

Exergy-Based Sustainability Analysis for Tile Production From Waste Plastics in Uganda

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This paper presents an exergy-based sustainability analysis of manufacturing roof tiles from plastic waste in Uganda. This work focuses specifically on the developing country context and on utilizing waste material. A summary of the current Ugandan plastic waste situation, 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 is presented. The total exergy consumed to produce one batch of 75 tiles is over 240 MJ, the potentially recoverable exergy is nearly 17 MJ (8% of consumed exergy), and the realistic recoverable exergy is over 6.4 MJ (nearly 3% of consumed exergy). Recycling plastic waste into roof tiles saves a net 188 kg of CO₂ from entering the atmosphere per batch when compared with open burning. If all of Kampala's plastic waste was converted to roofing tiles, nearly 560 tonnes of CO₂ could be saved per year. [DOI: 10.1115/1.4045540]

Keywords: energy conversion/systems, energy systems analysis, renewable energy, exergy analysis, plastic recycling, developing country context

1 Introduction

1.1 Motivation. In the last six 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].¹ 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]. About 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 or have inadequate leachate treatment plants, and the landfill 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. Over 75% of Ugandans live in rural areas and rely on subsistence agriculture.² 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 groundwater [9]. Additionally, 60% of stray cattle in Uganda die from the 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.

1.2 Prior Studies of Waste Plastic Use. Uganda generates approximately 600 tonnes of plastic waste daily.³ Plastic bottles

and bags are the most common type of plastic waste, and they are generally thrown anywhere after use [5]. 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 [10]. 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 official 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 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 kids 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.

Kampala has 40–50 plastic recycling plants [11], but many are not profitable [12]. 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 [12].

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 [12].

1.3 Products Made From Plastic Waste. A range of organizations make products from recycled plastics in Africa. They can be categorized into four types:

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¹https://www.newvision.co.ug/new_vision/news/1313667/recycling-business-ease-city-plastic-waste

²<https://www.cia.gov/library/publications/the-world-factbook/geos/ug.html>

³<http://www.sb.com/blog/plastic-waste-collection-recycling-uganda>

- (I) Highly industrialized companies
- (II) Small businesses
- (III) NGOs
- (IV) Student/academic projects

Resintile in Uganda produces roofing tiles (Fig. 1) from waste plastic using industrial machinery requiring over 120,000 USD in startup costs. They employ five managers, two assistants, and 16 shift workers and sell between 90,000 and 120,000 tiles per year. Other industrial companies in Kenya produce roof tiles and fence posts from recycled plastic.

A startup in Burkina Faso called TECO₂ (Roofing ECOlogic and ECONOMics) is creating thin roof tiles from used low-density polyethylene (LDPE) bags. They are working with labs in France to develop a process that fuses the plastic instead of burning to reduce the release of fumes [14]. In Uganda, Wazi Recycling is starting to make pavers 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 [15]. They plan to eventually expand into also producing interlocking building bricks and foundation blocks and slabs [16].

NGOs often use simple technology, more fitting to rural areas, 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. 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 who 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 high-density polyethylene (HDPE) plastic reinforced with rice husks and banana fibers for his thesis. While the product is aesthetically pleasing and of high quality, manufacturing it is a multi-step, time-consuming process [17]. An interesting low-tech solution in rural Kenya was developed by Stefan van der Heijden, a masters student of Integrated Product Design at the Delft University of



Fig. 1 Resintile roof tiles[13]

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 [10,18].

Additionally, researchers have shown the potential of using pyrolysis to recover high calorific value fuel gas from plastics [19–21]. Although the pyrolysis of plastics is not yet implemented at an industrial scale in Uganda, it has been proven in laboratory experiments [22] and small-scale community experiments [23].

1.4 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.” [24].

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.

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% (Fig. 3) [25]. 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).

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-sqm house, Resintile tiles are 7.3% cheaper than clay tiles when considering the cost of tiles and timber supports.

To increase their market and recycle more plastic, Resintile could consider producing different products from waste plastic. The authors' market assessment and interviews with other organizations

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.

Fig. 2 Comparison of roofing options in Uganda

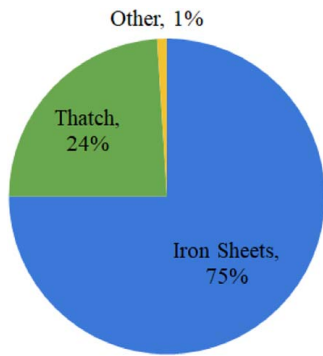


Fig. 3 Percent of Ugandan roof types

working with plastic waste in Uganda suggest wall tiles and extruded profile products, such as pipes or gutters, could be more profitable than roofing tiles. Existing organizations also claim compound pavers are profitable products.

Resintile could also increase sales by lowering their prices which would require reducing production costs. The highest cost is electricity which 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 reduce production costs.

1.5 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 overall efficiency in the 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 current plastic waste situation in Uganda and the 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.

2 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 (Fig. 4). 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. 5. 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, and fuses all the inputs



Fig. 4 Photo of tile forming press used at Resintile

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.

3 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 with respect to the environment. 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). Exergy analysis helps engineers identify the amount, type, location, and causes of losses in a system to help identify means of improvements [26].

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 °C or 33 °C (the average temperatures inside the manufacturing room away from and near the extruder). The values of the thermal material properties and their sources used in this analysis are listed in Table 1. 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.

3.1 Consumed Exergy

3.1.1 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,⁴ a conversion loss of 15% due to

⁴<https://www.hydropower.org/country-profiles/uganda>

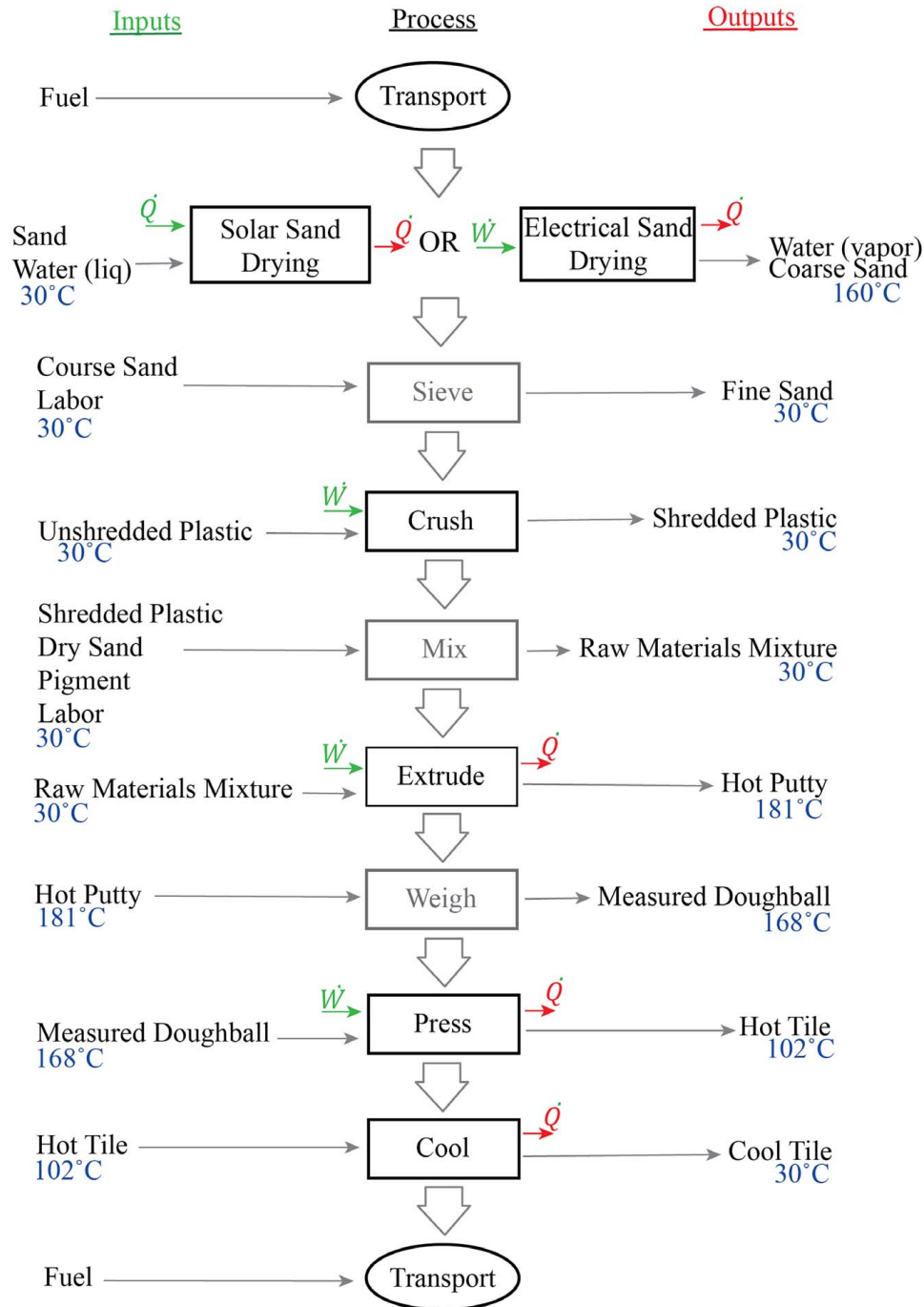


Fig. 5 Resintile process flow diagram

Table 1 Thermal material properties

	HDPE	LDPE	PP	Sand (silicone dioxide)	Iron oxide
Specific heat (kJ/kg K)	2.20 [27]	2.20 [27]	2.00 [27]	0.739 [28]	0.650 [29]

losses in potential energy at the dam, transformer losses at the power station, and pumping losses in the pumping station was used [30,31]. Additionally, electrical energy is lost when transporting through power lines from the dam to the factory. Conductivity

losses of 10% were used [32].

$$Ex_{elec} = \frac{E_R}{\eta} = \frac{Pt}{\eta} \quad (1)$$

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 $(1 - 0.15) * (1 - 0.10) = 0.765$. The exergy used by the machines is greater than the electric energy consumed because of conversion and transportation losses.

3.1.2 Drying Sand. To calculate the exergy for drying the sand in the sun, phase change principles were used. The damp sand is actually composed of two inputs: solid sand particles that undergo sensible heating and water that 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 Eq. (2), and the energy required to evaporate the water was found using Eq. (3) [26].

$$Q_{sens} = m * C_p * (T - T_o) \quad (2)$$

$$Q_{evap} = m_w * h_{lv} \quad (3)$$

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

$$MC(\%) = \frac{M_w - M_d}{M_d} * 100\% \quad (4)$$

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 and sensible heat, the carnot efficiency was used.

$$Ex_{evap} = \left[1 - \frac{T_o}{T} \right] Q \quad (5)$$

For the exergy consumed in the sensible heating of the sand, the final temperature of the sand when dried was used for T . For the sensible heating of the water, an average of the initial temperature of the water and 100 °C was used for T . For the exergy from the latent heat of the water, the vaporization temperature of 100 °C was used for T .

3.1.3 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

$$\epsilon = \gamma LHV \quad (6)$$

where γ is the exergy factor of a fuel and LHV is the lower heating value. For diesel, Kotas gives $\gamma = 1.07$ and $LHV = 42.652$ as shown in Table 2.

To convert specific exergy to exergy, the density of the fuel and fuel efficiency of the vehicle were used to convert to exergy per kilometer, which was multiplied by the distance vehicles traveled.

$$Ex_{transport} = \epsilon \rho \xi \frac{0.001m^3}{1L} d \quad (7)$$

where ρ is the density of the fuel, d is the distance traveled in kilometers and ξ is the fuel efficiency of the vehicle in liter per kilometer. A value for ξ of 0.29 for heavy duty diesel vehicles was used from a 2015 Makerere University report [34].

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

$$Ex_{non-flow} = Ex_{ph} + Ex_o + Ex_{kin} + Ex_{pot} \quad (8)$$

where

$$Ex_{pot} = PE \quad (9)$$

$$Ex_{kin} = KE \quad (10)$$

$$Ex_o = \sum_i (\mu_{i0} - \mu_{i00}) N_i \quad (11)$$

$$Ex_{ph} = (U - U_o) + P_o(V - V_o) - T_o(S - S_o) \quad (12)$$

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

Table 2 Exergy analysis related data for fuel [33]

Fuel	LHV (kJ/kg)	Exergy factor
Diesel	42.652	1.070

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, Eq. (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, Eq. (12) can be simplified as

$$ex_{ph} = c \left(T - T_o - T_o * \ln \left(\frac{T}{T_o} \right) \right) \quad (13)$$

because the change in internal energy and entropy can be written using the specific heat of the material and various relationships of temperature [35]. This is a 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.

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

3.3.1 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 $1/(h * A)$ 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 with the heat loss calculated when a conduction resistor ($R_{cond} = x/(k * A)$) 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 [36].

$$Ra_H = \frac{g\beta\Delta TH^3}{\alpha\nu} \quad (14)$$

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.

$$Nu * Ra_H^{-1/4} = 0.387 \quad (15)$$

Equation (15) is valid when $Pr = 0.72$ (the Prandtl number at room temperature air). The Rayleigh number from Eq. (14) was used in Eq. (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 ($Nu = hH/k$).

The extruder is broken into three 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 and 5.0 W/m² K. 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 Eq. (5) 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.

3.3.2 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, Eq. (5) was used with T equal to the experimentally measured temperature of carbon steel exposed to the Ugandan sun (91 °C).

The realistic scenario was calculated by multiplying 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 [35].

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. A detailed capital cost impact and payback time analysis is beyond the scope of this initial study, but the authors are working on another publication that will include a techno-economic analysis of various recycling options for plastic waste in Uganda.

3.4 CO₂ Emissions. To quantify the sustainability impact of the Resintile process, we wanted to calculate the amount of CO₂ emissions saved. The amount of exergy consumed in operating the machines was equated to kilograms of CO₂ emissions using a conversion factor of 4.9 g of CO₂/kWh of hydro electricity used (for run of river hydroelectric plants) [37]. The same conversion was used to quantify the amount of CO₂ saved if the suggested recommendation to the manufacturing process was implemented. The fuel used in transportation was converted to CO₂ emissions using 8.89 kg CO₂/gallon of gasoline given by the U.S. Energy Information Association.⁵ The sum of CO₂ emissions equivalently released by the Resintile production process was compared with the amount of CO₂ 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 CO₂. To understand Resintile's positive impact on sustainability, the amount of CO₂ that would have been released from burning the plastic used to make roofing tiles was calculated. The amount of CO₂ 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 [38].

⁵https://www.eia.gov/environment/emissions/co2_vol_mass.php

4 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 and 4 and Figs. 6 and 7 display the results of this exergy analysis. All numbers were calculated for a batch of 75 tiles.

For drying sand, 10,780 kJ of solar energy is required. 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 240 MJ of exergy. Nearly 17 MJ (8%) is potentially recoverable. To recover the most amount of exergy, we focused on the largest exergy sink—the extruder. Table 5 shows how wrapping the extruder barrel in insulation could recover 190 kJ of exergy per batch—a 30% improvement compared with 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 6 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 2.5% of the total exergy consumed in the production process

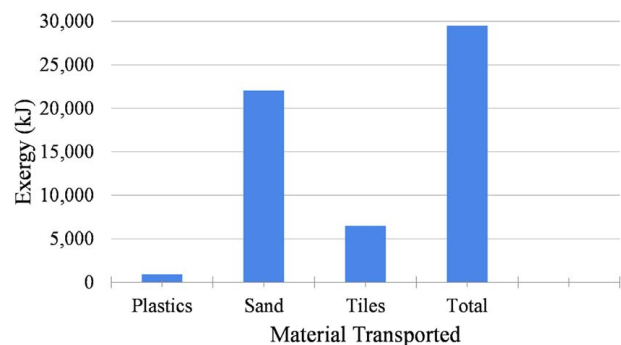


Fig. 6 Resintile transportation exergy results

Table 3 Resintile process exergy results

Exergy consumed (kJ)	Process	Exergy potential for recovery (kJ)
29,491	Transportation	0.00
10,781	Drying sand	10,366
3482	Crushing plastic	0.07
123,797	Extruding	5200
73,529	Pressing	1412
241,081	Totals	16,977

Table 4 Resintile transport exergy results

Material	Distance (km)	Exergy consumed (kJ)
Inputs		
Sand	140	22,049
Plastic	14	945
Outputs		
Tiles	35	6497
Total		29,491

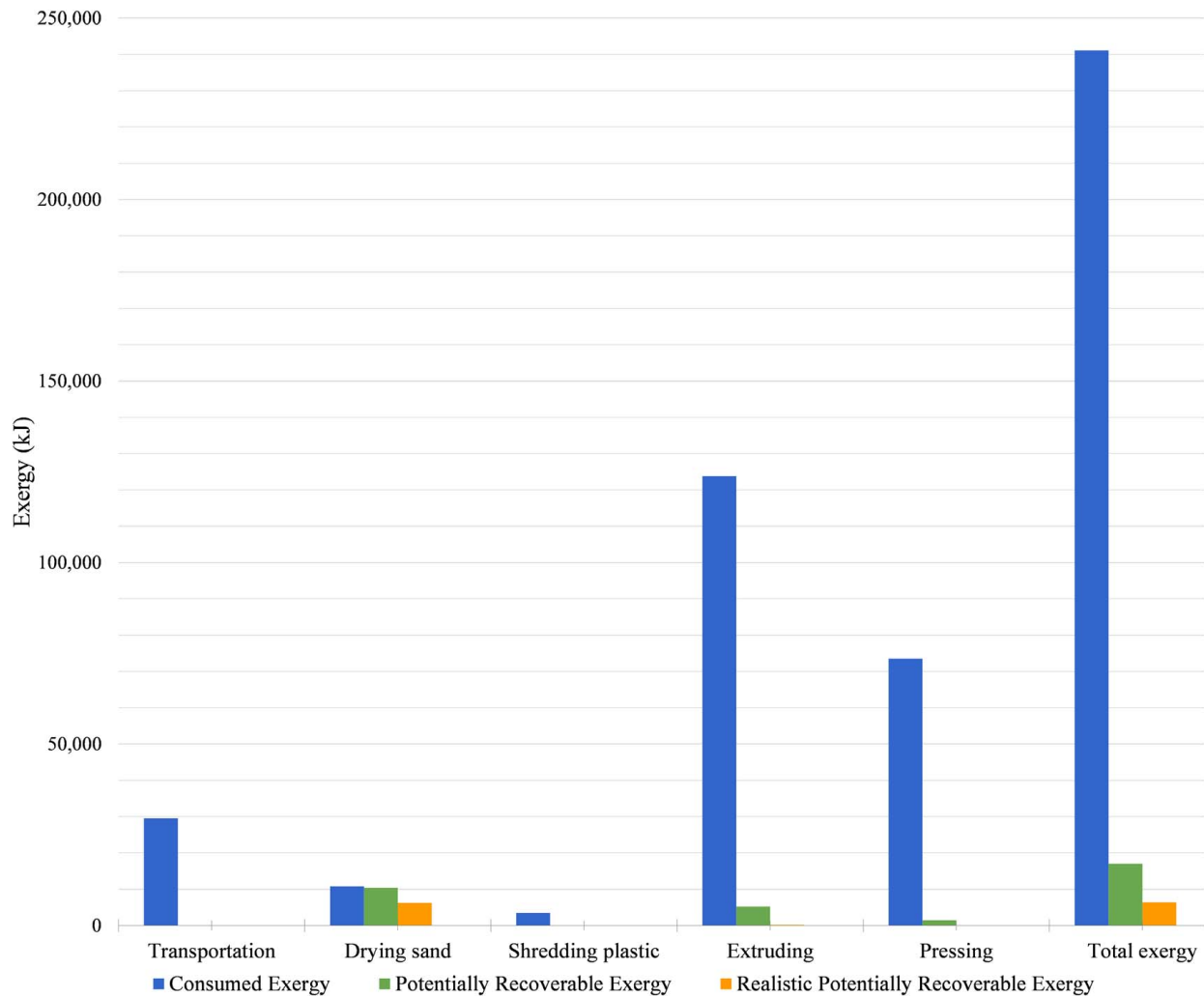


Fig. 7 Resintile process exergy results

Table 5 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 6 Solar exergy

Solar usage	Efficiency	Exergy (kJ)
Current	6–19%	10,780.5
Ideal heat engine	16.9%	10,365.17
Realistic heat engine	10.1%	6,219.1

Table 7 Overall impact on CO₂ 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	0.009	26.2
Net kg CO ₂ saved with recommendations	187.9	558,336.3

Note: The bold values show the net savings based on all the other values presented in the table.

and could be used to dry the sand or power some of the machines for free.

If both the heat engine and insulation around the extruder barrel were added, over 6.4 MJ of exergy could realistically be recovered, which is almost 3% of the 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 CO₂. If all of Kampala's plastic waste (180 tonnes/day) was made into roofing tiles, it would prevent nearly 560 tonnes of CO₂ 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 market, they would need 135,720 tonnes of plastic or 754 days worth of Kampala's plastic. Table 7 summarizes the results of Resintile's contribution to reducing CO₂ emissions.

5 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) since 21.4% of Ugandans live in poverty. 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.

6 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 240 MJ of exergy. The potentially recoverable exergy is nearly 17 MJ (8% of consumed exergy), and the realistic recoverable exergy is over 6.4 MJ (nearly 3% of consumed exergy). Recycling plastic into one batch of roofing tiles prevents 188 kg of CO₂ from entering the atmosphere when compared with open burning. If all of Kampala's plastic waste was converted to roofing tiles, nearly 560 tonnes of CO₂ could be saved per year.

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Nomenclature

c	= specific heat
d	= distance traveled
g	= gravitational constant
h	= convection coefficient
k	= thermal conductivity
t	= operation time
x	= thickness of insulation
A	= surface area of extruder
H	= characteristic length
P	= rated machine power
S	= entropy
T	= temperature (in K)
U	= internal energy
V	= volume
h_{lv}	= latent heat of vaporization
m_w	= mass of water
M_w	= mass of wet sample
M_d	= mass of dry sample
N_i	= moles
P_o	= pressure at ground state
Q_{evap}	= latent energy
R_{cond}	= conduction resistor
R_{conv}	= convection resistor
S_o	= entropy at ground state
T_o	= ground state temperature (in K)
U_o	= internal energy at ground state
V_o	= volume at ground state
KE	= kinetic energy
PE	= potential energy
KCCA	= Kampala City Council Authority
NGO	= non-governmental organization

Nu	= Nusselt number
PP	= polypropylene
Ra	= Rayleigh number
ex_{ph}	= specific physical 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_o	= chemical exergy
Ex_{ph}	= physical exergy
Ex_{pot}	= potential energy exergy
$Ex_{transport}$	= exergy for transportation
CO_2	= carbon dioxide
$TECO_2$	= roofing ECOlogic and ECONomics
α	= thermal diffusivity
β	= thermal expansion coefficient
γ	= exergy factor of fuel
ϵ	= specific chemical exergy
η	= efficiency factor
μ_{io}	= chemical potential
μ_{ioo}	= chemical potential at ground state
ν	= kinematic viscosity
ρ	= density of fuel
ξ	= fuel efficiency of vehicle

References

- [1] Geyer, R., Jambeck, J. R., and Law, K. L., 2017, "Production, Use, and Fate of All Plastics Ever Made," *Sci. Adv.*, 3(7), p. e1700782.
- [2] Parker, L., 2017, "A Whopping 91% of Plastic," National Geographic," <https://news.nationalgeographic.com/2017/07/plastic-produced-recycling-waste-ocean-trash-debris-environment/>
- [3] Kinobe, J. R., Gebresenbet, G., Niwagaba, C. B., and Vinnerås, B., 2015, "Reverse Logistics System and Recycling Potential At a Landfill: A Case Study From Kampala City," *Waste Manage.*, 42, pp. 82–92.
- [4] Reporter, 2013, "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
- [5] WaterAid, 2011, "Solid Waste Management Arrangements and its Challenges in Kampala: A Case Study of Bwaise II Parish," Kawempe Division.
- [6] Nampijja, D., "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
- [7] Njeru, J., 2006, "The Urban Political Ecology of Plastic Bag Waste Problem in Nairobi, Kenya," *Geoforum*, 37(6), pp. 1046–1058.
- [8] Wiedinmyer, C., Yokelson, R. J., and Gullett, B. K., 2014, "Global Emissions of Trace Gases, Particulate Matter, and Hazardous Air Pollutants From Open Burning of Domestic Waste," *Environ. Sci. Technol.*, 48(16), pp. 9523–9530.
- [9] Oehlmann, J., Schulte-Oehlmann, U., Kloas, W., Jagnytsch, O., Lutz, I., Kusk, K. O., Wollenberger, L., Santos, E. M., Paull, G. C., Van Look, K. J., and Tyler, C. R., 2009, "A Critical Analysis of the Biological Impacts of Plasticizers on Wildlife," *Philos. Trans. R. Soc., B*, 364(1526), pp. 2047–2062.
- [10] van der Heijden, S., 2018, "Product Design for Effective Development Aid," M.S. thesis, TU Delft, Delft.
- [11] Boonekamp, C., 2018, "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.
- [12] Kaheru, S., 2018, "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.
- [13] Namakajjo, W., 2018, "Resintile (EA) Ltd.," Product Overview Report, Resintile (EA) Ltd.
- [14] Grellier, C., 2016, "Turning Plastic Waste into Roofs in Burkina Faso," Makery. <http://www.makery.info/en/2016/11/08/transformer-les-dechets-plastiques-ent-tois-au-burkina/>. Accessed November 28, 2018.
- [15] Katwesigye, B., 2018, "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.
- [16] Katwesigye, B., 2018, Wazi recycling. <http://wazirecycling.com/>. Accessed November 28, 2018.
- [17] Pramath, R., 2018, "Personal Communication via Skype," Mr. Pramath Completed His Masters Dissertation Research With Waste for Life, an NGO Making Roofing Tiles From Plastic Waste in Sri Lanka.
- [18] van der Heijden, S., 2018, "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.
- [19] Igarashi, M., Hayafune, Y., Sugamiya, R., Nakagawa, Y., and Makishima, K., 1984, "Pyrolysis of Municipal Solid Waste in Japan," *ASME J. Energy. Res. Technol.*, 106(3), pp. 377–382.

- [20] Lin, Y.-H., Wei, T.-T., Yang, M.-H., and Lee, S.-L., 2012, "Postconsumer Plastic Waste Over Post-Use Cracking Catalysts for Producing Hydrocarbon Fuels," *ASME J. Energy. Res. Technol.*, **135**(1), p. 011701.
- [21] Suresh Kumar Reddy, K., Kannan, P., Al Shoaibi, A., and Srinivasakannan, C., 2012, "Thermal Pyrolysis of Polyethylene in Fluidized Beds: Review of the Influence of Process Parameters on Product Distribution," *ASME J. Energy. Res. Technol.*, **134**(3), p. 034001.
- [22] Owusu, P. A., Banadda, N., Zziwa, A., Seay, J., and Kiggundu, N., 2018, "Reverse Engineering of Plastic Waste Into Useful Fuel Products," *J. Anal. Appl. Pyrolysis*, **130**, pp. 285–293.
- [23] Okwoko, P., 2019, "We Love Plastics," <https://www.afrigreensustain.ug/2019/12/10/exploring-the-application-of-pyrolysis/>, January.
- [24] Export.gov, 2017, "Uganda Construction," Technical Report, Export.gov. www.export.gov/article?id=Uganda-Construction
- [25] UBOS, 2017, "The Uganda National Household Survey 2016/17," Technical Report, Uganda Bureau of Statistics. www.ubos.org/onlinefiles/uploads/ubos/pdf%20documents/2017_UNHS_26092017-Final_Presentation.pdf
- [26] Dincer, R., 2007, *Exergy: Energy, Environment, and Sustainable Development*, Elsevier New York. ISBN: 9780080445298.
- [27] Crawford, R. J., 1998, *Plastics Engineering*, 3rd ed., Butterworth-Heinemann, Woburn, MA.
- [28] Yaws, C. L., 2014, "Yaws Critical Property Data for Chemical Engineers and Chemists," Knovel. <https://app.knovel.com/hotlink/toc/id:kpYCPDCECD/yaws-critical-property/yaws-critical-property>
- [29] David, R., 2009, *CRC Handbook of Chemistry and Physics*, 90th ed., CRC Press, Boca Raton, FL.
- [30] Wall, G., 1990, "Exergy Conversion in the Japanese Society," *Energy*, **15**(5), pp. 435–444.
- [31] Wall, G., Sciubba, E., and Naso, V., 1994, "Exergy Use in the Italian Society," *Energy*, **19**(12), pp. 1267–1274.
- [32] Wall, G., 1986, "Exergy – A Useful Concept," Ph.D. Thesis, Chalmers University of Technology, Göteborg, Sweden.
- [33] Kotas, T. J., 1985, *The Exergy Method of Thermal Plant Analysis*, 1st ed, Butterworth-Heinemann, Oxford, UK.
- [34] Mutenyo, J., Banga, M., Matovu, F., Kimera, D., and Lawrence, K., 2015, "Baseline Survey on Uganda's National Average Automotive Fuel Economy," Technical Report, Makerere University. https://www.globalfuelconomy.org/media/461028/africa_vehicle-fuel-economy-baseline-for-uganda.pdf
- [35] Sonntag, Borgnakke, and Wylen, V., 2003, *Fundamentals of Thermodynamics*, John Wiley & Sons, Inc, San Francisco, CA.
- [36] Bejan, A., 2013, *Convection Heat Transfer*, 4th ed., John Wiley & Sons, Inc., Hoboken, NJ.
- [37] Raadal, H. L., Gagnon, L., Modahl, I. S., and Hanssen, O. J., 2011, "Life Cycle Greenhouse Gas (ghg) Emissions From the Generation of Wind and Hydro Power," *Renew. Sustainable Energy Rev.*, **15**(7), pp. 3417–3422.
- [38] Valavanidis, A., Iliopoulos, N., Gotsis, G., and Fiotakis, K., 2008, "Persistent Free Radicals, Heavy Metals and Paks Generated in Particulate Soot Emissions and Residue Ash From Controlled Combustion of Common Types of Plastic," *J. Hazard. Mater.*, **156**(1–3), pp. 274–284.