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Evaluating Uganda’s waste management system for the production of refuse-derived fuel (RDF) and its potential implementation in the country’s growing cement industry

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
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Vienna, 01.10.2019

Affidavit

I, **RICHARD DAVID LEE, BSC, BA**, hereby declare

1. that I am the sole author of the present Master's Thesis, "EVALUATING UGANDA'S WASTE MANAGEMENT SYSTEM FOR THE PRODUCTION OF REFUSE-DERIVED FUEL (RDF) AND ITS POTENTIAL IMPLEMENTATION IN THE COUNTRY'S GROWING CEMENT INDUSTRY", 86 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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ABSTRACT

In the country of Uganda in Sub-Saharan Africa, a World Bank-funded development project has been implemented under the Clean Development Mechanism of the Kyoto Protocol for the purpose of improving waste management and reducing emissions from untreated household waste. This project has set up twelve active composting facilities throughout the country. The residues resulting from the composting process are currently landfilled. Municipal solid waste quantity and composition data recorded on nine of the twelve active facilities was thoroughly reviewed to show that the residues contain enough combustible material to process further to create two different forms of refuse-derived fuel—one primarily composed of paper and one primarily composed of plastics. The theoretical quantitative values of each RDF was then derived, as well as their lower heat values based on their composition. It was then shown that both RDFs would serve as viable fuel replacements for clinker production in Uganda's growing cement industry, therefore reducing the demand for primary fossil-based fuel sources, and ultimately, leading to a net carbon dioxide gas emission reduction, should the alternative fuel production scheme be implemented.

KEYWORDS: Uganda, waste management, refuse-derived fuel, compost residuals, fuel replacement, cement production, Clean Development Mechanism, emissions reductions

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LIST OF ABBREVIATIONS

Alternative Fuels	AFs
Certified Emission Reductions	CERs
Clean Development Mechanism	CDM
Chemical Oxygen Demand	COD
Component Project Activities	CPA
Environmental Impact Assessment	EIA
Foreign Direct Investment	FDI
Global Environment Fund	GEF
Greenhouse Gas	GHG
High-density Polyethylene	HDPE
Higher Heating Value	HHV
Kampala Capital City Authority	KCCA
Landfill Gas	LFG
Low-density Polyethylene	LDPE
Lower Heating Value	LHV
Mechanical Biological Treatment	MBT
Material Flow Analysis	MFA
Municipal Solid Waste	MSW
National Agricultural Advisory Services	NAADS
National Environment Management Authority (of Uganda)	NEMA
Non-governmental Organization	NGO
Polyethylene terephthalate	PET
Polypropylene	PP
Polyvinyl Chloride	PVC
Program of Activities	POA
Refuse-derived Fuel	RDF
Sub-Saharan Africa	SSA
Uganda Schillings	UGX
United Nations Framework Convention on Climate Change	UNFCCC
Waste-to-Energy	WTE

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Sincerely yours,
Richard David Lee

1. INTRODUCTION

1.1 Motivation of the study/Rationale

Development projects are almost always well intentioned, but they are not always well-designed in the first place, or more commonly, not very well executed once funds and materials are made available (Easterly, 2007). Sometimes the implementation of the project is comprehensive and consistent in the beginning phases, but with time, with wavering commitment and funds, the project's key pillars begin to lose active support, and the full benefits of the project fail to be realized (Easterly, 2007).

The best development projects are designed with the intention for long term growth and sustainability (sustainability in this context refers to all three pillars of sustainability as denoted by the United Nations: social, economic, and environmental). For projects to be viable in the long term, the identification of synergies is absolutely crucial to link them up with other projects and expand the scope of their social, economic, and environmental benefits in the region.

With this in mind, in taking a close look at a current World Bank-funded composting project being implemented in Uganda under the Clean Development Mechanism, the potential to link up two very different industries in Uganda has been recognized as a potential opportunity to develop synergies that would benefit both composters in nine Ugandan municipalities and Ugandan cement producers, while at the same time leading to an even further reduction in greenhouse gas emissions (Kleeman, et al., 2018).

The rationale behind this study then is the realization that building off of other projects and local resources already in place is the best way to achieve even greater sustainable development outcomes. In this case, that means for the industries of Uganda, the economic opportunities and quality of life for the local people, and local environmental benefits with far-reaching, global impacts.

1.2 Background and context of the study

1.2.1 Description of Uganda's waste management system

Waste management is an essential component of human societies for two particularly important reasons, namely 1) to protect human health and 2) to maintain an environmental quality suitable for living organisms—to include humans (Brunner & Fellner, 2007). In practice though, waste management has been often less than ideally prioritized by state, city, and municipality governments, often at the expense of the individuals living in society and the surrounding ecosystems which societies depend on for their sustenance and natural resources.

Figure 1.1: Homes running adjacent to the official dumpsite in Kampala
SOURCE: The Uganda Waste Report, ©Timothy Bouldry, 2018

In the context of developing countries, the waste management situation is often marked by even grimmer outcomes, due to limited financial resources, inconsistent infrastructure, political instability and/or unwillingness, a lack of monitoring and enforcement capabilities, and other more pressing problems competing for public funds (Wilson, 2007). This problem is compounded by the fact that with lower levels of development in a country, there are higher proportional costs for waste management observed. According to the World Bank, solid waste management costs as a percentage of a given municipality's budget is marked by the following: 4% of high income countries, 11% of middle income countries, and finally, 19% of low income countries (Kaza, et al., 2018). With so many public services and systemic problems competing for public funds, it is simple to see why waste management systems in developing countries might be lacking in their overall effectiveness.

In Uganda, waste management is decentralized and left up to the individual municipalities themselves to organize and fund (Christensen, et al., 2014). This can be done directly by and through the municipality itself (e.g., Kampala Capital City Authority), or they can contract other companies to manage the generated MSW. The National Environment Management Authority (NEMA) is responsible for setting the legal framework that helps guide this process, but do not play a major role otherwise in the individual waste management systems (NEMA, 2019). Purchasing of waste management equipment is also done individually by each municipality, but is facilitated and supported by Uganda's Ministry of Works and Transport (UMOWT, 2019).

Figure 1.2: Waste collection by contractors in Kampala City (Nafula, 2016)

Generally speaking, waste collection and overall management of collected municipal solid waste (MSW) in Uganda is more efficient and covers higher percentages of the population in urban centers, like Uganda's capital (and largest) city Kampala, along with medium sized cities like Gulu, Lira, Mbarara, and Jinja.

Commonplace in Uganda are unofficial temporary storage sites and worse, illegal dumpsites. For example, according to Kinobe and colleagues, in Kampala City alone, only 35 of the total 168 temporary storage sites observed throughout the city were officially recognized by the Kampala Capital City Authority (KCCA) (Kinobe, et al., 2015). In addition to the 168 temporary storage sites, 59 illegal dumpsites were identified (Kinobe, et al., 2015). And while the city's estimated 1,500-2,500 tons of generated MSW per day is managed by state and private waste handlers, only about 40-45% of the total waste generated is collected and properly disposed of in the city's only official, authorized landfill, Kiteeza (Kinobe, et al., 2015). Kiteeza itself would be designated as a sanitary landfill, per its original design, but since its expansion from 0.04 km^2 to 0.11 km^2 there have been areas within the landfill that do not have a liner (Kinobe, et al., 2015), allowing untreated leachate to enter into the surrounding groundwater. This poses a particular problem to the health of city residents because the landfill is built on a wetland only some 12 km north of the city (Kinobe, et al., 2015).

Figure 1.3: Inactive leachate aeration tank at the Kampala dumpsite
SOURCE: The Uganda Waste Report, ©Timothy Bouldry, 2018

Even though Kampala is only a single case of waste management in Uganda, and a prime example of its insufficiency, it may also serve as a good indicator of the status of waste management more broadly in Uganda. As stated, Kampala is by far the country's largest city, with 1.9 million night time residents and the population doubling in size during the day (Kinobe, et al., 2015); and with its waste management system, it plays a leading role in setting the standard for the rest of the country. That is because the next largest cities in Uganda are much smaller in size (most not exceeding 150,000 residents), and the extent of their waste management systems are typically lacking even more in design and scope, often marked by irregular, unregulated collection of waste, illegal open dumpsites, unprotected waste picking for recyclable materials, and open air burning of waste.

For example, in the western Kasese district, and particularly, Kasese municipality, there are similar trends observed. Although some legislation has been passed to punish illegal dumping with fines up to 20,000 Ugandan Schillings (~7-8 USD), the lack of resources to enforce said legislation has been all but effective in curtailing the problem (Christensen, et al., 2014). Widespread informal dumping can be seen throughout the city, and the formal waste management system orchestrated through the municipality is simply insufficient to meet the waste generation needs (Christensen, et al., 2014). Three waste trucks were stated to be in operation that carry an average 20 tons of MSW per day to the town's composting facility, and these were cited as regularly out of operation or out of fuel due to lack of funding (Christensen, et al., 2014). This is in comparison to the estimated 230 tons of MSW generated per day, which is likely to increase due to the city's rapid population expansion (Christensen, et al., 2014). As such, the vast majority of the waste ends up being informally treated or transported to the city's 25 formal collection points (skips overflowing with waste) by individuals and families, often via informal recycling/waste picking, household burying and burning, or direct unprotected transfer of waste (Christensen, et al., 2014). Furthermore, although the town's composting facility produces an approximate 3 tons of compost per day, almost none of it is being sold or used, given a lack of local acceptance by agriculturalists (Christensen, et al., 2014).

Figure 1.4: Skips overflowing with MSW in Jinja
SOURCE: The Uganda Waste Report, ©Timothy Bouldry, 2018

Additional reports from the Masaka District detail similar observations of towns much smaller than Kasese (~100,000 people (Christensen, et al., 2014)) and Kampala. After a visit to Kinoni, Kyazanga, Lwengo, and Kalisizo, a representative from WasteAid UK, noted that many of the waste management practices in each town were not only insufficient, but also unhealthy—with reports of medical waste being emptied by hand into skips without protective clothing, open burning of waste, and waste being used to fill holes in the areas surrounding people's homes (Bates, 2016). That said, there were also reports of a highly organized informal recycling sector in each town, with PET bottle collection being prioritized and sold to a company in Kampala, and recyclable metals being collected and taken to Jinja for sale (Bates, 2016). Nevertheless, with an inadequate number of skips and inconsistent waste collection, even the 25 formal collection points were observed to be overflowing with waste (Bates, 2016).

Figure 1.5: Open air waste burning at an unofficial dumpsite in Mbarara
SOURCE: The Uganda Waste Report, ©Timothy Bouldry, 2018

Although Uganda has experienced dramatic trends of urbanization in recent years, still about 77% of the entire population live in rural areas (World Bank Group, 2019). Unfortunately, rural areas of Uganda are also, by and large, the most underserved areas in terms of waste management. This can be seen simply by reading through the 2019 list of nationally licensed waste handlers maintained by NEMA. Of the 97 licensed waste handlers, only about 25% licensed are outside the city of Kampala (NEMA, 2018). This is particularly worrisome, when one considers and compares the aforementioned population of Kampala (1.9 million evening residents) with the total population of Uganda: 42,862,958 (World Bank Group, 2019). The disproportion of service is alarming, since about 75% of the registered waste handlers are catering to only roughly 5-10% (if one considers the daytime population of Kampala too) of the total population.

While there have already been multiple attempts to modernize and improve the waste management system, for example, by implementing waste separation facilities and by formalizing the recycling sector, they have all proven to be premature. These types of more advanced (and technical) waste management solutions are most effective when the greater majority of waste generated is collected and transported to, for example, a mechanical biological treatment plant (MBT) for better end results.

Figure 1.6: Informal waste pickers at the Jinja dumpsite
SOURCE: The Uganda Waste Report, ©Timothy Bouldry, 2018

So in the case of Uganda, as a major first step, expanding and optimizing waste collection, should be the ultimate priority of local municipalities, since, as of yet, primarily wealthier districts, governmental institutions and private enterprises continue to be the best served areas in Uganda. This will, of course, prove to be particularly difficult, given that over 70% of waste management costs in developing countries are attributed to collection and transportation of waste (Kinobe, et al., 2015), and funding for such services are already lacking throughout the country (e.g., less than 10% of Kasese muncipality's total revenue goes toward solid waste management, given that 66% of its revenues come from the national government, and 88% of those funds are already allocated in advance; there are, additionally, no revenues from service fees for waste collection (Christensen, et al., 2014)).

To address the problem, additional value chains might be developed to increase and/or create the budget to bolster MSW collection and treatment. In Kasese municipality, there are no formal fees for waste collection services, obviously contributing to a lack of funds for such services to be sufficient (Christensen, et al., 2014). Impeding the development of value chains for some materials found in MSW further is the fact that in many small towns and municipalities in Uganda, there is no separation of waste at the source (Bates, 2016). This leaves generation of the value chains for many recyclable materials, like PET plastic bottles and metals, almost exclusively to informal waste pickers/recyclers.

Figure 1.7: Sandals created by a coop specializing in repurposing old tires
SOURCE: The Uganda Waste Report, ©Timothy Bouldry, 2018

Although some value chains for recyclables have already been well-established more formally by NGOs, coops, and small, privately owned enterprises (see Figure 1.8 below) (Bouldry, 2018), there are still many opportunities to expand these further and add additional chains for other waste fractions within MSW nationwide.

Figure 1.8: A women's coop sorting plastic bottles for recycling in Kampala
SOURCE: The Uganda Waste Report, ©Timothy Bouldry, 2018

Two examples include the non-compostable, non-recyclable materials with a high heat value, and the compostable organic waste fractions of MSW. Creation of the value chain for the latter is already underway through the UNFCCC's Uganda Municipal Solid Waste Programme (detailed in the next section), by attempting to produce a marketable compost from Uganda's MSW. The value chain for the former relies on the potential to convert said materials into a refuse-derived fuel (RDF), a valuable fuel replacement in cement production. Creating these value chains from MSW would drive improved waste management outcomes by generating new sources of revenue.

1.2.2 Description of Uganda's composting project organized under the Clean Development Mechanism

Under the 1997 Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC), nations that signed on to it agreed to specific, legally binding emission reduction targets to be reached during the first phase, which ran until 2008

(UNFCCC, 2019). A second phase—set to run until 2020—of reduction targets was set and adopted under the Doha Amendment (UNFCCC, 2019). Importantly, there were three different reduction mechanisms set out by the Kyoto Protocol to assist nations with reduction targets actually fulfill their commitments (UNFCCC, 2019). The most important to this thesis and projects regarding waste management in Uganda is the Clean Development Mechanism (CDM). According to the Kyoto Protocol, certain types of projects can qualify for what came to be termed certified emission reduction credits (CERs) that can be traded and bought by industrialized nations seeking to reduce their own emissions (UNFCCC, 2019). The result is, industrialized nations can invest money in development projects in developing countries that lead to a net reduction of greenhouse gases. The CERs that are derived then may be sold back to countries investing in the project, or others, to generate income to for the developing country and/or pay back the loans for the projects (UNFCCC, 2019).

Illegal open dumping and even authorized dumping of unprocessed municipal solid waste (MSW) in managed dumpsites poses environmental problems that go beyond untreated leachate contaminating the surrounding groundwater. Another substantial problem is the greenhouse gases (GHG) that result from decomposition of the untreated waste. Landfills and dumpsites with a high concentration of organic waste (e.g., from food waste) have a tendency to decompose under anaerobic conditions where only specific types of bacteria are able to produce energy in the absence of oxygen. In doing so, they produce methane (CH_4) gas instead of carbon dioxide (CO_2). Methane is about 20x as potent of a greenhouse gas than carbon dioxide is (under the first round of commitments for the Kyoto Protocol the value of 21x was used, and during the second round the value was taken to be 25x as potent), and as such, lower concentrations are still contributing extensively to the average global temperature rise (Tumuhairwe & Kakeeto, 2015).

In some developing countries, actions have been taken to reduce the amount of methane gas that escapes to the atmosphere from already landfilled untreated waste by, for example, covering and/or closing the landfill, collecting the landfill gas (LFG) via special vents, and either burning the gas simply to completely oxidize the methane and reduce the net greenhouse effect; or by burning it to produce electricity via a steam turbine (Bakaly & Fransen, 2011). Unfortunately, for smaller dumpsites the collection of LFG is not always a possibility, like many of the dumpsites serving smaller municipalities in

Uganda (Tumuhairwe & Kakeeto, 2015). There have been other projects in the region that have qualified for certified emission reduction credits under the Clean Development Mechanism of the Kyoto Protocol by doing just that—for example, the "Kampala Solid Waste Project" in Uganda, complete with a proposal for LFG flaring under the CDM (World Bank Group, 2015).

Another much more effective and useful option is to treat the MSW before it is landfilled to reduce the organic fraction that ultimately leads to the methane production.

That is exactly the designed intention of the "Uganda Municipal Waste Compost Programme" operating under the Clean Development Mechanism (Tumuhairwe & Kakeeto, 2015). With a loan from the Word Bank Group, seventeen different municipalities in Uganda in total were able (or will be able) to procure the financial resources necessary to establish individual composting sites (Tumuhairwe & Kakeeto, 2015). So far twelve of the seventeen are in operation (Okurut, et al., 2018). Each municipality conducted an environmental impact assessment (EIA) to determine the potential environmental risks and effects that a composting site might have on the planned plot of land, but following the approval of NEMA, the governing body set with the task of overseeing the entire programme of activities (PoA), they were able to invest in their projects (Tumuhairwe & Kakeeto, 2015).

Similar steps were taken by each municipality. First, boundaries for the site had to be established via fencing, along with the roofing/housing for the composting windrows (Tumuhairwe & Kakeeto, 2015). Second, establishment or improvement of the surrounding roads and infrastructure leading to the sites had to be carried out (Tumuhairwe & Kakeeto, 2015). This was an essential step for MSW to be delivered daily to each composting site consistently and efficiently. Thirdly, water and electric connections needed to be established to the new sites for proper functioning of the facilities (Tumuhairwe & Kakeeto, 2015). Finally, aeration equipment (i.e. tractors) and skips for the necessary temporary storage of compost and compost residuals before they are delivered for sales and disposal respectively had to be purchased (Tumuhairwe & Kakeeto, 2015).

Upon completion of these steps, then the composting sites were commissioned and the first deliveries of municipal solid waste began on September 2, 2009 to the first few municipalities (Tumuhairwe & Kakeeto, 2015).

By composting the organic fraction of the household waste, the project does not only reduce the net GHG emissions, but it also leads to a marketable product to be sold to local farmers as fertilizer (Okurut, et al., 2018). This, in turn, reduces the need for chemical fertilizers (environmental effects), or the handling of raw waste (health effects), which was oftentimes being directly deposited indiscriminately on agricultural land by farmers as a fertilizer.

Figure 1.9: Compost purification via sieving at the Mukono composting plant
SOURCE: The Uganda Waste Report, ©Timothy Bouldry, 2018

Furthermore, the composting sites significantly reduce the amount of waste going to landfills and encourage higher collection rates of MSW that is generated in each respective municipality. That means disposal sites will have a longer lifetime of service. Plus, with a higher proportion of inert waste materials being disposed of, the resulting leachate has lower concentrations of chemical oxygen demand (COD) that might contaminate groundwater (Okurut, et al., 2018).

Although most projects of the CDM are precisely designed and thoroughly reviewed before being executed on a countrywide scale, as is often times the case, the full effects of the composting project has taken time to be realized. As previously stated, only 12 of the planned 17 composting sites have been established, and while all of them are functioning, almost none of them are fulfilling their expected optimum capacities laid out by the initial project documents. For example, on average, only 47 tons of waste are collected and delivered to each composting site for processing, while the project document calls for 70 (Okurut, et al., 2018). Furthermore, on average, only 36% of the waste being generated in each municipality is actually being collected for biomass processing (Okurut, et al., 2018). Obviously, much of the untreated waste is still being disposed of, leading to anaerobic decomposition and methane emissions.

More important to this project, is the fact that of the MSW being brought to each municipality and composted, a large proportion of non-compostable materials is being separated out and simply deposited at a dumpsite or burned. First, recyclable non-compostable materials, like PET, HDPE, and PP bottles; metals like iron and aluminum; and cardboard, are picked out by hand to be sold to local recyclers. Following the composting process, additional impurities and non-compost materials are sieved out to purify the compost. These materials are then burned indiscriminately or delivered to the final disposal site, even though there is a high proportion of combustible material: to include non-recyclable plastics (based on type or quality {e.g., dirty}), non-recyclable paper products (wet, dirty, etc.), rubber, textile scraps, wood, and so on. These residuals of the compost process are, therefore, a viable potential fuel source, given a couple of additional processing steps.

Figure 1.10: Compost and separated residues at the CDM composting plant in Arua

1.2.3 Description of refuse-derived fuel production in the context of sub-Saharan Africa

All waste streams contain some proportion of materials with a higher calorific value than the other proportions in the mixture. The general idea behind refuse-derived fuel production then is simply to separate these materials from the rest of the waste stream to create a waste fraction where the heat value is concentrated and can be burned for thermal energy recovery. When this is done properly and consistently, RDFs can be utilized as fuel replacements in specific industries. For the purpose of this study, the focus is on the cement industry.

For refuse-derived fuels to be produced from MSW, a number of technologies need to be employed:

First and foremost, some sort of separation and sorting technology needs to be used to separate waste fractions with higher calorific value from those with less energy.

Depending on the composition, sometimes it is best to first use a cutter or shredder to homogenize the particle size of the solid waste for better separation (Bilitewski, 2011). Separation technologies generally capitalize on differences in physical properties between the waste fractions to split them into multiple categories (Bilitewski, 2011). For example, oftentimes, the combustible materials like paper, plastics, and textiles are larger in size than the non-combustibles like organic waste, sand, glass and this difference is exploited to separate them (Bilitewski, 2011). Others focus on separating out recyclable materials like iron, aluminum, and recyclable plastics (Bilitewski & Christensen, 2011). Others still work to separate out fractions that are counter-productive in RDF upon burning. Examples would include heavy metals like mercury and lead, and materials containing chlorine like polyvinyl chlorine (PVC) (Rotter, 2011). But most commonly, the physical properties used to isolate waste fractions are particle size and density of the materials, by using, for example, a trommel screen or oscillating screen for separation based on particle size, or different types of air classifiers (e.g. zigzag, airbed, and cross-current) or ballistic separators for separation based on density (Bilitewski, 2011).

Secondly, if a size reduction technology has not already been used to assist the separation stage, a cutter or shredder would then be used to reduce and homogenize particle size of the combustible waste fractions for higher surface area and more consistent complete combustion of the fuel (Bilitewski, 2011). Just for this reason, most cement producers utilizing refuse-derived fuels have requirements for particle size of the fuel. For example, Cimentos de Mozambique, a sub-Saharan African cement producer already utilizing waste paper as RDF, and medical waste and carbon dust from aluminum production as alternative fuels (AFs), requires that the particle size of the RDF not exceed 10.0 millimeters for it to qualify for use in their primary firing system (UNEP, DTU, & CTCN, 2015). Ohorongo Cement in Namibia, also applies similar criteria requirements to the RDF it utilizes.

Finally, compacting technologies are used to reduce the volume of the RDF and increase its bulk density for intermediate storage and, eventually, shipping (Bilitewski, 2011). One of the largest disadvantages of RDFs are their low densities and high volumes per unit of recoverable thermal energy, limiting their use in practice by making transportation costs higher and completely inefficient from an energy perspective beyond a certain shipping distance. Compaction attempts to overcome this obstacle by increasing the energy density and bulk density (Bilitewski, 2011), so more fuel can travel per unit volume, reducing transportation costs and emissions. Pellet presses are most commonly used. These include ring matrix presses, flat matrix presses, and John Deer presses, among others (Bilitewski, 2011).

Balers are also used to compact cardboard and certain types of plastic, but this technology is usually used to ship materials for further processing at a later stage (Rotter, 2011). For example, if Ugandan composters wanted to sell RDF to cement producers, but did not have the funding to invest in separation and size reduction technologies, then a baler might be used instead to compact certain waste fractions to be shipped to the cement producers, where they would sort and shred the baled waste onsite to produce RDF.

In the case of sub-Saharan Africa, there have already been a number of examples where RDF has been produced and implemented in the cement industry. Cimentos de Mozambique of Intercement, for example, recently developed and implemented its strategy for co-processing in its cement plant. First, the MSW was quantified and assessed for the regions of Maputo and Matola and it was determined that of the 200,000 tons of MSW generated per year, about 64,000 tons (32%) was solid waste that could be processed for RDF production (Cimentos de Mozambique, 2015). From there, about 30% of this solid waste was separated out for recycling and the remaining 70% of the solid waste would be ground into RDF to be co-processed in the cement kiln (Cimentos de Mozambique, 2015). Ultimately, implementation started in 2017 with the goal of reaching at least 40,000 tons of RDF co-processed per year by the end of 2018 (Cimentos de Mozambique, 2015), but follow-up reports have yet to be published confirming their progress.

For the RDF to be produced for Cimentos de Mozambique, a chain of the mechanical processes described above had to be linked up in a process line for the combustible waste fractions to be utilized. This included joining a primary shredder, an iron separator, a heavy fraction separator, and finally, a second, finer shredder in that specific order to produce the final product, RDF (Cimentos de Mozambique, 2015). Finally, for the RDF to be used in the kiln, a number of adjustments to the cement plant had to be made. The most important were the addition of fuel silos that can temporarily store the RDF before use and a special RDF feed-in system into the burners (both primary and secondary firing systems) (Cimentos de Mozambique, 2015).

It is very important to note that once a 10% fuel replacement with RDF in a cement plant has been reached, a number of modifications to the plant might be necessary for further substitution of RDF for traditional fuel sources. In addition to the modifications listed for the Cimentos de Mozambique plant above, typical cement plant adjustments might also include: a debaler, weight/dosing mechanisms, material handling (mechanical versus pneumatic transport), pipe above burner, flexible multi-fuel burner, calciner, emission analysis system, and a triple gate system for solid RDF feeding that reduces "false air" intake (World Bank Group, 2017).

1.2.4 Description of cement production and Uganda's cement industry

Carbon dioxide emissions from cement production account for around 9.5% of the world's total CO_2 emissions (Olivier, et al., 2014). As would be expected, this is due to two specific aspects of cement production: 1) the sheer volumes of cement that are being produced annually worldwide; and 2) the actual process itself whereby cement is produced. In 2016, 807 million tons of cement were produced globally to meet the ever-increasing demands for construction and infrastructure projects of countries around the world; most notably in China and India (WBCSD, 2016). Within the actual production process, there are two primary places where CO_2 is emitted as a byproduct: 1) the chemical conversion of calcium carbonate ($CaCO_3$) to lime (CaO) (responsible for roughly 60-70% of the emissions); and 2) the fuel burned to heat the raw materials to the temperature necessary to catalyze the chemical reaction (30-40% of emissions) (Olivier, et al., 2014).

First, limestone and clay are quarried from natural reserves which are generally abundant in most regions of the world. The raw materials are then grinded to a suitable consistency and level of homogenization, before being heated to 1,500 degrees Centigrade (Lafarge, 2019). There are two phases of heating that take place: first in a secondary firing system to preheat the raw materials, and then in a primary firing system to bring the limestone mixture up to the optimal temperature and hold it there long enough (residence time) for the chemical conversion to take place (Rotter, 2011). This primary heating process takes place in a long rotating kiln with a single flame at the lower end.

Once this calcination has occurred, where calcium carbonate in the limestone mixture has been converted to lime, it is then known as clinker. The clinker is then mixed with any number of additional additives (e.g. Gypsum) to fine-tune the setting and resultant physical properties of the cement, and ground into a fine powder to form the finished product—cement (Lafarge, 2019). Depending on the production process and availability of other suitable raw materials, a variable percentage of clinker may be substituted out of the cement to reduce the CO_2 emissions per ton of produced cement (Worrell, et al., 2001). This is commonplace in many European countries, but to what extent Ugandan cement producers carry out this practice was not determined (by the resources available to the author of this study), leading to the necessary assumption that Ugandan cement contains more than 90% clinker, an oftentimes unnecessarily high percentage for the most common applications of cement.

The country of Uganda has four main cement producers that make up almost all of the cement production of the country: Tororo Cement Limited, Hima Cement Limited, Kampala Cement Company Limited, and Simba Cement Uganda Limited. Hima Cement is a subsidiary of France's Lafarge and Simba Cement Uganda is a subsidiary of Kenya's National Cement Company Limited (Lafarge, 2019). There are many limestone deposits throughout the country (see Figure 1.11 below), but the two largest are in Hima and Tororo, hence the apt placement and naming of two of the cement producers and their corresponding mining activities (Uganda Investment Authority, 2016). In 2018, it was estimated that the total production capacity of Uganda's cement producers was around 6.8 million tons of cement (Global Cement, 2018), with Tororo, Hima, Kampala, and Simba having 44%, 28%, 15%, and 13% of the market share respectively (Khisa, 2018). Although domestic demand does not meet the current supply capacity of the producers, demand and sales in neighboring countries such as Rwanda, eastern Democratic of Congo, western Kenya, and South Sudan, have relieved worries of excess supply (Global Cement, 2018).

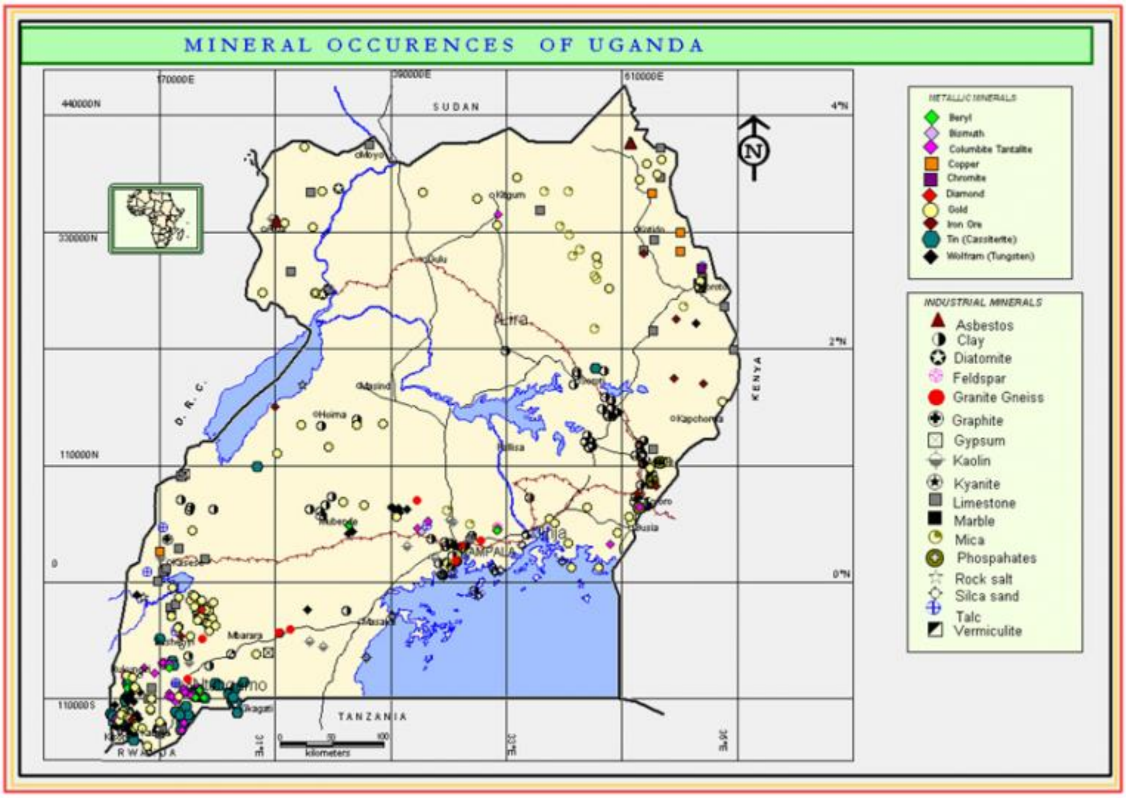


Figure 1.11: Map of mineral occurrences in Uganda (Uganda Investment Authority, 2016)

Even as the average MJ per ton of clinker on the African continent has decreased over time (from 3,800 MJ/ton in 2015 to 3,750 MJ/ton in 2016), the thermal energy demand for production of such tonnage of cement is nevertheless massive (WBCSD, 2016). In this regard, Ugandan cement producers have a vested interest in improving the efficiency of their processes by taking measures that lead to a reduction in the amount of energy required to produce each ton of cement. The two most reliable methods for doing this (besides switching from a wet to dry production process) are 1) to reduce the proportion of clinker in the overall cement by using other raw materials that do not degrade the quality of the cement; and 2) by implementing alternative fuels (AFs) that reduce the necessity to use primary fossil fuels as the exclusive energy source.

Already some of the cement producers in Uganda have begun using waste materials like coffee husks, sawdust, rice husks, and bagasse from sorghum stalks as AFs in their kilns (Lafarge, 2019), but the potential for additional substitution of the energy demand has yet to be fully realized via, for example, refuse-derived fuels from municipal solid waste.

1.3 Research questions

1. Based on the waste inputs to each active composting plant, what are the potential quantities of refuse-derived fuel that can be produced as a fossil fuel replacement in Ugandan cement production?

2. Based on the waste composition entering the active composting facilities, what would be the resulting composition and quality of the refuse-derived fuels from each facility, especially from the perspective of their heat values?

3. What is the potential for a net greenhouse gas emission reduction, especially in consideration of the primary fossil fuel resources preserved during clinker production, and in relation to the biogenic and fossil carbon fractions in the resultant refuse-derived fuels? How many tons of CO_2 equivalent could be saved?

1.4 Objectives

- Investigate whether small-scale composters in Uganda can benefit from converting their compost residuals into refuse-derived fuel instead of landfilling them at final disposal sites.

- Investigate whether a focus on refuse-derived fuel production as an additional step in the composting process helps improve the quality of their compost, making it more valuable and marketable to local agriculturalists, all while producing a second marketable product for additional revenue generation.

- Investigate whether linking two Ugandan industries, namely waste management and cement production, creates beneficial synergies that lead to positive economic and environmental outcomes, by reducing the need for primary fossil fuels (including costs for said fuel) and generating additional income for the composting facilities.

- Investigate whether the implementation of refuse-derived fuels as a substitute for heavy fuel oil and petroleum coke in clinker production can contribute significantly to Ugandan cement producers' growing energy demands.

- Investigate whether a net reduction in greenhouse gases could qualify for additional investment/funding under the Clean Development Mechanism of the Kyoto Protocol.

2. RESEARCH CHAPTERS

2.1 Methodology

2.1.1 Scope

Much of the scope is already predetermined by the CDM Uganda Municipal Waste Compost Programme, given that this project attempts to build off of this ongoing programme. Only the 9 (of the 17 total) Ugandan municipalities that were reported to be operational at the time of the 2015 CDM Monitoring Report will be considered. They include CPA's 1-9 as determined by the Monitoring Report and are in order as follows: Jinja (1), Fort Portal (2), Kabale (3), Kasese (4), Lira (5), Mbale (6), Mukono (7), Soroti (8), and Mbarara (9) (Tumuhairwe & Kakeeto, 2015).

Additionally, three Ugandan municipalities that play host to the country's four primary cement producers will also be considered. They are: Hima, Tororo, and Namataba.

Given that many different waste streams can be processed into different forms of alternative fuels (AFs), it is important to note that only residuals from composting municipal solid waste (MSW) will be considered in this project for RDF production. Other waste streams, such as agricultural waste, medical waste, industrial waste, and unprocessed MSW, are withheld from the scope intentionally. Only MSW is composted at the nine composting facilities, and the combustible waste fractions following this process are the focus (i.e., the residuals).

Four Ugandan cement producers are included in the scope of this project. They are the largest in operation and include: Tororo Cement Ltd, Hima Cement Ltd, Kampala Cement Company Ltd, and Simba Cement Uganda Ltd (also sometimes referred to as "National Cement Company Uganda (Khisa, 2018)).

Not within the scope are the economic considerations of processing residuals to produce refuse derived fuels. Examples include things like the investment costs (e.g., equipment), costs of fuels for transportation, human capital, and infrastructure improvements that lead to better waste collection and management in the composting municipalities.

Finally, important aspects of CO_2 determinations are excluded from the scope. For example, emissions from fuels used to transport RDFs to cement producers, or the emissions prevented by not dumping and landfilling paper. Only the CO_2 emissions related directly to burning of fuels (traditional or alternative) in the primary and secondary firing systems of the cement producers with integrated cement plants are considered for emission reduction calculations. Other gases and emissions from all of these processes are also excluded from consideration (e.g., dust, heavy metals, acids, particulate matter, NO_x, SO_x, and so on).

2.1.2 Methods and materials

i. Material flow analysis and mass balances

Using data retrieved from literature as inputs, STAN software (provided by the Technical University of Vienna) will be used to organize the waste fractions and their respective flows to develop a material flow analysis (MFA) diagram, depicting the individual theoretical and actual processes that make up the entire composting and theoretical RDF production system. This can be done with waste input quantities and waste composition inputs. For reference, a diagram of the procedure to develop an MFA is provided in Annex I from the "Practical Handbook of Material Flow Analysis" (Brunner & Rechberger, 2005).

Transfer coefficients for each material subjected to a particular process in the system will be determined based on actual data and reference values from the literature. Transfer coefficients derived from actual input and output data (e.g., organic waste input versus compost output) will provide suitable points of comparison for the MFA modeled after the expected outputs from the Program of Activities (POA) project document and the reference values observed in the literature.

ii. RDF Quantity

Based on the waste quantity inputs, waste composition, and recycling context of Uganda (e.g., manual picking), the transfer coefficients for the remaining combustible materials can be determined. Applying said transfer coefficient to the waste quantity values will determine how much refuse-derived fuel could have been produced in theory, had this scheme been in place during the monitoring period.

iii. RDF Quality

Waste composition data combined with the transfer coefficients derived for the MFA diagram, will then be used to show which specific combustible materials result in the respective paper and plastic RDFs upon separation. The lower heat values of the specific waste fractions can then be applied to the two mixtures based on their proportions to calculate the overall heat value of the two refuse-derived fuels (paper and plastic).

iv. Emissions

Emissions will be determined using the methodology outlined by the 2006 IPCC Guidelines for National Greenhouse Gas Inventories used to determine CO_2 emissions from burning MSW. This includes the following steps:

- Identify type of waste to be burned (Guendehou, et al., 2006): MSW in Uganda in this case
- Identify specific quantities of waste to be burned (Guendehou, et al., 2006)
- Determine the waste composition of the MSW and for each waste fraction, use "default values" (also supplied by the IPCC) to determine each individual waste fraction's "dry matter content, total carbon content, and fossil carbon fraction" (Guendehou, et al., 2006)

- Calculate the CO_2 emissions based on these values using the IPCC equation found in Annex II (Guendehou, et al., 2006)

This method will be applied to the waste fractions that comprise the paper and plastic refuse-derived fuels, and to the fuels determined to be in use for clinker production in Uganda's cement producers, from which the ultimate CO_2 reductions will be determined.

2.1.3 Data collection

As a first step in the study design, a number of critical decisions had to be taken:

- Would there be a field visit to Uganda to gather primary data?
- Which datasets would be used to determine the quantities and composition of the inputs for the ultimate output quantities and heat values of refuse-derived fuel to be derived?
- How many and which specific composters would be included in the scope of the study, given the selected datasets?

i. Forgoing primary field research in Uganda

The original design of the study included a field visit to Uganda with specific visits planned to Kampala, 3-4 of the composting facilities (e.g., Soroti, Lira, Jinja, Fort Portal), and even a potential visit to one of the cement manufacturers (e.g., Hima Cement Limited or Tororo Cement Limited). Additionally, the visit would have included meetings with officials from the National Environment Management Authority, researchers from Makerere University (Kampala) responsible for taking waste and compost samples under the CDM composting project, waste handlers, especially those collecting MSW for delivery to the composting facilities, and even representatives of the Belgian Development Agency and World Bank, responsible for funding and helping to implement the project.

Should this field visit have been possible, primary data from the aforementioned personal meetings and interviews, field sampling of waste and compost residues, and the results of a predetermined formal survey, requesting more precise information about each of the composting facilities would have all been available for data processing and analysis. Unfortunately, upon multiple failed attempts to acquire funding for said field visit via multiple avenues—university scholarships, student stipends, sponsorship by an NGO or research institute, and finally, personally derived funding—the ultimate decision had to be taken to forgo such a research trip, given the personal financial limitations of the author.

ii. Choosing reliable data from the literature

In the wake of this decision to forgo primary field research, a new study design had to be formulated to address the research questions. Most importantly, a full reliance on literature and past research studies had to be realized as the sole source of data for this study.

As such, given the availability of a number of datasets regarding waste collection information, waste composition at the composting sites, and the composition of landfilled compost residues, it was of utmost importance to determine which would be most reliable and accurate for the purpose of this study. The decision came down to two reliable sources of information: the officially reported data in the CDM Project Monitoring Report for the period of May 1, 2012, to December 31, 2013 (Tumuhairwe & Kakeeto, 2015); and the waste analysis data collected by Makerere University and reported by NEMA from 2006 (Kyambadde, 2006).

Ultimately, the decision was taken to use both datasets for two different specific purposes: 1) the CDM Monitoring Report to derive quantities of MSW entering into each composting facility (Table 2.1 below) (Tumuhairwe & Kakeeto, 2015); and 2) the data reported by NEMA from 2006 for the composition of the waste at each of the nine composting municipalities (Figure 2.1 below) (Kyambadde, 2006). *Id est*, one for determining the quantities of RDF possible, and the other for the theoretical composition of the RDFs produced by each composter.

Table 2.1: MSW input quantities taken from the 2015 CDM Monitoring Report (Tumuhairwe & Kakeeto, 2015)

CPA Number	Municipality Name	Total MSW (tons)
1	Jinja	30,927
2	Fort Portal	32,851
3	Kabale	34,324
4	Kasese	18,222
5	Lira	11,874
6	Mbale	31,548
7	Mukono	28,315
8	Soroti	19,233
9*	Mbarara*	17,474*
	TOTAL	224,768

* Monitoring period of 12 December 2012 – 31 December 2013; CPAs 1-8 from 1 May 2012 – 31 December 2013

Although NEMA's data is likely out of date at this point, given that it is thirteen years old and Uganda has experienced many demographic and economic changes that would indeed lead to changes in the waste composition throughout the country (World Bank Group, 2019), it is still a data set with more specific information regarding the composition of the incoming MSW; with details that are important to the eventual heat value determinations of the refuse-derived fuel to be described. Additionally, it is based on more reliable testing procedures in a university laboratory setting, therefore, even being older, it can be assumed that this data is more realistic and accurate than the data presented by the CDM Monitoring Report.

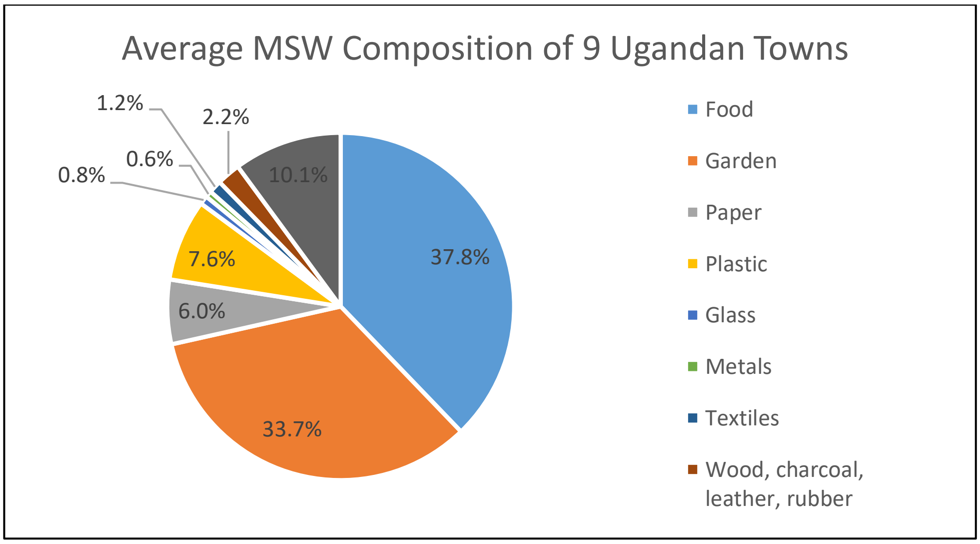


Figure 2.1: Average MSW composition taken from the 2006 NEMA study (Kyambadde, 2006)

Any data that was unavailable for Uganda or any of its municipalities (especially those involved in this study) was taken from other literature involving countries in the Sub-

Saharan Africa (SSA) region, where similar determinants of waste are assumed to be true. In particular, an example for specific waste sub-fractions to serve as a model for this study was required to reach the level of waste composition specificity necessary for a more accurate heat value determination of the theoretical refuse-derived fuels. Waste composition samples from a study in Ghana were used based on their accuracy, similarities to Uganda's waste circumstances, and more simply, the sheer availability of the data.

iii. Scope readjustment based on available data

Theoretically, it should have been possible to determine values of RDF production for each of the 17 municipalities enrolled in the full scope of the CDM Programme of Activities, but only 9 of the 17 were selected for the purpose of this study. The 9 include those listed in Table 2.1: Jinja, Fort Portal, Kabale, Kasese, Lira, Mbale, Mukono, Soroti, and Mbarara. The decision to analyze data and generate values for only 9 of the 17 composting facilities was based on a number of factors.

First and foremost, based on the National Environment Management Authority's Annual Corporate Report for Fiscal Year 2017/2018, which covers the period of July 1, 2017, to June 30, 2018 (Central Intelligence Agency, 2019), only 12 of the 17 composting facilities were actually actively composting waste (as of June 30, 2018) (Okurut, et al., 2018). Additionally, the most viable data sets that were selected for the purpose of this study (described in the previous subsection), only include specific information on the 9 composting facilities that have been selected, likely because during the time of reporting the additional three facilities were not yet in operation. As such, the data available on the additional three municipalities—namely, Arua, Hoima, and Masindi (Okurut, et al., 2018)—was either negligible or nonexistent, leading to the ultimate decision that they should be left out of the scope of this study.

iv. Generation of heat values for RDFs

Based on the composition of the compost residues from each of the nine municipalities, the heat values for the resultant RDFs that could be generated were estimated based on the reference values in Annex IV. While there are no established heat value standards for particular waste fractions, the comprehensive samples and substance compositions from a Danish household in Christensen's "Solid Waste Technology & Management" book, provide a reliable basis for use, given that the carbon content of many materials, like plastics, for example, are likely very similar internationally (Riber, et al., 2009).

Admittedly, these values are by and large representing waste samples from predominantly European countries, and therefore, European climates and sub-climates, which, of course, differ entirely from the climate of Uganda. This would undoubtedly affect the moisture content of the incoming waste fractions and sub-fractions, but since there were no additional reliable sources identified for sub-Saharan Africa, this simply needed to be accepted as a limitation of this study.

v. Theoretical values

In addition to theoretical reference values for the heat values, for the sake of some calculations, the proposed MSW input per municipality was set at 70 tons per day. This is the design capacity described in the CDM Monitoring Report of the Program of Activities of the Uganda Municipal Waste Compost Programme. This is an idealized value used to develop theoretical RDF values to be reached as waste collection nationwide improves over time.

2.2 Results and study findings

2.2.1 Overall system process

Before any of the values for different waste fractions could be processed for the sake of estimating potential RDF outputs, the overall system, with its individual process steps, needed to be determined. The process steps of each composting municipality were observed in detail individually to ultimately derive and describe the overall system of material flows, which, with very little deviation, was the same for each municipality. As expected, the quantities of the flows were found to vary significantly from municipality to municipality, but for a general system description this was not a necessary element of consideration.

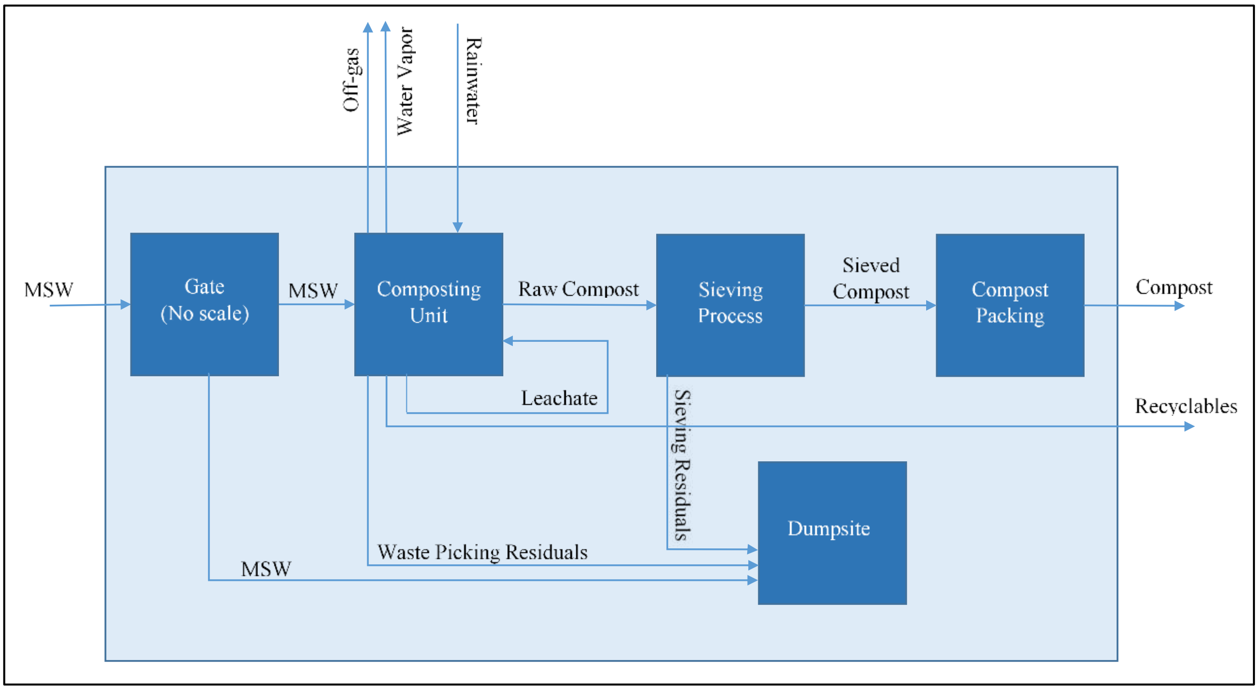


Figure 2.2: Overall system process for Uganda's Municipal Waste Compost Programme

2.2.2 Description of each individual process and material flow

i. Municipal solid waste collection and entry gate

The entire process starts with municipal solid waste collection in the respective communities where a composting site has been established. Generally speaking, waste collection has been organized by the municipal authorities either by undertaking the collection themselves using public funding to hire staff and purchase waste collection equipment, or by contracting out the public service to third-party private waste handlers.

The MSW is then transported via trucks to the composting site, where it must gain entry to the facilities. There is a quick check to ensure that the waste is truly MSW and therefore, suitable for the composting process, and that it is not some other type of specific waste stream (e.g., medical waste or construction waste) that could potentially contaminate or reduce the quality of the overall compost. Theoretically, to gain entry to the composting facility, the trucks should have to drive across scales that determine the total weight of the truck filled with MSW for monitoring purposes (empty truck then weighed upon exiting and the difference determines the amount of MSW deposited).

Unfortunately, it was found that most of the compost sites do not have scales, or of those that did, most were not functional or not in use.

During the primary dry season of Uganda, taking place between June and August (there is a second, lighter dry season between December and February) (CIA, 2019), composting becomes difficult in many parts of the country. For composting to be successful, the compost must remain moist during the entire duration of the process. If the moisture content drops below 12-25%, then very little biological activity can occur (Krogmann, et al., 2011). Even with water being produced by respiring microorganisms, the compost has a tendency to dry out during these months and stop the decomposition process. As such, it’s not always feasible for the composting facility to accept all of the MSW that it receives. This is due either to the halting of compost production altogether as a result of these dryer months, or because the facility simply doesn’t have the capacity (staff, or otherwise) to compost the sheer quantities of incoming waste.

Any of the MSW that’s unable to be utilized by the facility, is then therefore sent directly to the local disposal site.

ii. Composting windrows and associated material flows

During the composting process, the MSW is spread out in large rows and composted in aerobic conditions for anywhere between 12-72 weeks (Krogmann, et al., 2011). The retention time depends on the composition of the feedstock or waste input and how often the compost is turned. A large (windrow) turning machine (in this case, a tractor with a front-end loader) mixes the decomposing waste between one and seven times per month to ensure that the compost has a consistent temperature and moisture content, as well as to increase porosity so that aerobic conditions are maintained (Krogmann, et al., 2011). As the waste decomposes, it emits mass amounts of carbon dioxide, water, and an additional mixture of other off-gases (not significant to the scope of this study), as microorganisms break down the organic carbon in the waste to use its chemical energy.

During this process, staff of the composting facility also pick out non-compostable materials from the compost by hand to improve its quality/purity. These manual waste picking residuals are then either classified as recyclable materials (certain types of paper, plastics, and metals) to be sold for additional revenue, or they are deemed inadequate for recycling and sent to the local dumpsite for final disposal.

Figure 2.3: Manually picked plastic bottles in Masindi

The windrows of each composting facility is equipped with roofing intentionally to avoid excess leachate production and unnecessarily high moisture levels during the wet seasons. Nevertheless, leachate is produced via the water resulting from the respiration process of aerobic microorganisms within the compost. Both rainwater and leachate are collected and mixed in with the compost to maintain optimal moisture levels for the process to continue, especially during the dry season. Some facilities are equipped with rain harvesting containers where water can be stored through dry periods exactly for this purpose.

Figure 2.4: Man working in front of the Mukono composting windrows
SOURCE: The Uganda Waste Report, ©Timothy Bouldry, 2018

Finally, the resulting material at the end of the 12-72 week composting process (Krogmann, et al., 2011) is raw compost, ready for final sieving and purification.

iii. Sieving process and compost packing

Before the final compost is packed in plastic sacks and ready to be sold to local farmers as a fertilizer, it is sieved. This sieving process is most often completed with a manual hand-crank sieve, but some facilities have more advanced technologies due to funds from the World Bank (e.g., gas-powered trommel sieve). The ultimate purpose is to reduce the number of impurities still contained within the compost from the original solid waste. This might include inert materials like ash, glass, gravel, and metals, as well as combustible materials like different grades of plastic, cardboard, paper, textiles, and wood.

Once siphoned off from the compost, the sieving residuals are then sent to the local dumpsite for final disposal (the primary intervention possibility for RDF production). The final compost is then packed into the aforementioned sacks for shipment, with ideally the highest quality attainable given the technologies and techniques implemented.

iv. Final disposal site

Any undesirable materials, i.e. residuals and excess MSW, are sent to the local designated final disposal site. It is these particular residuals of the entire composting process that are the primary focus of this study. Because of their composition and heat values, a large proportion of the residuals are combustible and viable for refuse-derived fuel production.

Figure 2.5: Sieved residuals to be sent to the disposal site in Masindi

The disposal sites themselves have been by and large determined to be dumpsites. Although, the dumpsites are managed to varying degrees and capacities by the local authorities or contracted waste handlers, no particular dumpsite within the nine respective municipalities that are the focus of this study qualified to be categorized as a landfill or sanitary landfill.

2.2.3 *Material flow analysis of composting plants*

First, a material flow analysis diagram was developed to show the actual material flows based on the data from the CDM Monitoring Report. The values have been rounded, but it is clear to see the already high level of inefficiency in compost production, making up only 2.4% of the total MSW input (3.3% of organic waste). See Figure 2.6 below.

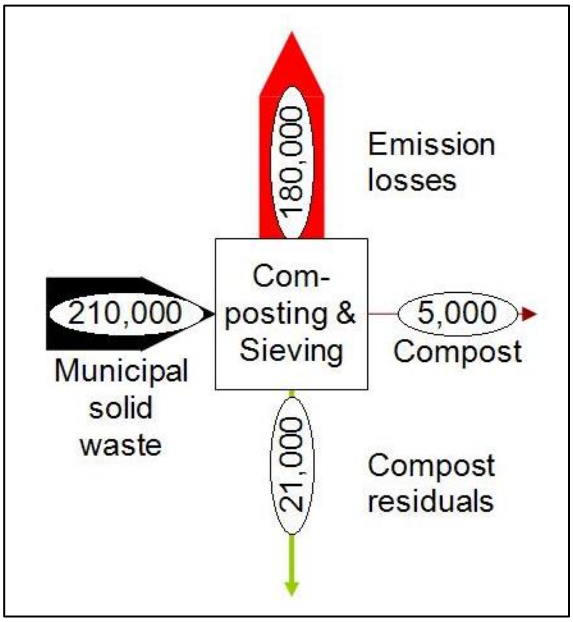


Figure 2.6: Total material flows in tons of 8 composting plants in Uganda between May 2012 and December 2013

As previously stated, two sets of data were combined to obtain the most specific information available and realize the most accurate results for this study. This began with determining the material flows within the composting facilities and balancing the masses of each flow based on the overall inputs and outputs. The CDM Monitoring Report was used to provide the actual values for the MSW quantity inputs of each composting facility during the reporting period of each respective CPA, while the NEMA reported data was employed to determine the composition of the waste fractions within the MSW. This data was then combined with values recorded for a typical composting facility composting mixed bio-waste, taken from Boldrin et al. (see Annex III), to determine the transfer coefficients of the inputs and outputs. See Table 2.2 below for details.

Table 2.2: Theoretical outputs based on actual MSW inputs at nine composting facilities for the monitoring period between May 2012 and December 2013 (Tumuhairwe & Kakeeto, 2015)

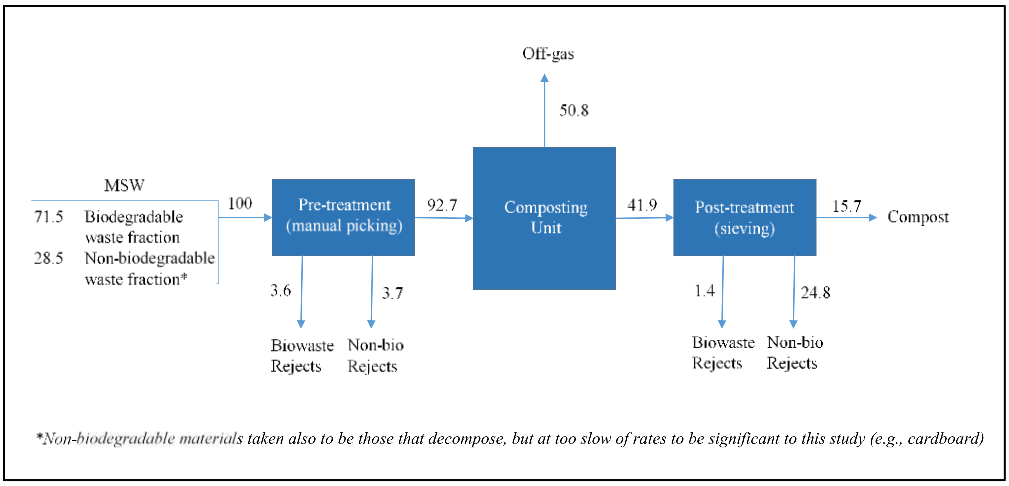
	INPUT	Input Contents				OUTPUTS					
CPA	MSW (tons per monitoring period)	Organic MSW (tons)	Paper (tons)	Plastic (tons)	Other MSW (tons)	Compost Off-gases (tons)	Compost (tons)	Paper RDF (tons)	Plastic RDF (tons)	Paper and Plastic Recycling (tons)	MSW Outputs (Residuals) (tons)
1	30,927	22,113	1,856	2,350	4,608	15,699	4,865	928	1,645	1,076	6,714
2	32,851	23,488	1,971	2,497	4,895	16,675	5,167	986	1,748	1,143	7,132
3	34,324	24,542	2,059	2,609	5,114	17,423	5,399	1,030	1,826	1,194	7,452
4	18,222	13,029	1,093	1,385	2,715	9,249	2,866	547	969	634	3,956
5	11,874	8,490	712	902	1,769	6,027	1,868	356	632	413	2,578
6	31,548	22,557	1,893	2,398	4,701	16,014	4,963	946	1,678	1,098	6,849
7	28,315	20,245	1,699	2,152	4,219	14,373	4,454	849	1,506	985	6,147
8	19,233	13,752	1,154	1,462	2,866	9,763	3,025	577	1,023	669	4,175
9*	17,474*	12,494*	1,048*	1,328*	2,604*	8,870*	2,749*	524*	930*	608*	3,794*
Total	224,768	160,709	13,486	17,082	33,490	114,092	35,356	6,743	11,958	7,822	48,797
$TC_{x/MSW}$	1	0.715	0.06	0.076	0.149	0.5076	0.1573	0.03	0.0532	0.0348	0.2171

*Monitoring period of 12 December 2012 – 31 December 2013

As can be observed, had the amount of compost expected to be produced from these values of MSW been produced, then more than 35,000 tons of compost would have been made available to local farmers. This value was unfortunately much lower due to the many inefficiencies at each individual composting site. Furthermore, the MSW inputs reflect 20 months of monitoring, indicating daily waste inputs far below the 70 tons prescribed by the project design document of the POA.

The purpose of this table is primarily to show the theoretical quantities of plastic and paper RDF that could have been produced during this period, had the infrastructure and intention to do so been in place.

Corresponding to this table, a mass balance diagram was constructed to better visualize and understand the quantities of material flows in the entire system. Values from Annex III were also used to develop the values in Figure 2.7 below, where 22% of the organic waste input is converted to compost (based on POA design), 7% of the organic waste is rejected and disposed of, and the rest of the organic waste is given off as off-gas in the form of carbon dioxide and water.

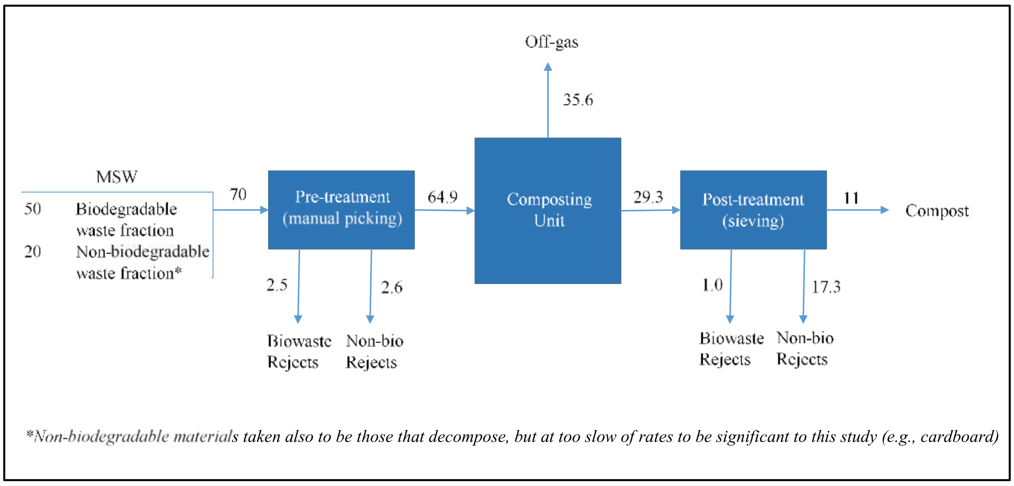


*Non-biodegradable materials taken also to be those that decompose, but at too slow of rates to be significant to this study (e.g., cardboard)

Figure 2.7: Mass balance for a typical composting plant under Uganda's Municipal Waste Compost Programme

2.2.4 Idealized material flows

While input values were provided by the 2015 Monitoring Report from the CDM composting project, the original programme of activities (the project design document) explicitly stated that the design of each composting facility would provide an input capacity of 70 tons of MSW per day. Furthermore, the compost output was set for 22% of the biowaste fraction of the MSW input, also per the POA design. In actuality, both of these values have proven to be, on average, much lower than originally prescribed by the designers of the project. Nevertheless, the ultimate efficiency goals of each composting facility are to reach these values (an input of 70 tons of MSW per day, and a 22% compost output) during the course of the entire project timeline, which runs until October, 2028 (Tumuhairwe & Kakeeto, 2015).



*Non-biodegradable materials taken also to be those that decompose, but at too slow of rates to be significant to this study (e.g., cardboard)

Figure 2.8: Mass balance for composting facility with daily input of 70 tons MSW

As such, a second mass balance diagram (Figure 2.8 above) and a material flow analysis (MFA) diagram have been generated using an input of 70 tons of MSW per day (for a total of 25,550 tons per year) that reach any given active composting facility within the scope of the project. Additionally, the compost output was set to 22%, based on the 71.5% biowaste fraction taken directly from the averages of the waste composition of all nine municipalities provided by NEMA's data (Kyambadde, 2006). These values can be seen clearly in Figure 2.9 and the accompanying Table 2.3 below.

The transfer coefficients, in Table 2.3 labeled as "$TC_{x/MSW}$", refer directly to what percentage each input/output fraction have in relation to the overall mass input of municipal solid waste. As such, one can see how the masses are balanced throughout the entire process to convert organic carbon to useable fertilizer for local farmers, and how the paper and plastic waste fractions are separated from the overall MSW for them to be utilized as refuse-derived fuel. The coming sections will describe in detail the heat values of the RDFs and their viability for use in the cement industry.

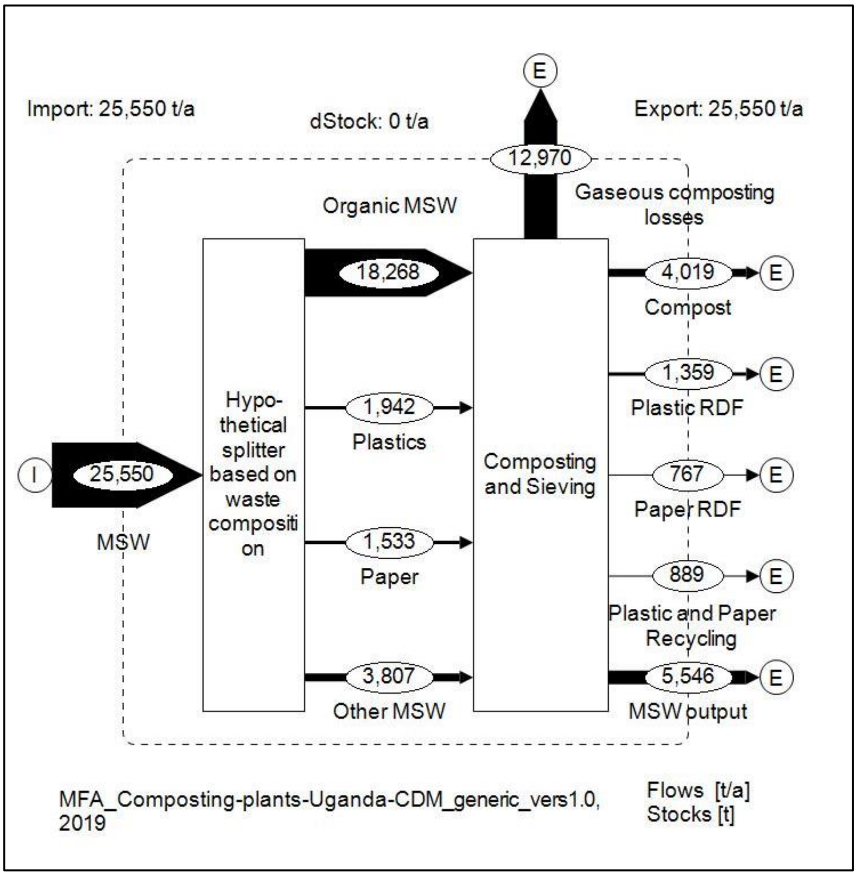


Figure 2.9: Idealized Material Flow Analysis based on 70 tons MSW/day input

It is easy to see that between the hypothetical splitter and the composting process that the MSW output increases, which at first glance, might not be 100% clear. There are two additional inputs to the resulting MSW output responsible for this: 1) bio-waste rejects that are not completely suitable or degraded during the composting process and are sieved out of the compost before packaging and shipping; and 2) the fraction of paper in the MSW that is not suitable for recycling or burning as part of the paper refuse-derived fuel, because, for example, it's too wet or contaminated.

Table 2.3: Mass balance and transfer coefficients for idealized Ugandan composting facility

	INPUT	Input Contents				OUTPUTS					
Idealized Model	MSW (tons/year)	Organic MSW (t/yr)	Paper (t/yr)	Plastic (t/yr)	Other MSW (t/yr)	Compost Off-gases (t/yr)	Compost (t/yr)	Paper RDF (t/yr)	Plastic RDF (t/yr)	Paper and Plastic Recycling (t/yr)	MSW Outputs (Residuals) (t/yr)
Idealized CPA	25,550	18,268	1,533	1,942	3,807	12,969	4,019	767	1,359	889	5,547
$TC_{x/MSW}$	1	0.715	0.06	0.076	0.149	0.5076	0.1573	0.03	0.0532	0.0348	0.2171

Given the inputs and the average MSW composition taken from the NEMA data, the transfer coefficients were calculated and the output values were determined. In this case, it's important to note that the fixed 22% compost output applies exclusively to the organic waste fraction in the inputs, hence why it is 15.73% of the overall MSW.

It was estimated that about 30% of the plastics in the MSW would be of high enough quality to be recycled. The rest of the plastics would be separated from the MSW and further processed to be used as an RDF with a high heat value. Paper, by contrast, was taken to be much more easily tarnished by the other waste fractions in the MSW and even subjected to (assumed to be negligible for the purpose of this study) the beginnings of the decomposition process brought about by the composting windrows. As such, 50% of the total paper content was taken to be viable for RDF production, while 20% was taken to be of high enough quality still to be recyclable, and the final 30% was transferred to the final MSW output, containing all other reject materials of the process. Presumably, upon deeper investigation a small fraction of this reject paper fraction would also end up in the off-gases as a result of some decomposition, but as already stated, this was taken to be a negligible for this study.

The emissions, described here in Table 2.3 as off-gases, would be primarily carbon dioxide (CO_2) and water vapor, as shown in Figure 2.9, as long as the aerobic conditions are maintained throughout. As this is an idealized compost facility, this can be assumed. As already stated, there may be even higher values for the off-gases, given that other parts of the MSW might additionally decompose that were not considered here in this model.

Finally, the MSW output with reject materials is worth mentioning, because only the values for paper and plastic RDFs were derived in this study. For the sake of simplicity, this was intentional, but in actuality, other waste fractions in the MSW might also be useful to include in each RDF for their respective heat values. Some examples of these materials include: rubber, textiles, charcoal, leather, and wood (Kyambadde, 2006).

2.2.5 RDF quantity estimations

Based on the material flows generated using the 70 tons MSW per day input values, theoretically, each composting plant has the ability to produce 767 tons of paper RDF per year and 1,359 tons of plastic RDF per year. This results in an RDF potential of 6,903 tons per year for paper and 12,231 tons per year for plastic, as can be seen in Table 2.4.

Table 2.4: Theoretical RDF yields based on design capacity inputs

CPA Name and Number	Paper RDF Yield (t/yr)	Plastic RDF Yield (t/yr)
1.) Jinja	767	1,359
2.) Fort Portal	767	1,359
3.) Kabale	767	1,359
4.) Kasese	767	1,359
5.) Lira	767	1,359
6.) Mbale	767	1,359
7.) Mukono	767	1,359
8.) Soroti	767	1,359
9.) Mbarara	767	1,359
TOTAL (tons/year)	6,903	12,231

If considering the total outputs of all of the active composting facilities (including Arua, Hoima, and Masindi), then these values become 9,204 and 16,308 tons per year for paper and plastic RDF respectively. Eventually, all seventeen composting facilities will be active, and the maximum potential output based on this initial conception will jump up to 13,039 and 23,103 tons per year.

Unfortunately, there is a long way to go before these values will be attained. Based on the waste input quantities reported between May 1, 2012, and December 31, 2013, even if paper and plastic had been separated out from the other residual fractions and processed to generate RDF during this period, the potential values would have been far below the proposed idealized values in Table 2.4. For the estimated RDF values that could have been generated during this period, see Table 2.5 below.

Table 2.5: Potential RDF yields based on the actual quantities of MSW entering the respective composting sites (Tumuhairwe & Kakeeto, 2015)

CPA Name and Number	MSW 5/2012-12/2013	Adjusted MSW (tons/year)	Paper RDF Yield (t/yr)	Plastic RDF Yield (t/yr)
1.) Jinja	30,927	18,556	557	987
2.) Fort Portal	32,851	19,711	592	1,049
3.) Kabale	34,324	20,594	618	1,096
4.) Kasese	18,222	10,933	328	581
5.) Lira	11,874	7,124	214	379
6.) Mbale	31,548	18,929	568	1,007
7.) Mukono	28,315	16,989	509	904
8.) Soroti	19,233	11,540	346	614
9.) Mbarara*	17,474*	17,474	524	930
TOTAL (t/yr)	224,768	141,850	4,255	7,546

*data for CPA 9 (Mbarara) is taken from the period December 2012 to December 2013

For a proper 1:1 comparison of the theoretical optimized values, and the theoretical values based on the actual waste inputs entering the composting facilities, the monitoring data had to be modified slightly. The monitoring period for CPAs 1-8 took place during the course of 20 months (May 1, 2012, to December 31, 2013), and not a single year's time (Tumuhairwe & Kakeeto, 2015). Therefore, to derive the theoretical values that would be expected to be produced based on the inputs in a full calendar year, each MSW quantity for CPAs 1-8 was multiplied by 0.6. This, of course, is not a perfectly sufficient estimation, as there would be variation to be expected on a monthly basis in terms of the MSW that is readily delivered to each site, but it nevertheless provides a reasonable enough estimate for the sake of comparison.

CPA 9 (Mbarara) in particular, had a monitoring period from December 12, 2012, to December 31, 2012 (Tumuhairwe & Kakeeto, 2015). While this is about two weeks longer than a full calendar year, for the sake of simplicity, this monitoring period was taken to be 12 months. Therefore, the values from the "MSW 5/2012-12/2013" column are carried through and the same as those listed in the "Adjusted MSW" column in Table 2.5, and are not in any way modified like the values for CPAs 1-8. Again, it is dually noted that this does not provide a perfect estimation of the values, but for the purpose of this study, the estimates generated are suitable for their general purpose of comparison against the optimized theoretical values.

These values show that with an improvement in waste collection and transport to each individual composting site, as well as a higher level of effectiveness and efficiency during the course of the sorting, composting, sieving, and additional processing steps, that about an additional 40% improvement in the potential for RDF production could be achieved. Naturally, these are all theoretical numbers in general, as no composters are producing and selling refuse-derived fuel currently, but it's simply another indicator of how much more each municipality could benefit from improving their waste management processes.

2.2.6 RDF quality criterion

In addition to the potential quantity of refuse-derived fuel that might be attained through Uganda's composting facilities, of significant consideration is also the quality of the potential fuels that would be generated. As would logically follow, the quality of the RDFs is directly linked to the composition of the municipal solid waste inputs, as well as the processing steps that separate, sort, and homogenize the specific waste fractions that result in the fuels. For the purpose of this study, the primary quality criterion that were assessed, were the heat content of the potential fuel and the specific origins of the combustible carbon products within the RDFs (biogenic versus fossil). Other quality criterion are also considered and discussed in some detail below, but ultimately withheld from full inclusion of the scope of this study.

Ultimately, the RDFs in this study have been framed based on paper and plastic waste divisions. This makes for a very convenient differentiation between the biogenic and fossil carbon in the resulting CO_2 emissions, as the paper RDF would be comprised exclusively of biogenic carbon, and the plastic RDF exclusively fossil carbon. The most common combustible waste fractions with their lower heat values (LHV) have been taken from Riber et al. in Christensen's "Solid Waste Technology & Management" book (2011) and organized into ‘paper’, ‘plastic’, and ‘other’ categories below in Table 2.6 to correspond with the RDFs described in this study. Riber’s full list of waste fractions with corresponding details can be found in Annex IV.

Table 2.6: Lower heat values for specific waste fractions. Taken from Riber et al., 2009.

Paper waste divisions	*Lower heating value (MJ/kg)*	*Paper waste divisions (continued)*	*Lower heating value (MJ/kg)*	*Plastic waste divisions*	*Lower heating value (MJ/kg)*	*Other waste divisions*	*Lower heating value (MJ/kg)*
Newsprint	14.6	Paper/Carton Containers	13.5	Soft Plastic	34.1	Wood	15.6
Magazines	10.6	Cardboard	12.2	Plastic Bottles	32.5	Shoes and Leather	12.9
Advertisements	14.4	Milk Cartons & Alike	17.4	Hard Plastics	36.1	Rubber Products	27.2
Books and Phonebooks	13.4	Carton with Aluminum Foil	19.6	Non-recyclable Plastics	29.2	Textiles	18.5
Office Paper	11.2	Dirty Paper	13.2			Soil	4.6
Other Clean Paper	12.0	Dirty Cardboard	14.5				

Although the potential to incorporate other combustible components of the MSW, like those listed under “Other waste divisions” above in Table 2.6, would undoubtedly increase the RDF output quantities, and likely even raise the average heat value, should a single, homogenized refuse-derived fuel be produced, as previously stated, for simplicity’s sake, they were excluded from this model of RDF production.

Other quality criterion for refuse-derived fuels include ash content, water content, concentration of heavy metals, and chlorine and fluorine content. All of these vary with varying waste composition, and affect different aspects of the RDF when it is ultimately used for energy recovery. Water content can affect flash points of the RDF and reduce the fuel’s heat value; heavy metals are toxic and affect the quality of the emissions; and chlorine and fluorine can form acids that corrode cement kilns over time upon burning, while also degrading emission quality (hence why polyvinyl chloride {PVC} is oftentimes excluded from burning in refuse-derived fuels). These criterion are, of course, of important consideration for any refuse-derived fuel, but outside the scope of this study.

2.2.7 Paper RDF heat value estimations

During the literature review, there was no reliable data detailing the specific sub-fractions of the various waste fractions in Uganda's average MSW that was necessary to make an accurate heat value estimation of the two respective refuse-derived fuels. The more general waste categories were ascribed to the waste fractions in the literature reporting information on solid waste generation and composition in Uganda. Unfortunately, there is no general heat value associated with the more general characterizations of "paper" and "plastic". As such, other examples needed to be employed to fill the information gaps. In this case, a more detailed waste composition report was available on Ghana's MSW (Miezah, et al., 2015). While it cannot be assumed that the specific waste compositions (especially the sub-fractions of particular waste fractions) of both countries are identical, given that they are both Sub-Saharan African countries with reasonably similar climates, and that there were enough similarities between the more general waste fractions, Ghana's MSW was taken to be a suitable measure of comparison (especially in the absence of other suitable examples for comparison).

To use such data from the published study in Ghana, the proportions of the paper sub-fractions in Ghana's waste composition had to be derived. First, the reference values from the study (see Annex V), which included a division between high-, middle-, and low-income classes, were averaged. From there the proportions of each paper sub-fraction were derived (see Table 2.7 below) to then ultimately be applied to the theoretical quantities of paper RDF calculated in the previous sections.

Table 2.7 Proportions of paper sub-fractions taken from Ghana's MSW composition (Miezah, et al., 2015)

Paper sub-fraction	Averaged paper sub-fraction (% total Ghanaian MSW)	Averaged total paper (% total Ghanaian MSW)	Proportion of paper sub-fraction in total paper fraction
Newspaper	0.4920	5.3610	0.0918
Office print	0.5033	5.3610	0.0989
Tissue paper	1.4483	5.3610	0.2702
Cardboard/packaging paper	2.8903	5.3610	0.5391

The LHVs for each type of paper taken from Table 2.6 were then multiplied with the calculated proportions of each sub-fraction and added up to determine the lower heat value for the resultant paper RDF. See Table 2.8 below.

Table 2.8: Lower heat values of paper sub-fractions used to estimate overall LHV of paper RDF

Paper sub-fraction	Lower heat value (MJ/kg)	Proportion of paper sub-fraction in total paper fraction	Lower heat value of resultant paper RDF (MJ/kg)
Newspaper	14.6	0.0918	1.3403
Office print	11.2	0.0989	1.1077
Tissue paper	8.0	0.2702	2.1616
Cardboard/packaging paper	12.2	0.5391	6.5770
TOTAL	--	1	11.1866

With the lower heat value for the resultant paper RDF determined, the value was then used to generate approximations for the total amount of energy that could be generated from the refuse-derived fuel produced by each composting site, should they begin separating the paper waste fraction from the rest of the compost and MSW to produce a paper RDF. See Table 2.9 below for details.

Table 2.9: Energy output potential from Uganda's theoretical paper refuse-derived fuel production

CPA Name and Number	Paper RDF Yield (kg/yr)	Lower heat value of paper RDF (MJ/kg)	Total Energy Output Potential (MJ/yr)
1.) Jinja	557,000	11.2	6,238,400
2.) Fort Portal	592,000	11.2	6,630,400
3.) Kabale	618,000	11.2	6,921,600
4.) Kasese	328,000	11.2	3,673,600
5.) Lira	214,000	11.2	2,396,800
6.) Mbale	568,000	11.2	6,361,600
7.) Mukono	509,000	11.2	5,700,800
8.) Soroti	346,000	11.2	3,875,200
9.) Mbarara	524,000	11.2	5,868,800
TOTAL	4,255,000	--	47,667.2 GJ/yr

2.2.8 Plastic RDF heat value estimations

The same calculations had to be carried out for the plastic sub-fractions of Ghana’s MSW. In this particular case, values for the total plastic composition of Ghana’s MSW, on average, were higher than that of the combined average of plastic waste being delivered to the composting facilities. This is probably due to Ghana’s higher level of economic development, which is almost always strongly correlated with waste composition. Ghana’s GDP per capita is $1,641, while Uganda’s is $604 (World Bank Group, 2019). This would explain a higher percentage of plastic in Ghana’s waste, as it would be expected there would be more finished and packaged products, due to a higher level of industrial activity and import of foreign goods. That said, it still provides a reasonable means of comparison to Uganda’s MSW, because of all of the other similarities between the two nations, and because Uganda has experienced a great deal of growth in the past 15-20 years that would lend itself to an increasing amount of plastic going into the household waste. Additionally, since the MSW composition data used for Uganda is quite old, it is very likely that the plastic content of the waste is actually higher than presented in this study, and potentially even closer to the values provided from the MSW composition study in Ghana. Nevertheless, it is the best data provided in the literature to use for comparison and must be accepted as a limitation of the study.

As before, the reference values from the study (see Annex V), which included a division between high-, middle-, and low-income classes, were averaged. From there the proportions of each plastic sub-fraction were derived (see Table 2.10) to then ultimately be applied to the theoretical quantities of plastic RDF calculated in the previous sections.

Table 2.10: Proportions of plastic sub-fractions taken from Ghana’s MSW composition (Miezah, et al., 2015)

Plastic sub-fraction	Averaged plastic sub-fraction (% total Ghanaian MSW)	Averaged total plastic (% total Ghanaian MSW)*	Proportion of plastic sub-fraction in total plastic fraction
Plastic film/LDPE	3.6857	13.8277	0.2666
PET	2.9053	13.8277	0.2101
HDPE	3.0813	13.8277	0.2228
Polypropylene (PP)	1.4003	13.8277	0.1012
Polystyrene (PS)	0.5757	13.8277	0.0417
Other Plastics	2.1793	13.8277	0.1576

*Excluding polyvinyl chloride (PVC)

As stated previously, about 30% of the plastic from each composting facility in Uganda is projected to be collected for recycling. Currently, recyclers in Uganda only have the capacity to recycle PET and HDPE. This added an extra step of calculations to derive the heat value of the resultant plastic RDF, as there would not be a direct 1:1 transfer of the general MSW plastic sub-fractions observed in Ghana's MSW, since some plastic will have been separated out to be recycled.

To keep the values in accordance with the original mass balance values and transfer coefficients stated in previous sections, the amount of PET and HDPE determined to be recycled was based on 30% of the total plastic to be recycled from the overall MSW stated previously. These values work out to be 0.1456 and 0.1544 respectively, leaving only 0.0645 and 0.0684 of PET and HDPE respectively in with the rest of the RDF. With these values, the adjusted proportion of plastic sub-fractions in the total plastic RDF were derived and displayed in Table 2.11.

Table 2.11: Proportions of plastic sub-fractions in RDF adjusted for recycling

Plastic sub-fraction	Adjusted proportion of plastic sub-fraction to include recycling	Remaining proportion of plastics directed to RDF	Proportion of plastic sub-fraction in resultant plastic RDF
Plastic film/LDPE	0.2666	0.7	0.3809
PET	**0.0645**	0.7	0.0921
HDPE	**0.0684**	0.7	0.0977
Polypropylene (PP)	0.1012	0.7	0.1446
Polystyrene (PS)	0.0417	0.7	0.0596
Other Plastics	0.1576	0.7	0.2251

With the adjusted values reflecting a more accurate depiction of the plastic sub-fractions that actually end up getting directed to the final product (plastic RDF), the lower heat value of the plastic RDF could be estimated. Based on the reference values from Riber's table in Annex IV, polypropylene and polystyrene with the "other plastics" category make up the "non-recyclable plastics" category seen below in Table 2.12. This was done because in this specific case these two plastic types would fall under this category and would therefore (theoretically) have a similar heat value to the other non-recyclable plastics described in Annex IV.

Furthermore, it was taken that LDPE would be considered as a “soft plastic”, PET as “plastic bottles”, and HDPE as a “hard plastic”, in accordance with the reference categories for LHV’s in Annex IV.

Table 2.12: Lower heat values of plastic sub-fractions used to estimate overall LHV of plastic RDF

Plastic sub-fraction	Lower heat value (MJ/kg)	Proportion of plastic sub-fraction in total plastic fraction	Lower heat value of resultant plastic RDF (MJ/kg)
LDPE	34.1	0.3809	12.9887
PET	32.5	0.0921	2.9933
HDPE	36.1	0.0977	3.5270
Non-recyclable plastics*	29.2	0.4293*	12.5356
TOTAL	--	1	32.0446

*Non-recyclable plastics taken to be polypropylene and polystyrene combined with any other plastic types other than those listed and PVC

Just like before with the paper RDF, with the lower heat value for the resultant plastic RDF determined, the value was then used to generate approximations for the total amount of energy that could be generated from the refuse-derived fuel produced by each composting site, should they begin separating the plastic waste fraction from the rest of the compost and MSW to produce a plastic RDF. See Table 2.13 below for details.

Table 2.13: Energy output potential from Uganda’s theoretical plastic refuse-derived fuel production

CPA Name and Number	Plastic RDF Yield (kg/yr)	Lower heat value of plastic RDF (MJ/kg)	Total Energy Output Potential (MJ/yr)
1.) Jinja	987,000	32.0	31,584,000
2.) Fort Portal	1,049,000	32.0	33,568,000
3.) Kabale	1,096,000	32.0	35,072,000
4.) Kasese	581,000	32.0	18,592,000
5.) Lira	379,000	32.0	12,128,000
6.) Mbale	1,007,000	32.0	32,224,000
7.) Mukono	904,000	32.0	28,928,000
8.) Soroti	614,000	32.0	19,648,000
9.) Mbarara	930,000	32.0	29,760,000
TOTAL	7,546,000	--	241,504 GJ/yr

2.2.9 Discussion of theoretical values

It should be stated very clearly and/or reiterated that these values are strictly theoretical. Long term, improvements in waste management (especially waste collection) throughout Uganda, and more specifically, in these respective municipalities would need to be observed, to eventually reach the design input capacity of 70 tons of MSW per day and the optimized RDF outputs.

Furthermore, while it is convenient to cling to the potential to produce 47,667 GJ and 241,504 GJ annually from the paper and plastic RDF outputs respectively, this is, of course, not 100% realistic to expect, even should the stated quantities for MSW inputs and compost and RDF outputs be reached by any or all of the municipalities.

Implementation of the use of the two RDFs brings about a whole new dimension of consideration regarding their practicality. First, only the municipalities within a specific range of distance from the various Ugandan cement producers (the proposed industry to utilize these RDFs, as a partial replacement for primary fossil fuels) would realistically be able to benefit from the sales of RDF. The main reason being that the costs of transportation would likely exceed the revenues from selling the RDFs beyond a certain distance. A proper cost-benefit analysis would need to be conducted in regards to this issue, as cost estimates are outside the scope of this study. Nevertheless, researchers at the Institute for Water Quality, Resource and Waste Management in Vienna have suggested that any compost facilities within 100 kilometers of the cement producers would make viable prospects for full RDF supply chain development. But again, such a development would necessitate a comprehensive cost-benefit analysis.

Other investment costs would also likely serve as a barrier to RDF implementation. For example, the necessity of both composters and cement producers to invest in new processing equipment. For composters, this could mean more advanced sorting, size reduction, or compaction technologies, like a shredder or baler, and for cement producers this could mean plant upgrades like new RDF storage silos. More detail was provided in section 1.2.3.

2.2.10 Discussion of RDF as a suitable fossil fuel replacement

Regardless of the extent to which RDF could be utilized by the cement industry from a sheer quantity perspective, its suitability from a strictly heat value point of view is undeniable. Within cement production for the raw materials to reach 1,500 degrees Centigrade, the primary firing system must maintain a temperature of 2,000 degrees Centigrade (Rotter, 2011). This is only attainable with fuels that carry a heat value equal to or greater than 20 MJ/kg (Rotter, 2011). As such, refuse-derived fuels that contain a larger proportion of biomass/biogenic carbon and therefore, a lower average heat value—like in the case of this study's paper RDF—would not be suitable for the primary firing system, but could still be utilized to preheat raw materials in the secondary firing system (Rotter, 2011).

With this in mind, it is clear, based on their determined heat values of 11.2 and 32.0 MJ/kg that both the paper and plastic RDFs discussed in this study could be theoretically utilized in the secondary and primary firing systems respectively. Table 2.14 summarizes these comparisons.

Table 2.14: Fuel types and their suitability for cement kilns based on their heat values

Fuel Type	Heat Value (MJ/kg)	Suitability for Primary Firing System (>20 MJ/kg)	Suitability for Secondary Firing System (<20 MJ/kg)
Heavy Fuel Oil	40.4	YES	YES
Bituminous Coal	25.8	YES	YES
Petroleum Coke	32.5	YES	YES
Wood/Wood Waste	15.6	NO	YES
Solid Biomass	11.6	NO	YES
Paper RDF	11.2	NO	YES
Plastic RDF	32.0	YES	YES

It should also be mentioned that the cement producers in Uganda use petroleum coke and heavy fuel oil in their cement kilns (Kanda, 2019). The heat values of these raw materials are also listed in Table 2.14 for reference and it is clear to see that the plastic RDF has a comparable heat value, making it an excellent fuel replacement. Even though the plastic RDF still produces CO_2 emissions that contain fossil carbon from fossil fuels, it would still lead to an eventual decrease in net emissions via the decrease in the use of primary fossil fuel resources. The concrete estimations of emission reductions and potential for energy replacement are discussed in detail in the following chapters.

2.2.11 Paper RDF emissions

To determine the values for CO_2 emissions that would be generated upon burning the paper RDF for thermal energy utilization, methods from the 2006 IPCC were referenced for guidance (Guendehou, et al., 2006). The values for "Total Solids % Wet" for each paper sub-fraction were taken from Riber's table in Annex IV and multiplied with the values for "Total Carbon in mg/kg of Total Solids". This calculation theoretically provides the amount of combustible carbon in mg/kg for each paper sub-fraction, and therefore can then be used to determine the amount of carbon dioxide generated from burning the fuel. See Table 2.15 below for details.

Table 2.15: Combustible organic carbon content in paper RDF based on carbon content in paper sub-fractions

Paper Sub-fraction	Total Solids % Wet	Total Carbon in mg/kg TS	Combustible Carbon (mg/kg)	Proportion of Sub-fraction in Paper RDF	Combustible Carbon in Paper RDF (mg/kg)
Newspaper	87.0	448,000	389,760	0.0918	35,780
Office print	91.3	375,000	342,375	0.0989	33,861
Tissue paper	53.1	452,000	240,012	0.2702	64,851
Cardboard/packaging paper	83.5	409,000	341,515	0.5391	184,111
TOTAL	--	--	--	1	318,603

With the value for total combustible carbon per kilogram of paper RDF determined, the molar masses of carbon and carbon dioxide were used to calculate the amount of CO_2 emitted per kilogram of RDF burned, and ultimately, the amount of CO_2 generated per unit thermal energy utilized. See calculations below for clarity:

$$(318.603 \text{ grams C/kg RDF}) \ / \ (12.011 \text{ g/mol}) \ = \ 26.5259 \text{ mol C/kg RDF}$$

$$(26.5259 \text{ mol } CO_2\text{/kg RDF burned}) \ x \ (44.009 \text{ g/mol } CO_2) \ = \ 1{,}167 \text{ g } CO_2\text{/kg RDF}$$

$$(1{,}167 \text{ g } CO_2\text{/kg RDF burned}) \ / \ (11.2 \text{ MJ/kg RDF}) \ = \ 104.2 \text{ g } CO_2\text{/MJ}$$

In respect to the CO_2 output per megajoule of energy produced from the paper RDF, it could be stated that this level of CO_2 is relatively high. Comparatively, lignite and hard coal are cited as producing 100-115 g CO_2/MJ and 95 g CO_2/MJ respectively (Rotter, 2011). But two things should be brought into focus for more thorough consideration.

The first is that, while the estimated heat value of the paper RDF has been pursued in good conscience, and with the best available data, there is a good chance that it is not a 100% accurate. Some sources cite a heat value range as narrow as between 15 and 18 MJ/kg for refuse-derived fuels composed of predominantly biogenic waste fractions (Rotter, 2011), so there is a chance for this value to be higher than what was actually determined, especially if a contemporary thorough waste composition sampling project were to be undertaken and provide the actual values of specific paper sub-fractions in Ugandan MSW. Furthermore, the lower heat values used to derive the heat value of the paper RDF were taken from a European-based sample size, which would more than likely, on average, include wetter waste samples than the waste in the majority of Uganda's municipalities, where drying out of the compost is especially a problem during Uganda's dry season. With this in mind, average waste samples would likely have a higher LHV, since less water would need to be vaporized during the combustion process. Both of these factors would potentially drive the heat value of the paper RDF up and, therefore, drive the CO_2 output per megajoule down.

Secondly, even should the stated 104 grams CO_2 per megajoule be confirmed by follow-up field research, there is still one more significant aspect of the paper RDF emissions worth considering. Namely, the paper RDF is exclusively composed of paper and paper-like substances primarily generated from biogenic sources. That is, the carbon within the RDF that's being converted to CO_2 upon combustion, is plant-based and therefore climate neutral. So even if the emission output is higher than hoped for and higher than some fossil fuel sources, it can still lead to a net reduction of fossil-based CO_2 emissions, by reducing the amount of primary fossil fuels being burned in Uganda's cement kilns.

2.2.12 Plastic RDF emissions

To determine the values for CO_2 emissions that would be generated upon burning the plastic RDF for thermal energy utilization, the values for "Total Solids % Wet" for each plastic sub-fraction were again taken from Riber's table in Annex IV and multiplied with the values for "Total Carbon in mg/kg of Total Solids". This calculation theoretically provides the amount of combustible carbon in mg/kg for each plastic sub-fraction, and then therefore can be used to determine the amount of carbon dioxide generated from burning the fuel. See Table 2.16 below for details.

Table 2.16: Combustible organic carbon content in plastic RDF based on carbon content in plastic sub-fractions

Plastic Sub-fraction	Total Solids % Wet	Total Carbon in mg/kg TS	Combustible Carbon (mg/kg)	Proportion of Sub-fraction in Plastic RDF	Combustible Carbon in Plastic RDF (mg/kg)
LDPE	85.9	820,000	704,380	0.3809	268,298
PET	89.5	772,000	690,940	0.0921	63,636
HDPE	96.8	799,000	773,432	0.0977	75,564
Non-recyclable plastics*	92.9	710,000	659,590	0.4293	283,162
TOTAL	--	--	--	1	690,660

With the value for total combustible carbon per kilogram of plastic RDF determined, the molar masses of carbon and carbon dioxide were used to calculate the amount of CO_2 emitted per kilogram of RDF burned, and ultimately, the amount of CO_2 generated per unit thermal energy utilized. See calculations below for clarity:

$$(690.660 \text{ grams C/kg RDF}) \ / \ (12.011 \text{ g/mol}) \ = \ 57.5023 \text{ mol C/kg RDF}$$

$$(57.5023 \text{ mol } CO_2\text{/kg RDF burned}) \ \text{x} \ (44.009 \text{ g/mol } CO_{2)} \ = \ 2{,}531 \text{ g } CO_2\text{/kg RDF}$$

$$(2{,}531 \text{ g } CO_2\text{/kg RDF burned}) \ / \ (32.0 \text{ MJ/kg RDF}) \ = \ 79.1 \text{ g } CO_2\text{/MJ}$$

In the case of the plastic carbon dioxide emissions in regard to energy output, what has been estimated falls directly in line with the literature: an average range of 30 to 80 grams of carbon dioxide per megajoule has been observed from various types of refuse-derived fuels (Rotter, 2011). Although, the paper RDF's g CO_2 per megajoule was markedly higher (maybe counterintuitively), this is explained simply by the fact that plastics, although having a higher concentration of organic carbon than biogenic waste, have a much higher heat value on average.

Although the carbon emissions from the plastic RDF are fossil-based, meaning that they are originally derived from fossil fuel products and by-products and not a part of the short-term natural carbon cycle on Earth, the CO_2 output per megajoule is still markedly lower than that of lignite and hard coal (100-115 g CO_2/MJ and 95 g CO_2/MJ respectively (Rotter, 2011)), with a comparable, if not higher heat value per kilogram.

Should the plastic RDF be implemented, this would potentially lead to a net reduction of greenhouse gases overall, and would undoubtedly lead to a reduction in the amount fossil CO_2 entering the atmosphere, by reducing the amount of the primary fossil fuel resources necessary to produce the same energy outputs for cement production. A comprehensive emissions testing study would need to be conducted to verify the estimates as determined in this study. Especially important, would be an accurate depiction of fuel use for transportation of the RDF to the respective cement production facilities.

2.2.13 Energy replacement potential

While it is promising to see the energy generation values for the potential refuse-derived fuels produced from Uganda’s MSW, it is clearly not 100% accurate to assume that every municipality with a composting facility is strategically/ideally located to supply its RDFs to the country’s cement producers for cost-effective use. Beyond a certain distance, the costs of fuel for transportation and emissions from fuel consumption begin to overtake the economic and environmental benefits of producing and utilizing the RDFs in the first place. This particular distance would need to be determined from a comprehensive cost-benefit analysis of the whole system, but for the purpose of this study, an approximate 100 kilometer radius around the largest and most relevant Ugandan cement producers was drawn to see which of the CPAs would fall within these potential RDF implementation zones.

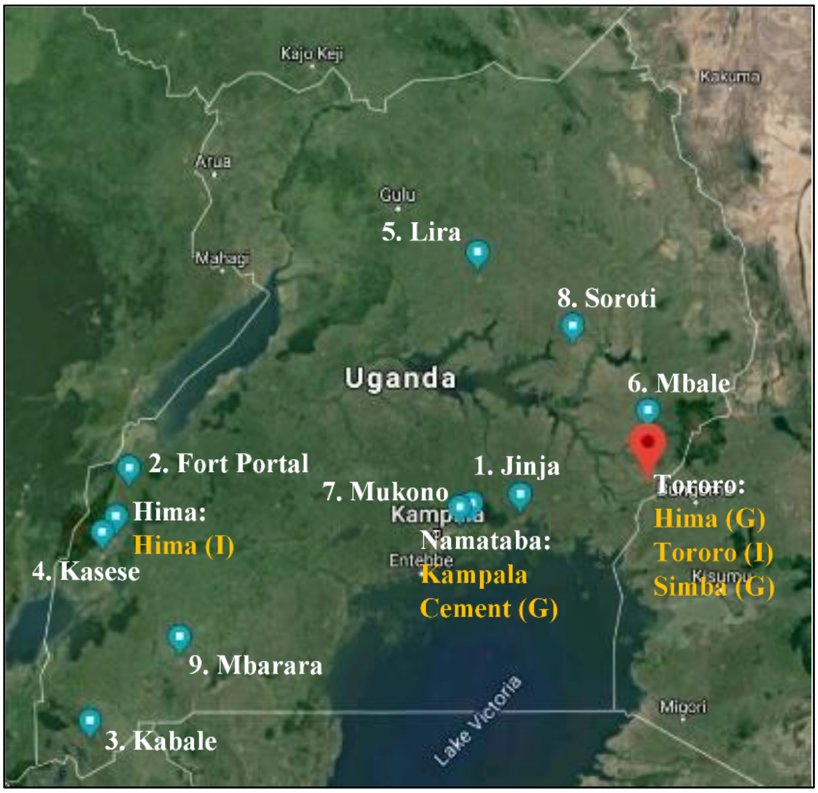


Figure 2.10: Map of Uganda with composters (white) and cement producers (orange)
SOURCE: Google Maps, ©2019

As can be observed in Figure 2.10, five of the nine CPAs discussed in this study fall within the respective potential implementation zones. They are Jinja (1), Ft. Portal (2), Kasese (4), Mbale (6), and Soroti (8). With time, as the rest of the CPAs outlined in the POA of the CDM project also begin actively composting waste, the potential for even higher levels of energy replacement will be made possible.

The towns marked in orange in Figure 2.10 above delineate the five various active cement plants and are labeled with an "I" or a "G", for "integrated plant" and "grinding plant", respectively. Integrated plants are equipped with rotary kilns that produce their own clinker and the grinding plants mix already prepared clinker with additives to produce cement. Clinker production is the most energy intensive part of cement production, so it is clear that Hima Cement Ltd. and Tororo Cement Ltd. would have a much higher annual energy requirement than their non-clinker-producing counterparts (Simba Cement Ltd. and Kampala Cement Company Ltd.). Cement producers that operate grinding plants most typically purchase clinker from other domestic suppliers or import it from abroad. In the case of Simba Cement, Kampala Cement, and Hima Cement's grinding plant in

Tororo, clinker is indeed imported from abroad, curtailing the localized energy requirements (Ugandan Ministry of Trade, Industry and Cooperatives, 2018).

The annual energy requirements for all cement producers of Uganda are estimated below using data taken from a plethora of sources. First clinker tonnage was used (Kanda, 2019) with the continental average for GJ/ton clinker (WBCSD, 2016) to derive energy requirements of the integrated plants, to include the 60%-40% thermal energy split ascribed to the secondary and primary firing respectively (Rahman, et al., 2017), then the cement production outputs (Khisa, 2018) were multiplied with the estimated energy requirement of finish grinding plants (Worrell, et al., 2001), and finally, added to the values generated for the integrated plants.

Table 2.17: Estimated energy requirements for clinker production in Uganda's integrated plants

Cement Producer	Clinker Production (tons/yr)*	Thermal Energy Intensity of Clinker Production (GJ/ton)	Secondary Firing Thermal Energy Requirement (GJ/yr)	Primary Firing Thermal Energy Requirement (GJ/yr)	Total Annual Clinker Energy Requirement (GJ/yr)
Hima Cement Ltd. (Kasese Plant)	500,000	3.75	1,125,000	750,000	1,875,000
Tororo Cement Ltd.	125,000	3.75	281,250	187,500	468,750

*Values taken from personal interview (Kanda, 2019)

Table 2.18: Estimated annual energy requirements of Uganda's cement producers

Cement Producer	Cement Production Output (million tons/yr)	Energy Intensity of Finish Grinding (GJ/ton)*	Annual Energy Requirement (excluding clinker) (GJ/yr)	Total Annual Energy Requirement (including clinker) (GJ/yr)
Tororo Cement Ltd.	3.0	0.6	1,800,000	2,268,750
Hima Cement Ltd.	1.9	0.6	1,140,000	3,015,000
Kampala Cement Company Ltd.	1.0	0.6	600,000	600,000
Simba Cement Uganda Ltd.	0.9	0.6	540,000	540,000

*Value applied for finish grinding with a ball mill—the most common finish grinding mill technology in use (Worrell, et al., 2001).

With the values generated earlier for the annual potential energy outputs based on the lower heat values and quantities of the respective paper and plastic RDFs, the total energy replacement potential per year could be generated based on the proximity of the composters to the cement producers. See Table 2.19 below for details.

Table 2.19: Total potential cement production energy replacement from compost RDFs

Cement Producer	CPA (number)	Individual Energy Output: Paper RDF (MJ/yr)	Total Energy Output: Paper RDF (MJ/yr)	Individual Energy Output: Plastic RDF (MJ/yr)	Total Energy Output: Plastic RDF (MJ/yr)	Total Energy Replacement Potential (GJ/yr)
Hima Cement Ltd.	Ft. Portal (2)	6,630,400	10,304,000	33,568,000	52,160,000	62,464
	Kasese (4)	3,673,600		18,592,000		
Tororo Cement Ltd.	Mbale (6)	6,361,600	16,475,200	32,224,000	83,456,000	99,931
	Soroti (8)	3,875,200		19,648,000		
	Jinja (1)	6,238,400		31,584,000		

Finally, should these RDFs be implemented in both Hima and Tororo's integrated plants, the annual energy replacement percentages seen in Table 2.20, Table 2.21, Table 2.22, and Table 2.23 would be observed.

Table 2.20: Energy replacement potential as percentage of energy requirement for secondary firing system

Cement Producer	Annual Energy Requirement of Secondary Firing (GJ/yr)	Paper RDF Energy Replacement (GJ/yr)	Percentage Replacement of Secondary Firing Energy Demand
Hima Cement Ltd.	1,125,000	10,304	0.9%
Tororo Cement Ltd.	281,250	16,475	5.9%

Table 2.21 Energy replacement potential as percentage of energy requirement for primary firing system

Cement Producer	Annual Energy Requirement of Primary Firing (GJ/yr)	Plastic RDF Energy Replacement (GJ/yr)	Percentage Replacement of Primary Firing Energy Demand
Hima Cement Ltd.	750,000	52,160	7.0%
Tororo Cement Ltd.	187,500	83,456	44.5%

Table 2.22: Energy replacement potential as percentage of total energy requirement for clinker production

Cement Producer	Annual Energy Requirement of Clinker Production (GJ/yr)	Total Energy Replacement (GJ/yr)	Percentage Replacement of Clinker Production Energy Demand
Hima Cement Ltd.	1,875,000	62,464	3.3%
Tororo Cement Ltd.	468,750	99,931	21.3%

Table 2.23: Energy replacement potential as percentage of total energy requirement for cement production

Cement Producer	Total Annual Energy Requirement (GJ/yr)	Total Energy Replacement (GJ/yr)	Percentage Replacement of Total Energy Demand
Hima Cement Ltd.	3,015,000	62,464	2.1%
Tororo Cement Ltd.	2,268,750	99,931	4.4%

As stated previously, as more and more of the other composting facilities become active and reach their design capacities, these values could increase further, and energy replacement could be expanded to higher percentages of replacement. Although theoretical, these figures show great potential.

2.2.14 Fuel burning emission reductions

Specific data provided on the respective fuel source mixes for each cement producer was simply not available, with the exception of information provided from a personal interview from a representative of Geocycle and Hima Cement Ltd. While the specific fuel mixture ratios are mostly unclear (excluding Hima Cement), based on fuel production and import data, the most likely implemented traditional fuel sources are petroleum coke and heavy fuel oil in Ugandan cement production (Knoema, 2019). Both are likely imported from Kenya (Mombasa, in particular). It was originally presumed that bituminous coal (hard coal) from South Africa and Mozambique would be the primary source of thermal energy in Ugandan cement production, but this has proven to be mistaken, given the import records on coal (Knoema, 2019).

In terms of non-traditional fuel sources, or rather, alternative fuels (AFs), multiple Ugandan cement producers have already begun implementing solid biomass fuels of various types at exceptionally high levels. The Hima cement plants in Kasese and Tororo have already substituted in 100% and 95% (respectively) of their energy requirements in their secondary firing systems with biomass in the form of ground rice husks (Kanda, 2019). Additionally, a substitution rate of up to 55% of biomass in the form of ground rice and coffee husks has taken place in the primary firing system at Hima's integrated plant in Kasese (Kanda, 2019). Finally, Simba Cement Ltd. was cited as using biomass in the form of wood logs for a 100% of its energy requirements in its grinding plant (Kanda, 2019).

All of these biomass substitutions already significantly reduce the need for primary fossil fuel consumption and their resulting CO_2 emissions, but nevertheless, adoption of the RDFs from this study would help reduce this consumption even further. For example, in the case of Tororo Cement, it was cited that 100% of their energy requirements are met with heavy furnace oil, and Hima's primary firing system in Kasese uses 30% petroleum coke, along with 5% heavy furnace oil (Kanda, 2019). The remaining 5% of the Hima plant in Tororo is also fulfilled with heavy furnace oil (Kanda, 2019).

Although there is a chance Kampala Cement Company also uses some form of biomass or other AF, there was no data available to confirm this, so it was simply left undetermined. A summary of these energy mixtures is provided below in Table 2.24.

Table 2.24: Energy divisions of each Ugandan cement plant (Kanda, 2019)

Cement Plant	Primary Firing System	Secondary Firing System
Hima Cement – Kasese	55% Biomass (rice and coffee husks) 30% Petroleum Coke 10% Industrial Waste 5% Heavy Fuel Oil	100% Biomass (rice husks)
Hima Cement – Tororo	--	95% Biomass (rice husks) 5% Heavy Fuel Oil
Tororo Cement Ltd.	100% Heavy Fuel Oil	100% Heavy Fuel Oil
Kampala Cement Company Ltd.	No Data	No Data
Simba Cement Ltd.	--	100% Biomass (wood logs)

To determine the potential for net emissions reductions, in conjunct with the values determined for plastic and paper RDFs in this study, values for lower heat values and carbon content per fuel type were taken from the 2006 IPCC National Greenhouse Gas Inventories Programme. Other sources were also available, but without much deviation from this international standard. A summary of these values is provided by Table 2.25 below.

Table 2.25: Fuel types used in Ugandan cement production and their LHVs and carbon dioxide emission content

Fuel Type	Lower Heat Value (MJ/kg)	CO_2 Emissions (g/MJ)
Heavy Fuel Oil*	40.4	77.4
Bituminous Coal*	25.8	94.6
Petroleum Coke*	32.5	97.5
Wood/Wood Waste*	15.6	112.0
Solid Biomass*	11.6	100.0
Industrial Wastes*	--	143.0
Paper RDF	11.2	104.2
Plastic RDF	32.0	79.1

*Values taken from the 2006 IPCC National Greenhouse Gas Inventories Programme (IPCC, 2006)

Where CO_2 reductions could be predicted, this was strictly related to combustion of fuels associated with cement production. With this in mind, traditional fuels were taken to comprise the net composition of CO_2 emissions, while fossil carbon-based alternative fuels were taken to make up the gross CO_2 emissions (in conjunct with the net emissions). Biogenic carbon-based alternative fuels were taken to be climate neutral altogether and not count towards the summation of net or gross CO_2 emissions. Within this criteria, the paper RDF is considered to be climate neutral (along with solid biomass AFs), and the plastic RDF was taken to be a part of the gross CO_2 emissions category.

As such, only the cement producers using traditional fossil fuels were considered for net CO_2 reductions. In the case of Simba Cement Ltd., given that they only have a grinding plant and that they use climate neutral solid fuel (biomass in the form of wood logs), the use of RDF would then become more of an economic consideration, should their fuel source be more expensive than paper RDF in the long term.

Table 2.26: Tororo Cement Ltd. fuel emission reductions for secondary firing system

Secondary Firing: CO_2 Emissions from Heavy Fuel Oil (tons/year)	CO_2 Emissions from Heavy Fuel Oil upon Paper RDF Energy Replacement (tons/year)	Climate Neutral CO_2 Emissions from Paper RDF (tons/year)	Difference in Gross Emissions	Difference in Net Emissions
21,769	20,494	1,716	-5.86%	-5.86%

Table 2.27: Tororo Cement Ltd. fuel emission reductions for primary firing system

Primary Firing: CO_2 Emissions from Heavy Fuel Oil (tons/year)	CO_2 Emissions from Heavy Fuel Oil upon Plastic RDF Energy Replacement (tons/year)	CO_2 Emissions from Plastic RDF (tons/year)	Difference in Gross Emissions	Difference in Net Emissions
14,513	8,053	6,601	+0.98	-44.51%

Table 2.28: Total fuel emission reductions for Tororo Cement Ltd.

Total CO_2 Emissions from Heavy Fuel Oil (tons/year)	CO_2 Emissions from Heavy Fuel Oil upon RDF Energy Replacement (tons/year)	CO_2 Emissions from Plastic RDF (tons/year)	Difference in Gross Emissions	Difference in Net Emissions
36,281	28,547	6,601	-3.12%	-21.32%

Given that Hima has both an integrated and a grinding plant with outputs of 0.9 million tons and one million tons of cement respectively (Global Cement, 2018), the emission calculations would need to be determined individually. Nevertheless, because Kasese has the only integrated plant receiving RDF, calculations were only carried out for this plant.

Table 2.29: Hima Cement Ltd. fuel emission reduction determinations for the primary firing system and overall for the integrated plant in Kasese

	Gross (all Non-Biogenic Fuel Sources)	Net (Primary Fossil Fuel Sources)
Primary Firing: CO_2 Emissions (tons/year)	35,565	24,840
CO_2 Emissions upon Plastic RDF Energy Replacement (tons/year)	30,479	19,754
CO_2 Emissions from Plastic RDF (tons/year)	4,126	--
Difference in Emissions	-2.70%	-20.47%

Emissions calculations for the secondary firing system were excluded intentionally, since they had already achieved a 100% fuel replacement of traditional fossil fuel sources with a biomass alternative. As such, any substitution of the paper RDF would strictly be based on an economic advantage, namely that it might be somehow less expensive than the rice husks in use.

As can be observed from Tables 2.26-2.29, the implementation of paper and plastic RDFs in each of these plants would not only reduce the amount of primary fossil fuels being used annually, but it would lead to an overall net and gross CO_2 emission reduction.

These fuel replacements translate over to an annual reduction of 1,605 tons of petroleum coke (at Hima's plant in Kasese) and 2,474 tons heavy fuel oil (at Tororo Cement Ltd.), and an annual net reduction of 12,820 tons of CO_2.

3. CONCLUSION

3.1 Limitations

3.1.1 Literature and available data

Although attempts have been made to quantify the potential outputs for two types of refuse-derived fuel, and to show the potential benefits of their implementation in Uganda's cement industry, there are a number of limitations regarding this body of work. While every value and dataset for reference in this thesis was taken and used in good conscience and with the highest possible academic standard/integrity, the availability of accurate or current data in a number of areas was lacking, and in some cases, not available at all. This forced the author of the study to make subjective judgment calls at times when upholding a purely scientific approach was not possible.

For example, when selecting the energy requirements for the finish grinding plants in Uganda, the decision was made to use the data for a ball mill in lieu of another type of grinding mill, given that the data about which mill technologies in use in Uganda's grinding plants was unavailable and that the most common milling technique internationally is a ball mill. Furthermore, this value was taken from a source that's almost 20 years old and energy efficiency improvements in the technology could make this figure obsolete—but it was the best data available to the author.

3.1.2 Theoretical values

All of the values in this thesis were derived based on a strictly theoretical premise. That being, the assumption that 70 tons of MSW would enter each composting facility and be optimally separated and processed to produce the paper and plastic RDFs. These determined values are, at least for the time being, completely unrealistic, as the data shows us that the vast majority of the composters are accepting quantities of MSW at values much lower than the proposed design capacity of the POA.

The reality is, for any of this RDF scheme to be feasible in the long term, marked improvements in Ugandan waste collection and waste management need to be made across the board and throughout the country, especially since the 17 composting sites, once all active, cover almost a full geographic spread of the country. This, of course, would demand additional investment from already lacking public funds of every municipality, or investment from private companies set to benefit from improved waste management. The likelihood of these improved waste management outcomes being fully reached in the near future is low. As such, consideration of full implementation of this RDF scheme will, additionally, have to be maintained as a future development.

3.1.3 Investment costs and cost-benefit analysis

All economic considerations were intentionally left out of the scope of this study. This is, of course, a major limiting factor to the viability of this RDF scheme's implication, as any investor (public, private, or otherwise) looking to provide the capital necessary to start producing, selling, and shipping these RDFs to Uganda's cement producers, would need to have an idea about the investment costs, especially in regards to equipment purchases, infrastructure improvements, maintenance, and operating costs; ROI; and long term economic benefits (e.g. profit margin of RDF sales, benefits of creating a new AF market, and so on).

A necessary follow-up study, therefore, would be a comprehensive cost-benefit analysis of the entire RDF scheme. This would provide the insights necessary for not only the general conclusion of likely long term “economic benefits” and the more concrete “energy saving and emission reduction benefits”, but rather provide the investment costs necessary to realize the outcomes determined in this study.

A major component of consideration is who accepts the burden of costs. For example, beyond a certain level of fuel substitution, cement plant modifications and upgrades need to be made. Before that, the capacity to transport RDFs to cement producers via trucks or trains needs to be established. Plus, the RDF production means processing equipment needs to be purchased (separation, size reduction, and compaction technologies), and the general infrastructure improvements that support efficient waste collection and deliver MSW in the first place. Which parts of the supply chain do cement producers invest in to guarantee their supply of fuel? And which parts of the supply chain are the composters responsible for? Do waste management improvements come from public funding, or would cement producers have to invest? And so on.

Simply to purchase shredding equipment might be too financially burdensome for a single composter. Even if a cement producer paid for the equipment to process the combustible waste fractions on site, it would necessitate the composters use compaction equipment to create a cost-effective shippable precursor to RDF. That is also an investment cost difficult to justify by individual composters who are already limited financially.

Ultimately, investment costs for any RDF production to occur might be too high currently, making a near future implementation of this scheme very unlikely.

3.1.4 Emissions

Emissions were only calculated using the fuels being burned for cement production in Uganda. Obviously, the actual calcination itself is responsible for even higher CO_2 emissions, even if only two Ugandan cement producers are producing clinker. Furthermore, the use of electricity in each plant would also contribute to the overall emission quantities, but this would be variable for gross and net emissions based on the source of the electricity (renewable versus fossil-based energy generation).

It should be further noted that the emission reductions would potentially be lower, should the emissions from gasoline for transportation of the RDFs to the cement producers also be tabulated with the fuels in the process. This may not be of too considerable concern, given that the trucks supplying cement to the various municipalities, could also be utilized to transport RDF on their way back to the cement facilities. Plus, given the design of the RDF production scheme, the distances for the RDF supply chain are much shorter than those for transporting heavy fuel oil and petroleum coke, potentially canceling out the emissions difference. Nevertheless, it would be a good topic of further investigation, especially comparing the costs of both AFs and RDFs.

Given that MSW would be processed further and burned as an energy source in this RDF scheme, some additional emissions would be avoided from landfilling paper and other biogenic sources of carbon that might eventually decompose under anaerobic conditions and produce highly climate active methane. Avoidance of indiscriminate burning of MSW also would decrease the amount and types of emissions given off from waste. Both of these considerations, would undoubtedly alter the ultimate CO_2 reduction determination (probably for the better).

Opportunities for additional greenhouse gas emission reductions can also be found in the production of other refuse-derived fuels, made from other biogenic sources of carbon. For example, RDFs made from wood (e.g., garden waste and tree branches) have a high potential for further reductions, but are not considered here. Such materials may already be collected informally though, and burned individually for cooking and heating water.

Finally, this study only considered carbon dioxide as an emission for the cement production process. This was intentional, as the primary focus was on greenhouse gases that contribute to global warming, but obviously, there are a number of other important pollutants emitted in these processes that affect other human and natural systems. These might include NO_x, SO_x, dust, heavy metals, acids, etc. Avoided methane production from anaerobic decomposition in dumpsites was already incorporated into the scope of the composting project, but, of course, in reaching the 70 tons MSW per day input, an additional reduction in methane would be likely, although not included here. Lastly, informal trash burning was not covered under the scope of emissions, but had it been this too would likely lead to a decrease in overall emissions. That is because, if the MSW would be burned at illegal dumpsites anyways without energy recovery, then those emissions would be added to the overall totals. With more RDF substitution, a reduction in informal trash burning would also be observed.

3.2 Applications of the findings

Ultimately, by combining these two industries, the creation of an additional value chain (RDF) from the same the initial precursor (MSW) is observed, and both sectors—waste management and cement production—stand to benefit in a myriad of ways.

Cement producers would (likely) save money in the long term by purchasing an alternative fuel at a (likely) lower price than the traditional fossil fuels they're using currently. This helps them save on their overall energy costs while also reducing their overall CO_2 emissions, which in turn, reduces their contribution to global anthropogenic warming and climate change. This CO_2 reduction is also a marketable asset for producers eager to show they're reducing their environmental footprint.

Composters stand to benefit by implementing processes that more efficiently and effectively separate out the non-organic waste fractions from their composts, making them purer and more marketable to local agriculturalists. In the process of doing so, they will also create an additional marketable product that can be sold to another industry, realizing beneficial synergies and boosting their revenues. Furthermore, the production and utilization of the RDFs described in the study would reduce the CO_2 emissions associated with a completely different industry, which was one of the primary purposes of the CDM's composting project in the first place (that is, emission reductions).

With the potential to save almost 13,000 tons of CO_2 and prevent consumption of over 4,000 tons of primary fossil fuels annually, it is realistic to suggest and even anticipate that follow-up projects by NGOs or other international organizations be pursued. Because ultimately, the 13,000 tons of CO_2 would translate over to a quantity of CERs that would be tradable under the CDM of the Kyoto Protocol that many developed nations across the world are very interested in purchasing. Thus enabling composters and NEMA to pay back their loans and eventually turn a profit on such CER sales.

Should this RDF production scheme ever be fully realized, it would make a premier example of economic, social, and environmental sustainability, as defined by the United Nations, and it would take Uganda few steps closer to a circular economy.

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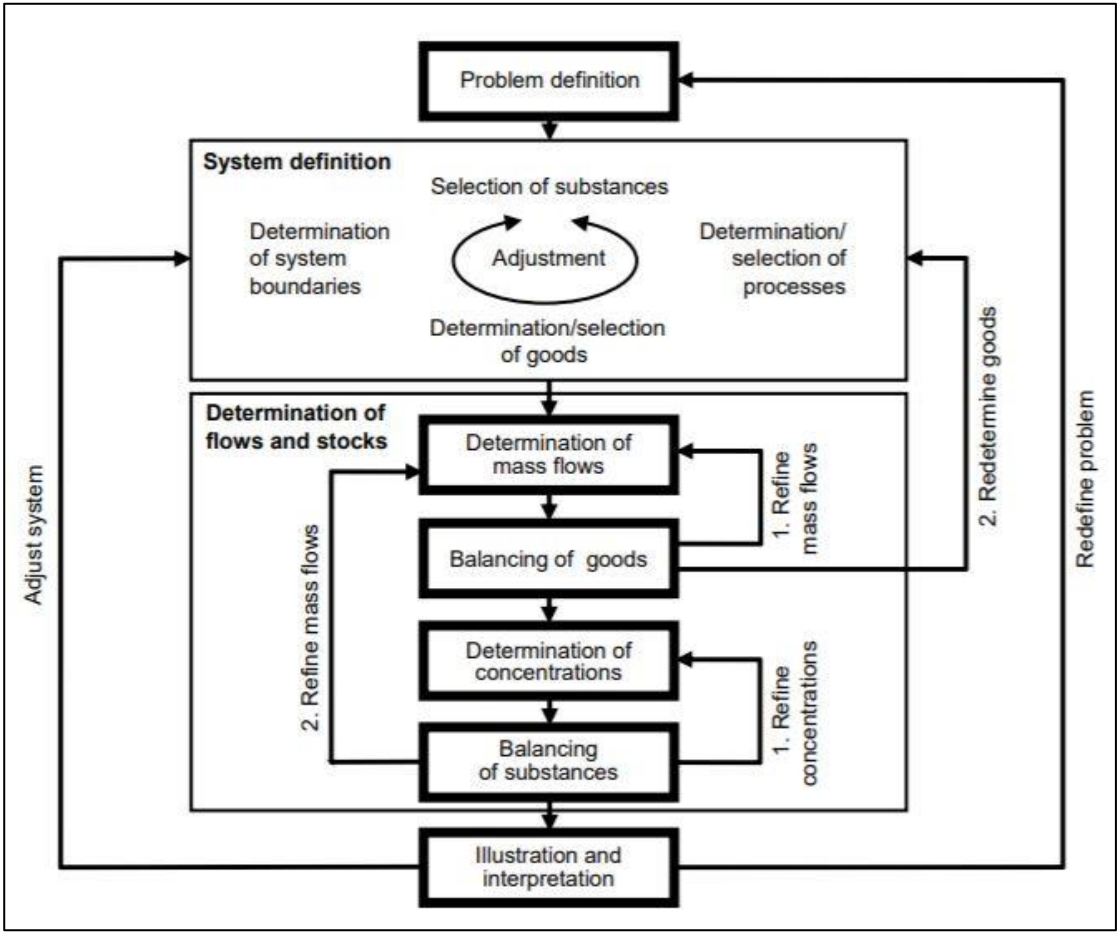
LIST OF TABLES

LIST OF FIGURES

ANNEX

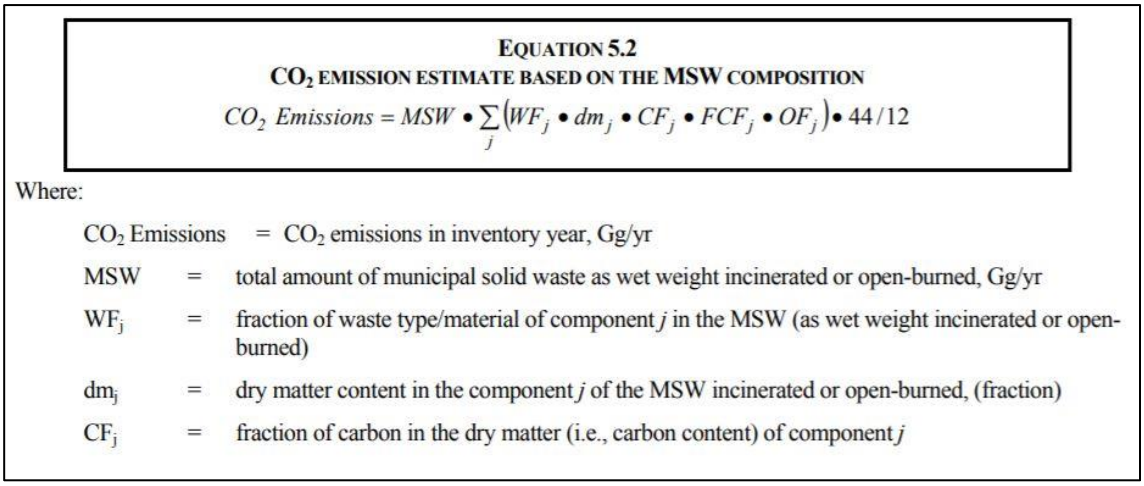
Annex I

Annex I: Procedure for developing a material flow analysis; taken from the "Practical Handbook for Material Flow Analysis" (Brunner & Rechberger, 2005)



Annex II

Annex II: IPCC CO_2 Emission estimate equation based on the MSW composition (Guendehou, et al., 2006)



EQUATION 5.2

CO_2 EMISSION ESTIMATE BASED ON THE MSW COMPOSITION

$$CO_2\ Emissions = MSW \bullet \sum_j (WF_j \bullet dm_j \bullet CF_j \bullet FCF_j \bullet OF_j) \bullet 44/12$$

Where:

CO_2 Emissions = CO_2 emissions in inventory year, Gg/yr

MSW = total amount of municipal solid waste as wet weight incinerated or open-burned, Gg/yr

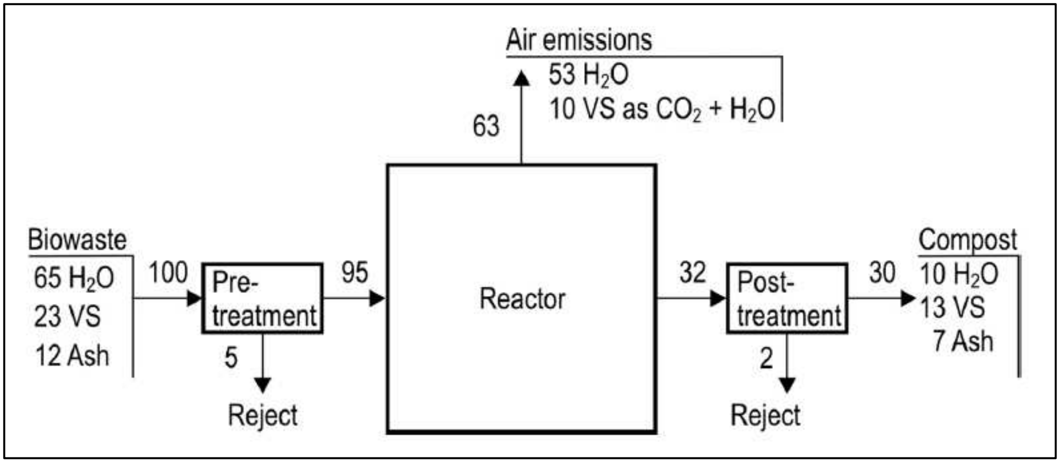
WF_j = fraction of waste type/material of component *j* in the MSW (as wet weight incinerated or open-burned)

dm_j = dry matter content in the component *j* of the MSW incinerated or open-burned, (fraction)

CF_j = fraction of carbon in the dry matter (i.e., carbon content) of component *j*

Annex III

Annex III: Mass balance for a typical composting plant using bio-waste (Boldrin, et al., 2011)



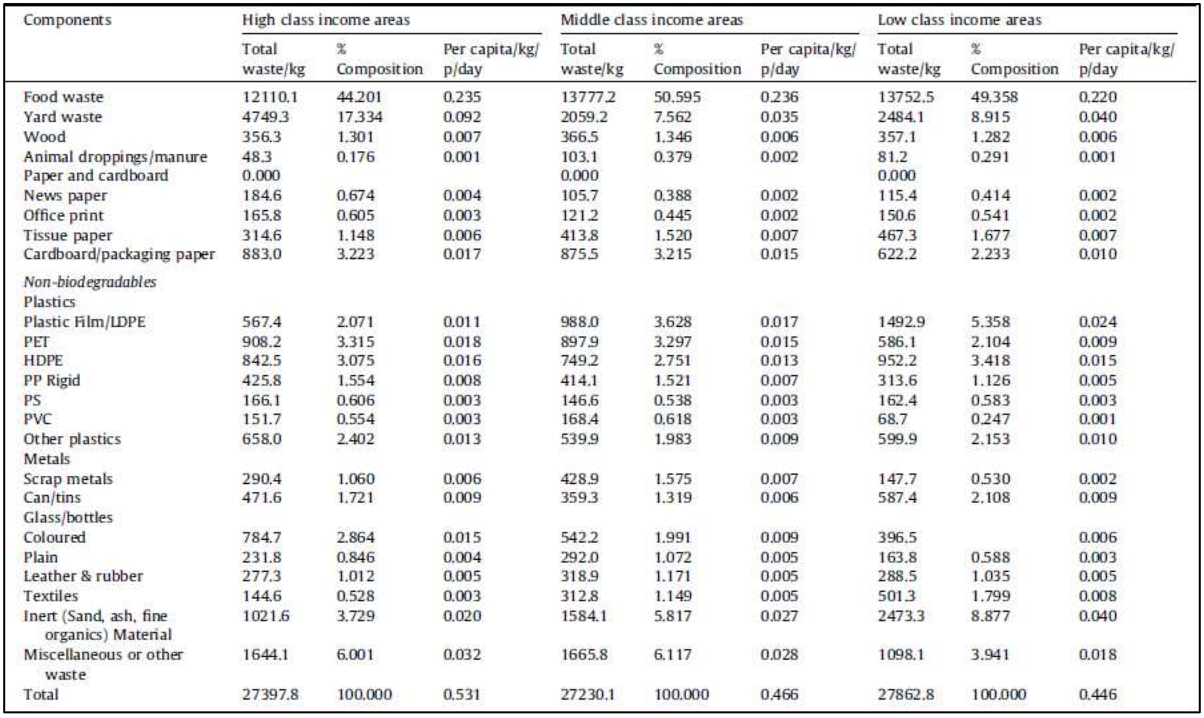
Annex IV

Annex IV: Chemical composition of common waste material fraction (Riber, et al., 2009)

Sample fraction	Heating value lower MJ/kg wet	Ash % TS	VS % TS	TS % wet	C-tot mg/kg TS	H mg/kg TS	O mg/kg TS	S mg/kg TS	N mg/kg TS	P mg/kg TS	K mg/kg TS	Al mg/kg TS	Fe mg/kg TS	Ca mg/kg TS	Na mg/kg TS
Veg. food	2.5	5.2	96.4	23.0	477000	66000	394600	1840	19000	2310	12700	1030	310	5550	3120
Animal food	9.2	8.7	94.2	42.9	565000	79000	182200	3780	70000	9960	5330	289	52	40900	10800
Newsprints	14.6	8.2	92.7	87.0	448000	57000	442100	319	1000	75	672	8850	1220	11100	246
Magazines	10.6	34	76.7	93.8	342000	42000	274500	724	1000	180	686	14600	1200	101000	898
Advertisements	14.4	27.4	75.1	91.3	346000	48000	329400	784	3000	155	899	32425	929	36025	1278
Books and phonebooks	13.4	17.9	86.1	89.5	406000	51600	380550	487	1200	114	699	12933	1185	40563	545
Office paper	11.2	20.7	87.8	91.3	375000	50000	366900	643	1000	38.2	118	1310	918	77700	774
Other clean paper	12.0	17.4	87.6	92.6	383000	50000	385300	1780	2000	95.7	730	11700	789	43900	977
Paper and carton containers	13.5	13.4	88.8	77.7	411000	56000	396100	1000	2000	129	374	12800	2910	26200	476
Cardboard	12.2	14	89	83.5	409000	54000	394800	631	1000	125	397	11900	2940	30900	416
Milk cartons and alike	17.4	1.2	98.8	83.2	523000	73000	387700	701	4000	330	472	1430	86	727	1500
Carton with alu-foil	19.6	9.6	90.3	83.9	516000	77000	307900	534	2000	189	571	55800	539	7820	1740
Kitchen tissues	8.0	2.7	97.9	53.1	452000	63000	447500	883	8000	1100	1510	681	720	3930	2060
Dirty paper	13.2	8.9	91.7	75.5	455000	65000	382500	1190	3000	330	1190	12600	433	10900	1090
Dirty cardboard	14.5	14.9	87.6	86.9	431000	58000	357500	1260	3000	347	790	21500	467	34600	2730
Soft plastic	34.1	4.4	95.8	85.9	820000	132000	1100	281	2000	217	673	692	305	1100	554
Plastic bottles	32.5	6.1	93.8	89.5	772000	113000	52000	1090	1000	270	372	66800	1830	3140	1330
Hard plastic	36.1	2.2	98.1	96.8	799000	105000	17300	988	55000	75.6	190	1430	1750	4160	422
Non-recyclable plastic	29.2	5.5	94.9	92.9	710000	97000	110600	520	5000	5610	1210	5650	849	10900	1170
Yard waste	5.9	24	78.5	51.8	430000	52000	259400	1900	15000	1980	12700	2360	1480	21100	944
Animals etc.	5.0	25.4	75.1	39.6	439000	64000	207700	4120	33000	15900	7390	4220	1930	27100	2410
Diapers and tampons	11.1	8.3	94.2	54.5	553000	80000	273300	718	9000	608	1410	454	152	9620	21900
Cottonsticks etc.	8.6	2.4	97.8	44.6	507000	74000	388300	606	4000	450	1170	667	386	2090	1360
Other cotton etc.	11.0	3.2	97.2	52.5	550000	78000	300300	641	38000	400	1620	711	164	3570	1020
Wood	15.6	10	90.6	84.1	521000	64000	304900	836	8000	274	2120	4400	945	9640	703
Textiles	18.5	3.6	96.6	94.0	521000	60000	348000	3970	32000	2300	706	879	340	4400	3590
Shoes, leather	22.9	12.6	89	93.3	613000	73000	137800	6594	3000	273	605	1863	2096	21522	1025
Rubber etc.	27.2	9.7	92.2	92.3	654000	84000	65900	6050	6000	313	559	1540	187	22800	347
Office articles	25.6	25.2	74.4	93.2	594000	69000	35600	551	22000	148	278	31600	22100	7610	575
Cigarette buts	11.6	15.2	88.2	65.9	432000	62000	334700	2290	14000	1630	17900	3080	1850	22800	1870
Other combustibles	21.9	26.9	76.4	90.5	542000	81000	96300	1760	9000	507	1770	3580	85100	28300	14500
Vacuum cleaner bags	4.6	60.5	41.9	70.8	208000	30000	120100	7310	31000	1110	4000	6470	4250	22900	7960
Clear glass	−0.3	100	0	88.0	0	0	0	832	0	64	3650	6860	477	67700	22400
Green glass	−0.1	100	0	96.6	0	0	0	111	0	96	7750	7620	1760	69000	24900
Brown glass	−0.1	100	0	95.0	0	0	0	92	0	122	7010	9870	2400	66800	26100
Other glass	−0.2	100	0	89.7	0	0	0	687	0	72	4433	7125	765.6	67850	22960
Al containers	−0.2	100	0	91.7	0	0	0	30	0	110	162	628000	345000	36	165
Al trays/foil	5.1	76.1	21.8	81.2	152000	27000	53500	297	4000	551	1190	861000	23900	1330	1670
Metal containers	−0.3	100	0	86.8	0	0	0	99	0	212	532	215000	727000	244	539
Metal-like foil	32.6	100	0	89.4	762000	117000	96000	189	4000	480	997	1520	150	955	849
Other of metal	−0.2	100	0	91.7	0	0	0	321	0	252	200	37800	640000	1500	390
Soil	4.6	43.9	58.3	54.4	300000	34000	205300	3740	11000	1370	4680	7300	12700	31600	9430
Stones and gravel	0.0	100	0	100	0	0	0	0	1030	439	17030	11842	13226	50066	11822
Residual	0.0	0	0	100	0	0	0	0	0	0		0	0	0	0
Ceramics	−0.1	100	0	97.7	0	0	0	104	0	152	18600	22100	7260	3450	5760
Cat gravel	−0.4	93.1	8.7	83.9	26000	7000	30300	1920	4000	1920	12200	21900	27700	21900	4950
Batteries	0.3	85.8	16.9	91.1	87000	11000	27000	1650	1000	10	39700	1300	60400	876	1480
Other non-combustibles	−0.8	97.7	3.4	63.4	13000	1000	7400	537	0	130	10400	11200	1600	45900	41700

Annex V

Annex V: Generation and composition of sub-fractions of household wastes from Ghana. Taken from: (Miezah, et al., 2015)



Components	High class income areas			Middle class income areas			Low class income areas		
	Total waste/kg	% Composition	Per capita/kg/p/day	Total waste/kg	% Composition	Per capita/kg/p/day	Total waste/kg	% Composition	Per capita/kg/p/day
Food waste	12110.1	44.201	0.235	13777.2	50.595	0.236	13752.5	49.358	0.220
Yard waste	4749.3	17.334	0.092	2059.2	7.562	0.035	2484.1	8.915	0.040
Wood	356.3	1.301	0.007	366.5	1.346	0.006	357.1	1.282	0.006
Animal droppings/manure	48.3	0.176	0.001	103.1	0.379	0.002	81.2	0.291	0.001
Paper and cardboard	0.000			0.000			0.000		
News paper	184.6	0.674	0.004	105.7	0.388	0.002	115.4	0.414	0.002
Office print	165.8	0.605	0.003	121.2	0.445	0.002	150.6	0.541	0.002
Tissue paper	314.6	1.148	0.006	413.8	1.520	0.007	467.3	1.677	0.007
Cardboard/packaging paper	883.0	3.223	0.017	875.5	3.215	0.015	622.2	2.233	0.010
Non-biodegradables									
Plastics									
Plastic Film/LDPE	567.4	2.071	0.011	988.0	3.628	0.017	1492.9	5.358	0.024
PET	908.2	3.315	0.018	897.9	3.297	0.015	586.1	2.104	0.009
HDPE	842.5	3.075	0.016	749.2	2.751	0.013	952.2	3.418	0.015
PP Rigid	425.8	1.554	0.008	414.1	1.521	0.007	313.6	1.126	0.005
PS	166.1	0.606	0.003	146.6	0.538	0.003	162.4	0.583	0.003
PVC	151.7	0.554	0.003	168.4	0.618	0.003	68.7	0.247	0.001
Other plastics	658.0	2.402	0.013	539.9	1.983	0.009	599.9	2.153	0.010
Metals									
Scrap metals	290.4	1.060	0.006	428.9	1.575	0.007	147.7	0.530	0.002
Can/tins	471.6	1.721	0.009	359.3	1.319	0.006	587.4	2.108	0.009
Glass/bottles									
Coloured	784.7	2.864	0.015	542.2	1.991	0.009	396.5		0.006
Plain	231.8	0.846	0.004	292.0	1.072	0.005	163.8	0.588	0.003
Leather & rubber	277.3	1.012	0.005	318.9	1.171	0.005	288.5	1.035	0.005
Textiles	144.6	0.528	0.003	312.8	1.149	0.005	501.3	1.799	0.008
Inert (Sand, ash, fine organics) Material	1021.6	3.729	0.020	1584.1	5.817	0.027	2473.3	8.877	0.040
Miscellaneous or other waste	1644.1	6.001	0.032	1665.8	6.117	0.028	1098.1	3.941	0.018
Total	27397.8	100.000	0.531	27230.1	100.000	0.466	27862.8	100.000	0.446