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# EXERGY-BASED SUSTAINABILITY ANALYSIS FOR TILE PRODUCTION FROM WASTE PLASTICS IN UGANDA

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## ABSTRACT

*This paper presents an exergy-based sustainability analysis of manufacturing roof tiles from plastic waste in Uganda. Exergy analyses measure the sustainability of industrial processes. This work focuses specifically on the developing country context and on utilizing waste material. A summary of the current plastic waste situation in Uganda, the environmental and health issues associated with plastic waste, current means of recycling plastic waste into new products, and an analysis of the Ugandan roofing market are presented. The motivation for this study is to examine the resources utilized to improve overall exergy efficiency, reduce production costs, and reduce negative environmental impacts. The company, Resintile, is the only manufacturer of roof tiles from plastic waste in Uganda. Their tiles comprised mainly of sand and plastic waste are manufactured in an industrialized process involving drying, extrusion, and pressing. The exergy consumed at each stage including transportation is presented. The extruder consumes the majority of the exergy, but wrapping insulation around the barrel could save over 3 MJ, and a heat engine could provide over 7.5 MJ of usable exergy. The total exergy consumed to produce one batch of seventy-five tiles is over 122 MJ, the potentially recoverable exergy is over 5 MJ (4.3% of consumed exergy), and the realistic recoverable exergy is nearly 10.7 MJ (8.7% of consumed exergy). The realistic can be greater than the potential by adding a heat engine to the sand drying process to generate usable exergy rather than merely recover consumed exergy. Resintile's plastic roof tiles save a net 86.3 kg of $CO_2$ from entering the atmosphere per batch of tiles and adoption of the suggested improvements to the manufacturing process would save an additional 3.8 kg of $CO_2$ per batch.*

## NOMENCLATURE

| | |
|---|---|
| $A$ | Surface area of extruder |
| $c$ | Specific heat |
| $CO_2$ | Carbon dioxide |
| $d$ | Distance traveled |
| $\varepsilon$ | Specific chemical exergy |
| $\eta$ | Power factor |
| $Ex_o$ | Chemical exergy |
| $Ex_{elec}$ | Exergy of electricity |
| $Ex_{evap}$ | Exergy for vaporization |
| $Ex_{kin}$ | Kinetic energy exergy |
| $Ex_{non-flow}$ | Total exergy of closed system |
| $Ex_{ph}$ | Physical exergy |
| $ex_{ph}$ | Specific physical exergy |
| $Ex_{pot}$ | Potential energy exergy |
| $Ex_{transport}$ | Exergy for transportation |
| $\gamma$ | Exergy factor of fuel |
| $h$ | Convection coefficient |
| HDPE | High-density polyethylene |
| $h_{lv}$ | Latent heat of vaporization |
| KCCA | Kampala City Council Authority |
| $KE$ | Kinetic energy |
| $k$ | Thermal conductivity |
| LDPE | Low-density polyethylene |
| $LHV$ | Lower Heating Value |
| $MC$ | Moisture content |
| $\mu_{io}$ | Chemical potential |
| $\mu_{ioo}$ | Chemical potential at ground state |
| $m_w$ | Mass of water |
| $M_w$ | Mass of wet sample |

| | |
|---|---|
| $M_w$ | Mass of dry sample |
| NGO | Non-governmental organization |
| $N_i$ | Particle Number of species i |
| $P$ | Rated machine power |
| $PE$ | Potential energy |
| $P_o$ | Pressure at ground state |
| PP | Polypropylene |
| $Q_{evap}$ | Latent Energy |
| $r_1$ | Radius of extruder barrel |
| $r_2$ | Outer radius of insulation |
| $R_{cond}$ | Conduction resistor |
| $R_{conv}$ | Convection resistor |
| $\rho$ | Density of fuel |
| $S$ | Entropy |
| $S_o$ | Entropy at ground state |
| $t$ | Operation time |
| $T$ | Temperature (in K) |
| $T_o$ | Ground state temperature (in K) |
| $TECO^2$ | Roofing ECOlogic and ECOnomics |
| $U$ | Internal energy |
| $U_o$ | Internal energy at ground state |
| $V$ | Volume |
| $V_o$ | Volume at ground state |
| $\xi$ | Fuel efficiency of vehicle |

## INTRODUCTION

### Motivation

In the last 6 decades, 8.3 billion metric tons of plastic were produced worldwide, equivalent in weight to 55 million jumbo jets [1]. Only 9% was recycled [2]. The issue of plastic waste is especially severe in developing countries where plastic waste poses environmental and health risks. For example, the capital city of Uganda generates approximately 180 tons of plastic waste daily, [3] and only 40-50% of the city's waste is collected [4, 5]. The remaining waste lays on roadsides, blocking drains and creating stagnant water that breeds malaria-bearing mosquitoes or is piled into heaps and burned, releasing lethal carcinogens. [6, 7] 40% of the world's garbage is burned in open piles releasing greenhouse gases and other pollutants unaccounted for in most global inventories. [8] Many landfills in Uganda are unlined and the contents are often burned to make room for new waste, so even plastic that reaches landfills is burned or leaches into the soil affecting groundwater. Waste plastic also negatively affects agriculture on which most of the developing world depends. In Uganda, 84% of the population lives in rural areas and relies on subsistence agriculture. [9] When exposed to rain and sun or even when dumped in un-lined landfills common in Africa, plastic bags can leach toxins into the soil and negatively affect crops and ground water. [10] Additionally, 60% of stray cattle in Uganda die from consumption of polythene bags. [6] The plastic that makes it to Kampala recycling plants is chopped into flakes or pellets and mainly sold to Asia. This inefficient international transportation emits significant amounts of greenhouse gases.

Recycling by making products from plastic waste locally reduces the environmental issues described above, generates environmental and community health benefits, creates local jobs, and closes a loop in the circular economy.

### Prior Studies of Waste Plastic Use

Uganda generates approximately 600 tons of plastic waste daily. [11] Plastic bottles and bags are the most common type of plastic waste and they are generally thrown anyhwere after use. [5] In cities and large towns, the municipality ususally hires street cleaners to sweep the streets and dump the waste in large skips which are transported by truck to a dumpsite. At the dumpsite, the waste is eventually buried or burned to create new space in the landfill and to combat flies. [12] Some businesses hire private waste companies to clean and transport their waste to the landfill, but in some cities, these companies are technically illegal since all waste is supposed to be managed by the municipality. The private companies are generally less expensive than the town pickup, so businesses still engage them.

Plastic that is collected is brought to offical landfills or dumpsites. In Kampala, the capital city, Kiteezi landfill is the only officially recognized landfill. Opened in 1996, it is located 12 km north of the city. 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. [3]

In private homes, many individuals dispose of their own waste by burning. For 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 kids pick up 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.

Kampala has 40-50 plastic recycling plants [13], but many are not profitable. [14] People who bring the plastics receive a few hundred shillings per kilogram depending on the type of plastic. Industries send their plastic waste directly to the recycling plants. At the plants, the plastic waste is sorted by type, cleaned, shredded, and packaged. Most of it is shipped to Asia. [14]

A recent partnership between Coca-Cola and the Kampala City Council Authority (KCCA) sets up community collection centers throughout Kampala. 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 to the Coca-Cola recycling plant. [14]

### Products Made From Plastic Waste

A range of organizations make products from recycled plastics in Africa. They can be categorized into four types:

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

Resintile in Uganda produces roofing tiles from waste plastic using industrial machinery requiring approximately 100,000 USD in startup costs. They employ 5 managers, 2 assistants, and 16 shift workers and sell between 90,000-120,000 tiles per year. Other industrial companies in Kenya produce roof tiles and fence posts from recycled plastic.

**FIGURE 1**. Resintile Roof Tiles *Provided by Resintile [15], used with permission

A startup in Burkina Faso, called TECO$^2$ (Roofing ECOlogic and ECOnomics) is creating thin roof tiles from used LDPE (Low-density polyethylene) bags. They are working with labs in France to develop a process that fuses the plastic to reduce the release of fumes compared to burning. [16] In Uganda, Wazi Recycling is starting to make paving tiles from plastic waste in Kampala. Pavers are shaped bricks used for covering compounds in Uganda. Although Wazi Recycling is still developing their process, their prototypes are cheaper to produce and stronger than conventional cement pavers, and they have already received many orders. [17] They plan to eventually expand into also producing interlocking building bricks and foundation blocks and slabs. [18]

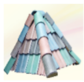
NGOs often use simple technology, more fitting to rural areas, and offer educational programs to teach communities about recycling. But NGOs struggle to scale. Their techniques are often open-source, but without high revenue streams, it is difficult to move beyond a few communities where they have local partnerships. For example, WasteAid UK is working in the Gambia to make paving tiles 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, but their process to melt the plastic can be hazardous to workers' health and the environment. 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 periodically 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.

An example of an academic project is Reddy Pramath, a masters student of materials science, who partnered with Waste for Life, an NGO in Sri Lanka to develop a composite roof made from waste HDPE (high-density polyethylene) plastic reinforced with rice husks and banana fibres. While the product is aesthetically pleasing and of high quality, manufacturing it is a multistep, time-consuming process. [19] 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. 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. [20] [12]

### 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 10% annually for the next several years. "Uganda faces an 8 million unit housing shortage," so "commercial...and residential construction in Uganda are booming." [21]

Figure 2 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. Because of their pricing, Resintile tiles fall in the same customer bracket as clay tiles, but the Resintile product is cheaper and resistant to fungus growth. For a 250 sq m house, Resintile tiles are 7.3% cheaper than clay tiles when considering cost of tiles

| 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^3$) | 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 2**. Comparison of Roofing Options in Uganda

and timber supports.

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%. [22] The other category includes clay tiles, concrete tiles, asbestos, and tin, so Resintile could potentially capture up to 1% of the Ugandan roofing market (75,400 roofs).

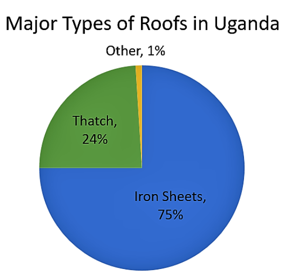



**FIGURE 3**. Percent of Ugandan Roof Types

### Scope of This Work

The scope of this work 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 identifies means to improve the efficiency thereby increasing sustainability and reducing operational costs. The exergy consumption study is supported by an overview of the current plastic waste situation in Uganda because recycling plastic into roofing tiles helps alleviate a host of environmental issues caused by littering and burning waste plastic. Resintile must be able to sell their roofing tiles to continue positively impacting environmental sustainability, so a market assessment of Ugandan roofs is also included. Selling more roof tiles equates to diverting more waste plastic from causing environmental harm.

## CURRENT EFFORTS TO USE WASTE PLASTIC IN UGANDA

An exergy analysis of a company in Uganda that manufactures roof tiles from plastic waste was conducted to understand its overall contribution to recycling sustainability. The company, called 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. The Resintile founders learned the process and technology from a company in South Africa who first learned it from factories in Europe. This exergy analysis of the Resintile fabrication process evaluated the energy and resources used to manufacture plastic roofing tiles with the hopes of improving efficiency, reducing operational energy costs, and understanding the 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 Figure 4. In the first step, moisture must be removed from the sand. This is normally done outside with solar energy, but if it is cloudy or raining (as in during rainy season), the sand must be dried inside the factory with a machine. 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, and fuses all the inputs into a hot putty. A specified mass of this putty is weighed, placed in a mold, and pressed to form a roof tile. It is removed from the mold, dipped in water, and laid under a weight to cool.

## EXERGY ANALYSIS FRAMEWORK

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 used in the whole process with regards to the environment. When analyzing a manufacturing process or plant, the 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 en-

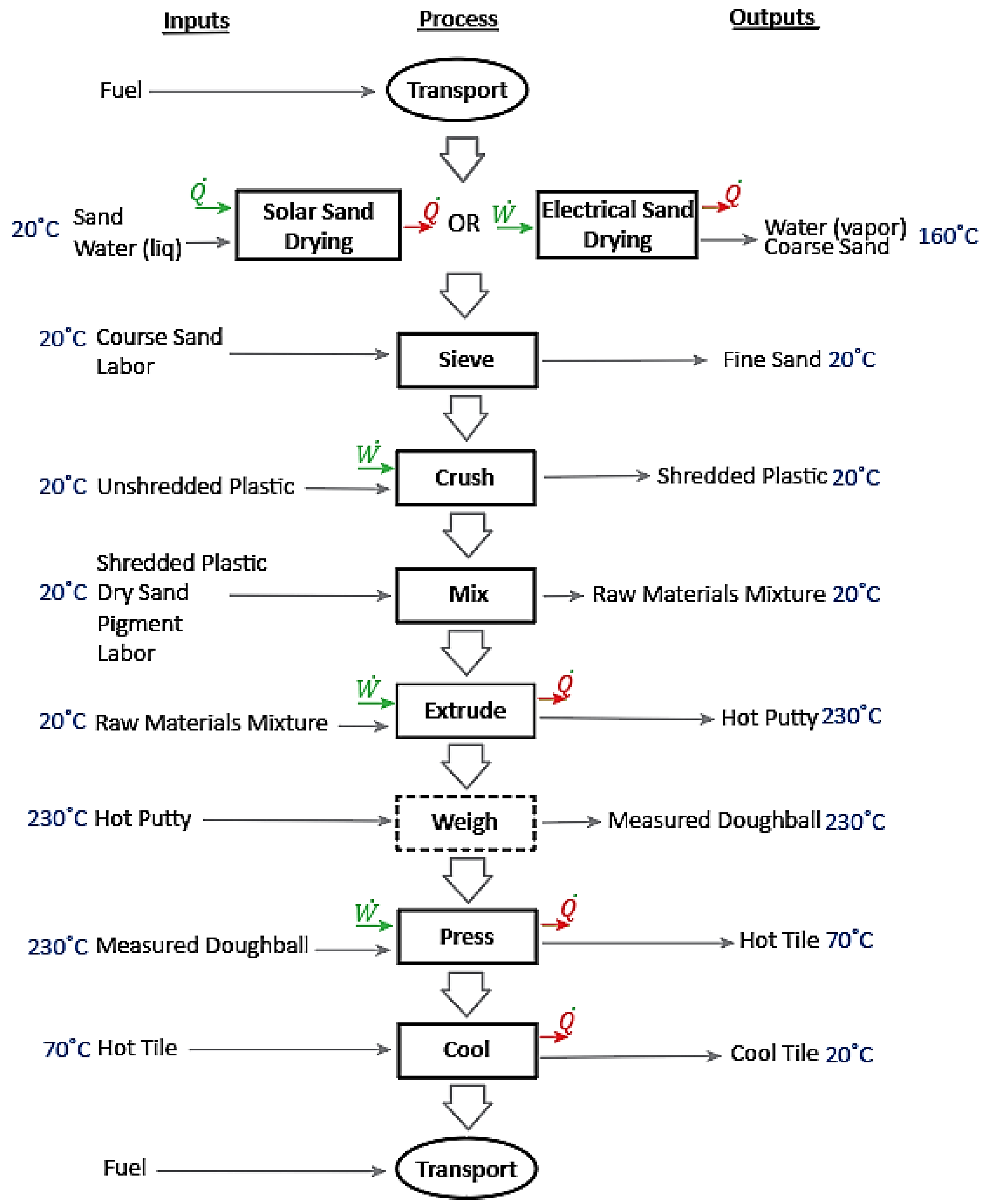



**FIGURE 4**. Resintile Process Flow Diagram

gineers identify the amount, type, location, and causes of losses in a system to help identify means of improvements. [23]

For this exergy analysis of the Resintile manufacturing process, the environment or the ground state was defined as standard atmospheric pressure and 20°C (the average temperature inside the manufacturing room). The value of the thermal material properties and their sources used in this analysis are listed in Appendix A. 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 consumed by the machines, their power ratings were utilized. Electrical energy is equal to exergy, so the electricity used by machines in the manufacturing process can be converted to electrical energy (and exergy) using Eqn. 1.

$$Ex_{elec} = E_P = \eta E_R = \eta Pt \qquad (1)$$

**FIGURE 5**. Photo of Tile Forming Press used at Resintile

where $P$ is the rated power of the machine in $kW$, $t$ is the time of operation in $s$, and $\eta$ is the power factor, which can be taken as 80%. [24]

**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 latent heating as it transforms from liquid water to water vapor. The sensible heat of the sand was calculated using Eqn. 11, and the energy required to evaporate the water was found using Eqn. 2 [23].

$$Q_{evap} = m_w * h_{lv} \tag{2}$$

where $h_{lv}$ is the latent heat of vaporization of water and $m_w$ is the mass of the water which was calculated from the moisture content

$$MC(\%) = \frac{M_w - M_d}{M_d} * 100\% \tag{3}$$

where $M_w$ is the mass of the wet sample and $M_d$ is the mass of the dry sample.
To calculate the exergy from the energy of vaporization, the carnot efficiency was used.

$$Ex_{evap} = \left[1 - \frac{T_o}{T}\right] Q_{evap} \tag{4}$$

**Transportation.** When analyzing exergy of a process, the transportation of materials and end products should also be considered. The specific chemical exergy for fuel is given by

$$\varepsilon = \gamma LHV \tag{5}$$

where $\gamma$ is the exergy factor of a fuel and $LHV$ is the lower heating value. For diesel, Kotas gives $\gamma = 1.07$ and $LHV = 42.652$. To convert specific exergy to exergy, the density of the fuel and fuel efficiency of the vehicle were used to convert to exergy per km, which was multiplied by the distance vehicles traveled.

$$Ex_{transport} = \varepsilon \, \rho \, \xi \, \frac{0.001 m^3}{1L} d \tag{6}$$

where $\rho$ is the density of the fuel, $d$ is the distance traveled in km and $\xi$ is the fuel efficiency of the vehicle in $\frac{L}{km}$. A value for $\xi$ of 0.29 for heavy duty diesel vehicles was used from a 2015 Makerere University report. [25]

### Potentially Recoverable Exergy.

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

$$Ex_{non-flow} = Ex_{ph} + Ex_o + Ex_{kin} + Ex_{pot} \tag{7}$$

where

$$Ex_{pot} = PE \tag{8}$$

$$Ex_{kin} = KE \tag{9}$$

$$Ex_o = \sum_i (\mu_{io} - \mu_{ioo}) N_i \tag{10}$$

$$Ex_{non-flow,ph} = (U - U_o) + P_o(V - V_o) - T_o(S - S_o) \tag{11}$$

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

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, Eqn. 11 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, Eqn. 11 can be simplified as

$$ex_{non-flow,ph} = c(T - T_o - T_o * ln\left(\frac{T}{T_o}\right)) \qquad (12)$$

because the change in internal energy and entropy can be written using the specific heat of the material and various relationships of temperature [26]. This is specific exergy given in a per mass basis (kJ/kg). Since the specific heat is a material property, the $Ex_{non-flow,ph}$ for each individual input material was calculated at each stage in the process then multiplied by the mass of that material needed to make one batch of 75 tiles. For each stage, the exergy of each input was summed to give the total potential exergy recoverable at each stage of the process.

## Practically Recoverable Exergy

However, all of this exergy cannot realistically be recovered in the real world. To capture and use this potentially recoverable exergy, we wanted to make the process more reversible and adopt changes to improve the efficiency of energy use. Our analysis included looking at insulating the extruder barrel and using a heat engine in the heat input process. These two recommendations are described below.

**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 $1/(hA)$ where $A$ represents the surface area of the extruder barrel. The heat loss, Q was calculated as $Q = (T_{extruder} - T_{ambient})/R_{conv}$. This Q was compared to the heat loss calculated when a conduction resistor ($R_{cond} = ln(r_2/r_1)/(2\pi Lk)$) representing the insulation was added in series with the convection resistor. The thickness of the insulation is $r_2 - r_1$ and $k$ is its thermal conductivity (0.033 W/m K).

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 preheat 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 under 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. In the ideal case, Eqn. 4 was used with $T$ equal to the maximum operating temperature of carbon steel (500°C) [27]. The realistic scenario was calculated by multiplying by an efficiency factor, $\eta$, 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. [26]

## $CO_2$ Emissions.

To quantify the sustainability impact of the Resintile process, we wanted to calculate the amount of $CO_2$ emissions saved. The exergy consumed or saved was converted to heat by dividing by the carnot efficiency. It was assumed this heat would be supplied by a diesel generator or power plant, and a conversion factor of 73.16 kg of $CO_2$ per million btu of natural gas given by the U.S. Energy Administration [28] was used to convert to kg of $CO_2$. 80-90% of Uganda's electricity is generated by hydropower, but the remainder is supplied by diesel or oil thermal plants. Additionally, when power goes off, Resintile uses a diesel generator. If the electricity supplied to Resintile is not generated by diesel, these results would be altered, but they provide a reasonable benchmark.

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. Stoichiometry was used to convert kg of polyethylene and polypropylene to kg of $CO_2$ in complete combustion. However, most waste plastic in Uganda is burned in open piles which experiences incomplete combustion. The stoichiometric values of $CO_2$ released were multiplied by an oxidation factor of 85% as given in an International Panel on Climate Change report. [29]

## RESULTS OF EXERGY ANALYSIS

The purpose of the exergy analysis was to identify areas in the process where destroyed exergy can be repurposed to useful exergy. Tables 1 and 2 and Figure 6 display the results of this exergy analysis. All numbers were calculated for a batch of 75 tiles.

For drying sand, the electric dryer requires 23.5 kW while the solar sand drying process was calculated to be 1.7 kW.

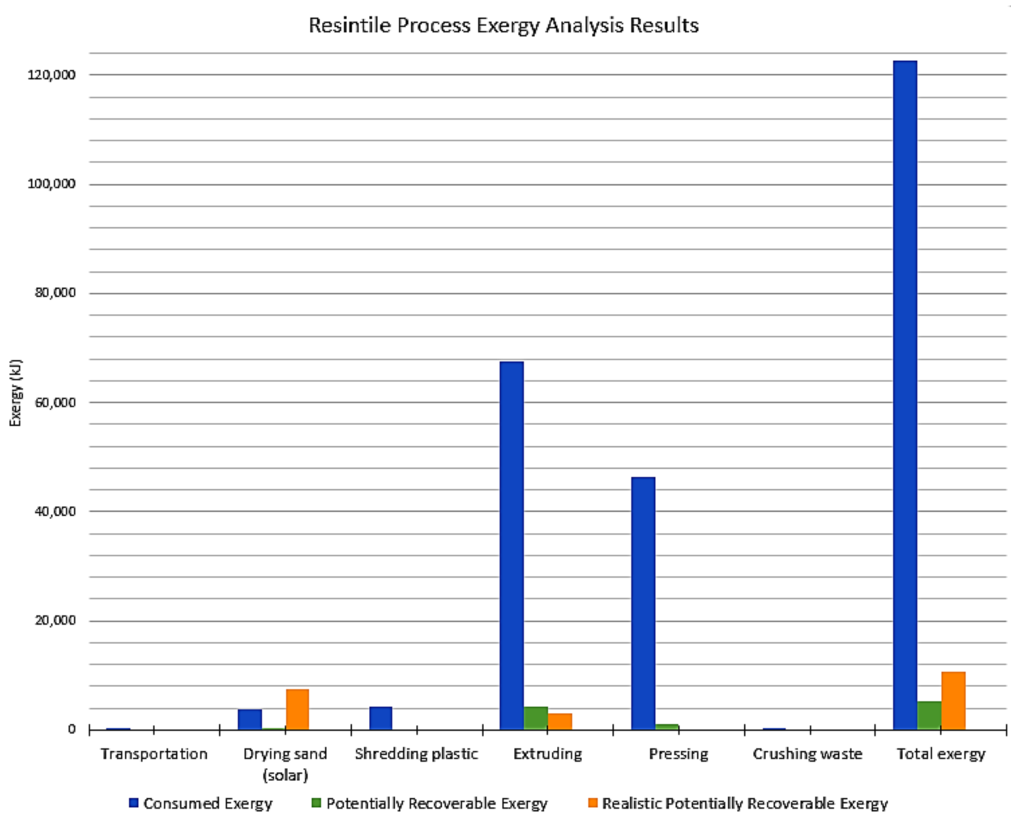



**FIGURE 6**. Resintile Process Exergy Analysis Results

**TABLE 1**. Resintile Process Exergy Analysis Results

| Exergy Consumed (kJ) | Process | Exergy Potential for Recovery (kJ) |
|---|---|---|
| 29.5 | Transportation | 0 |
| 3,805.0 | Drying Sand (Solar) | 29.46 |
| 4,262.4 | Crushing Plastic | 0 |
| 67,680.0 | Extruding | 4,217.5 |
| 46,500.0 | Pressing | 1,048.5 |
| 402.9 | Crushing Waste | 0 |
| **122,680** | **Totals** | **5,295.4** |

For melting and fusing the plastics together with the sand, the extruder exit temperature is set to 230 °C. This is hotter than the melting temperatures of the plastics (110, 135, 165 °C) 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 °C. 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.

To produce a batch of 75 tiles, the Resintile process consumes over 122.6 MJ of exergy. Over 5 MJ (4%) is potentially recoverable. To recover the most amount of exergy, we focused

**TABLE 2.** Resintile Transportation Exergy Analysis Results

| Material | Distance (km) | Exergy Consumed (kJ) |
|---|---|---|
| **Inputs** | | |
| Sand | 140 | 22.05 |
| Plastic | 14 | 0.63 |
| **Outputs** | | |
| Tiles | 35 | 6.79 |
| **Total** | | **29.47** |

on the largest exergy sink–the extruder. Table 3 shows how wrapping the extruder barrel in insulation could recover over 3 MJ of exergy from the plastic melting process and reduce the heat loss by 387% compared to the scenario of an extruder barrel exposed to natural convection.

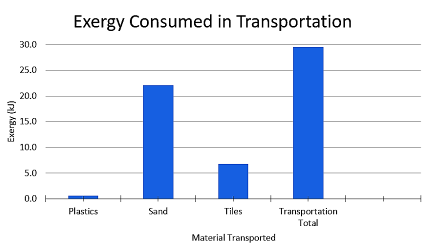



**FIGURE 7.** Resintile Transportation Exergy Analysis Results

**TABLE 3.** Exergy Recovered Through Insulating Extruder Barrel

| | |
|---|---|
| Exergy lost w/o insulation (kJ) | 4,217.5 |
| Exergy lost w/ insulation (kJ) | 1,089.5 |
| Exergy saved (kJ) | 3,128.0 |
| Improvement | 387% |

Another way to recover exergy is by adding a heat engine where the sand is dried by the sun outside. Table 3 shows that if the same amount of solar energy currently used to dry the sand was instead applied to a heat engine, approximately 7.5 MJ of exergy could realistically be used. This is 6% of the total exergy consumed in the production process and could be used to dry the sand or power some of the machines for free.

**TABLE 4.** Solar Exergy

| Solar Usage | Efficiency | Exergy (kJ) |
|---|---|---|
| Current | 4.82% | 3,805.0 |
| Ideal Heat Engine | 15.89% | 12,549.0 |
| Realistic Heat Engine | 9.54% | 7,529.4 |

If both the heat engine and insulation around the extruder barrel were added, nearly 10.7 MJ of exergy could realistically be recovered, which is 8.7% of the exergy consumed. This exergy saved amounts to 3.8 kg of $CO_2$ saved from entering the atmosphere for each batch of tiles if the electricity was produced using diesel. If all of Kampala's plastic waste (180 tons/day) was recycled into roofing tiles, the suggested improvements alone would save over 11,400 kg of $CO_2$ from entering the atmosphere. It is reasonable to consider turning all of Kampala's plastic into roofing tiles because if Resintile captured 1% of Uganda's roofing market, they would need 135,720 tonnes of plastic or 754 days worth of Kampala's plastic.

Additionally, recycling plastic into roofing tiles prevents the open burning of plastic. Each batch of tiles utilizes 40 kg of plastic, which if burned, releases 106.7 kg of $CO_2$. If all of Kampala's plastic waste was made into roofing tiles, it would prevent over 320 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.) Table 5 summarizes the results of Resintile's contribution to reducing $CO_2$ emissions.

## CONCLUDING REMARKS

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) since 21.4% of Ugandans live in poverty [22]. 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

**TABLE 5**. Overall Impact on $CO_2$ Emissions

| | **One batch of tiles** | **All of Kampala's plastic waste** |
|---|---|---|
| Kg $CO_2$ to produce tiles | 20.4 | 61,099.2 |
| Kg $CO_2$ released from burning | 106.7 | 320,035.2 |
| Net kg $CO_2$ saved | 86.3 | 258,936.0 |
| Kg $CO_2$ saved with recommendations | 3.8 | 11,427.2 |
| **Net kg $CO_2$ saved with recommendations** | **90.1** | **270,363.1** |

offers intense solar energy, which if utilized can reduce electricity costs.

Uganda's 600 tons of plastic waste produced daily [11] poses significant environmental and health issues because much of the plastic is burned, blocks drains, leaches into soil and groundwater, disrupts crops and animals, or lies scattered as litter. Waste pickers collect some of the plastic and bring it to recycling plants where it is shredded and usually exported. A few local Ugandan companies and NGOs recycle the waste plastic into roofing tiles, pavers, wastebins, or artwork.

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 nearly 122.7 MJ of exergy. The potentially recoverable exergy is over 5 MJ (4.3% of consumed exergy), and the realistic recoverable exergy is 10.7 MJ (8.7% of consumed exergy). The realistic can be greater than the potential by adding a heat engine to the solar sand drying process to generate usable exergy rather than merely recover consumed exergy. For each batch of tiles, recycling plastic into roofing tiles prevents 106.7 kg of $CO_2$ from entering the atmosphere from burning plastic, and adopting the suggested improvements to the Resintile process reduces $CO_2$ emissions by an additional 3.8 kg. If all of Kampala's plastic waste was converted to roofing tiles and the suggested improvements to the manufacturing process were made, Resintile would save over 270 tons of $CO_2$ from entering the atmosphere.

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## Appendix A: Properties

**TABLE 6**. Thermal Material Properties

| | **HDPE** | **LDPE** | **PP** | **Sand (silicone dioxide)** | **Iron oxide** |
|---|---|---|---|---|---|
| **Specific Heat (kJ/kg K)** | 1.237 [30] | 1.237 [30] | 2.350 [31] | 0.739 [32] | 0.650 [33] |
| **Melting Temperature (°C)** | 135 [32] | 110 [32] | 165 [32] | | |

**TABLE 7**. Exergy Analysis Related Data for Fuel *from Kotas [34]

| **Fuel** | **LHV (kJ/kg)** | **Exergy Factor** |
|---|---|---|
| Diesel | 42.652 | 1.070 |