemical, and metallurgical processes*. Hemisphere, Jan. 1987.

[153] J. Theulen. *Cement Kilns: A Ready Made Waste to Energy Solution?* Waste Management World. https://waste-management-world.com/a/cement-kilns-a-ready-made-waste-to-energy-solution. 2015.

[154] J. Theulen. “Cement Kilns: A Ready Made Waste to Energy Solution?” In: *Waste Management World* (2015).

[155] Grant Thornton. *Economic Overview – 2019, Economic Outlook - 2020*. 2019.

[156] UBOS. *The Uganda National Household Survey 2016/17*. Tech. rep. www.ubos.org/onlinefiles/uploads/ubos/pdf%20documents/2017_UNHS_26092017-Final_Presentation.pdf. Uganda Burea of Statistics, 2017.

[157] National Planning Authority of Uganda. *Third National Development Plan (NDPIII) 2020/21-2024/25*. 2020.

[158] A. Valavanidis et al. “Persistent free radicals, heavy metals and PAHs generated in particulate soot emissions and residue ash from controlled combustion of common types of plastic”. In: *Journal of Hazardous Materials* 156.1-3 (2008), pp. 277–284.

[159] Athanasios Valavanidis et al. “Persistent free radicals, heavy metals and PAHs generated in particulate soot emissions and residue ash from controlled combustion of common types of plastic”. In: *Journal of Hazardous Materials* 156.1 (2008), pp. 277–284. ISSN: 0304-3894. DOI: https://doi.org/10.1016/j.jhazmat.2007.12.019. URL: https://www.sciencedirect.com/science/article/pii/S0304389407017694.

[160] R. Vasudevan et al. “A technique to dispose waste plastics in an ecofriendly way – Application in construction of flexible pavements”. In: *Construction and Building Materials* 28 (2012), pp. 311–320.

[161] G. Wall. “Exergy - A Useful Concept”. http://exergy.se/goran/thesis/. PhD Thesis. Göteborg, Sweden: Chalmers University of Technology, 1986.

[162] Göran Wall. "Exergy conversion in the Japanese society". In: *Energy* 15.5 (1990), pp. 435–444. ISSN: 0360-5442. DOI: https://doi.org/10.1016/0360-5442(90)90040-9. URL: http://www.sciencedirect.com/science/article/pii/0360544290900409.

[163] Göran Wall, Enrico Sciubba, and Vincenzo Naso. "Exergy use in the Italian society". In: *Energy* 19.12 (1994), pp. 1267–1274. ISSN: 0360-5442. DOI: https://doi.org/10.1016/0360-5442(94)90030-2. URL: http://www.sciencedirect.com/science/article/pii/0360544294900302.

[164] WaterAid. *Solid Waste Management Arrangements and its Challenges in Kampala: A case Study of Bwaise II Parish, Kawempe Division*. 2011.

[165] Ceramic World Web. *Africa's Development Drives the Ceramic Market*. 2019.

[166] M. Forter Weber A. Watson and F. Oliaei. "Review Article: Persistent organic pollutants and landfills - a review of past experiences and future challenges". In: *Waste Management Research* 29.1 (2011), pp. 107–121.

[167] Weber et al. "Persistent organic pollutants and landfills - a review of past experiences and future challenges". In: *Waste Management Research* 29.1 (2011), pp. 107–121. DOI: 10.1177/0734242X10390730. URL: https://journals.sagepub.com/doi/10.1177/0734242X10390730.

[168] Wiedinmyer, Yokelson, and Gullett. "Global Emissions of Trace Gases, Particulate Matter, and Hazardous Air Pollutants from Open Burning of Domestic Waste". In: *Environmental Science and Technology* (2014).

[169] M. Workman et al. "An Assessment of Options for CO2 Removal from the Atmosphere". In: *Energy Procedia* 4 (2011), pp. 2877–2884.

[170] C. L. Yaws. *Yaws' Critical Property Data for Chemical Engineers and Chemists*. Knovel. https://app.knovel.com/hotlink/toc/id:kpYCPDCECD/yaws-critical-property/yaws-critical-property. 2012; 2013; 2014.

[171] Chuanbin Zhou et al. "Exergetic assessment of municipal solid waste management system in south Beijing". In: *Ecological Complexity - ECOL COMPLEX* 8 (June 2011), pp. 171–176. DOI: 10.1016/j.ecocom.2011.01.006.