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Municipal Solid Waste as a Resource for Generating Electricity: A Case Study of Harare

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ABSTRACT: The amount of Municipal Solid Waste (MSW) produced is rising due to urbanization and population growth. When MSW is properly handled, it becomes a renewable energy source, but when it is not, it poses significant environmental risks. This paper studies the MSW generated in the city of Harare, Zimbabwe and explores the scope of its usage as a resource for obtaining electricity. Daily 891 MT of MSW is generated out of which 356.4 MT is organic matter. Use of robotics and automation increases the system's efficiency and reliability. Through the thermal method of gasification of 356.4 MTs of organic matter obtaining syngas can produce 326.7 MWh electricity. Apart from organic matter MSW consists of inert and recyclable matter. After segregation, different type of matter can be processed and reused efficiently bringing net waste to zero thereby contributing to circular economy. The system contributes to United Nation's Sustainable Development Goal (SDG) 7 (Affordable and Clean Energy), 11 (Sustainable Cities and Communities) and 12 (Responsible Consumption and Production).

KEYWORDS: Municipal Solid Waste, waste management, organic matter, gasification, circular economy.

I. INTRODUCTION

Urbanization and increasing population is generating large amount of Municipal Solid Waste (MSW) in Harare, Zimbabwe's capital and largest city. It is estimated that the city generates 891 tonnes of MSW everyday which is posing challenges in collection and treatment. MSW is composed of 40 to 50% organic and biodegradable material together with substantial volumes of plastics, packaging, and bulky waste from domestic and commercial areas. Due to the diverse type of components in MSW, the most challenging task is of segregation of different components and employing the most suitable method for managing each of them [1] [2].

To efficiently manage the large amount of MSW generated, Harare's waste system needs modern fleets, higher disposal capacity, and fully resourced transfer and landfill sites. Official dumpsites need to be well managed or equipped, so as to eliminate leachate contamination of surface and groundwater and adversely affect the environment and public health. Increasing MSW also requires increased collection capability, failing which pushed residents to illegal dumping, backyard burning, open burning at dumpsites, or burying waste all of which elevates air pollution, vector-borne disease risk, and the likelihood of waterborne disease outbreaks [3].

A study of MSW management strategies in Amaveni suburbs in Kwekwe, Zimbabwe showed that exiting techniques are not contributing much to circular economy which is causing serious concerns to environment and biodiversity [4]. An assessment of the household's solid waste management practices and the feasibility of a transition towards a circular economy at Nkayi growth point was done by [5]. On collecting data it was found that move to a circular economy at Nkayi growth point is facing hindrance due to absence of local bylaws to enforce implementation of circular economy and lack of awareness by households. [6] reviewed Zimbabwe's waste management policies and found that while Zimbabwe's environmental policies address industrial waste control, they inadequately promote circular economy strategies, relying mainly on regulatory enforcement rather than incentives, with circular practices largely implemented on a voluntary basis.

Local as well as higher governing bodies design policies for waste management but it needs strict implementation, coordination between different agencies, focusing on public–private collaboration, future proposals for investment and

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expansion are required for securing the future. Alongwith the local governing authorities, the informal sector plays a significant role in Harare's waste economy. Scavengers, scrap-metal collectors, and small-scale recyclers recover materials from dumpsites and the waste stream, providing livelihoods and diverting valuable resources from disposal — yet they operate with little recognition, no formal protection, and expose themselves to hazardous conditions. Integrating and supporting these actors is widely identified as a pragmatic route to improve recycling and social outcomes [7].

II. GASIFICATION OF MUNICIPAL SOLID WASTE

Gasification is a thermochemical process that converts the organic fraction of municipal solid waste (MSW) into a combustible synthesis gas (syngas) under oxygen-starved conditions at high temperatures (typically 700–1,200 °C). Feedstock preparation (segregation, shredding, drying and removal of inerts/recyclables) is usually required to produce a more homogeneous fuel (RDF) suitable for reliable gasifier operation [8]. Inside the gasifier, partial oxidation and pyrolysis reactions break down MSW into syngas (primarily CO and H_2, with CH_4 and CO_2), plus a small fraction of char, tar and inorganic residues (ash/vitrified slag). Different gasifier types (fixed bed, fluidized bed, entrained flow, plasma) give different syngas quality and quantity of tar/ash, depending on feedstock, scale and desired application [9]. In the process of gasification the mass and volume of MSW is reduced by more than 70%, in contrast with open combustion. Due to this controlled heat treatment, syngas is easily purified, which reduces emissions of dioxins/furans and particulates during its use in engines and turbines for power generation. Syngas can be further upgraded to fuels (methanol, synthetic natural gas, hydrogen) or chemicals, supporting circular economy approaches. Gasification can also handle mixed and low-grade wastes that are difficult to recycle. However, feed variability, tar formation, chloride content (from plastics) and complex gas cleaning remain operational challenges [10].

Syngas yields and qualities vary strongly with MSW composition, pretreatment and gasifier type. Literature surveys report syngas volumes on the order of a few hundred to over a thousand normal cubic metres (Nm^3) per tonne of MSW (examples in the literature range roughly ~300–1,200 Nm^3/t), with lower heating values typically in the range ~4–10 MJ/Nm^3 depending on composition and operating conditions. These variations strongly influence the electrical energy yield, which is often reported in the literature as roughly a few hundred kWh per tonne of MSW (typical reported ranges ≈200–800 kWh/t depending on assumptions) [11]. Solid residues (char, ash, vitrified slag) are a much smaller fraction, typically on the order of 5–15% by mass of the original waste; when vitrified they are often inert and can sometimes be used in construction applications. Tar and wastewater from gas cleaning are minor but important by-products that require treatment [12].

III. USE OF ROBOTICS AND AUTOMATION IN MSW SEGREGATION, GASIFICATION PROCESS AND ELECTRICITY GENERATION

Use of Robotics and automation in managing MSW increases segregation efficiency, reduces risks for workers and increases energy recovery. Automated MSW management systems are capable of monitoring the environmental conditions so as to mitigate the ill effects of MSW on air earth and underground water bodies. Similarly the adverse effect of power generating system is controlled with the emissions maintained within permissible limits.

A. Robotics and Automation in MSW Segregation

MSW management at landfill/accumulation site begins with effective segregation. Manual segregation is limited by human capability and exposes workers to hazardous materials. Implement of robotics and automated systems uses Automated Material Recovery Facilities equipped with sensor-based and AI-driven technologies [13]. Metals, recyclable, inert and organic matter can be segregated using optical sensors, near-infrared (NIR) spectroscopy, X-ray sensors, magnetic separators, and eddy current separators. Sorting process can be optimized by AI-enabled robotic arms, combined with machine vision and deep learning algorithms, which can efficiently identify different types of waste according to their shape, texture, and material composition, facilitating swift and accurate sorting [14]. These intelligent systems work uninterruptedly with high accuracy, enhancing recovery rates and process consistency. Automated system provides Real-time monitoring of conveyor belts, waste flow rates, and system performance which maintains uniformity in production of Refuse Derived Fuel (RDF) produced by processing of segregated organic matter thereby stabilizing the gasification process. Overall, robotics enhances safety, productivity, and resource recovery in MSW segregation [15].

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B. Automation in the Gasification Process

Automated plants use Programmable Logic Controllers (PLCs) and distributed control systems (DCS) to regulate feed rate, temperature, pressure, equivalence ratio, and residence time. Variation of feedstock supply to the gasifier causes formation of tar or incomplete gasification. PLC controlled automated system maintains consistent input feedstock supply and optimizes the gasification process [16]. Quality of syngas produced is effected by type of feedstock/MSW, temperature, gasifying agent, equivalence ratio, feed rate and residence time. Automatic analyzers continuously examine syngas composition, including hydrogen (H_2), carbon monoxide (CO), methane (CH_4), and carbon dioxide (CO_2). Based on these measurements, control algorithms dynamically adjust operating conditions to maximize syngas quality and calorific value. As gasification takes place at high temperature, handling and inspection of the high temperature areas like refractory by humans can be dangerous which makes implementation of robotics necessary. Robotics is also used for ash and slag handling [17]. Predictive maintenance systems powered by artificial intelligence analyze sensor data to identify early signs of equipment wear, fouling, or corrosion, minimizing downtime and extending plant life.

C. Automation in Syngas Cleaning and Conditioning

Syngas produced from gasification contains impurities like particulates, tar, acid gases and trace contaminants. Automation help in cleaning of syngas through cyclones, wet scrubbers, fabric filters, and catalytic tar reformers all controlled by sensor-based feedback mechanisms to maintain optimal operating conditions [18]. Robots help in inspection, filter replacement, and maintenance of gas cleaning equipment, enhancing safety and reliability. Emissions from the cleaning and conditioning system are monitored and maintained within permissible limits by the automated control which also protects downstream power generation equipment from damage.

D. Robotics and Automation in Electricity Generation

Syngas can be used for power generation using gas engine, gas turbine or combined heat and power (CHP) systems. Apart from maintaining the optimal composition of syngas, automated systems regulate Automated control systems regulate fuel flow, air–fuel ratio, combustion temperature, and load matching in engines and turbines. Sensors in the automated system continuously monitors vibration, exhaust emissions, temperature and pressure, enabling real-time optimization and fault detection. In grid-connected systems, automation ensures synchronization, voltage regulation, and safe power export [19] [20]. Robots increase the efficiency and reliability of the power generating system by inspecting and maintaining generators, turbines, and heat recovery units, reducing downtime and operational risks. In CHP systems, automation optimizes simultaneous heat and power generation, maximizing overall system efficiency. Fig 1. shows different processes involved in the MSW to energy production system with involvement of robotics and automation in it.

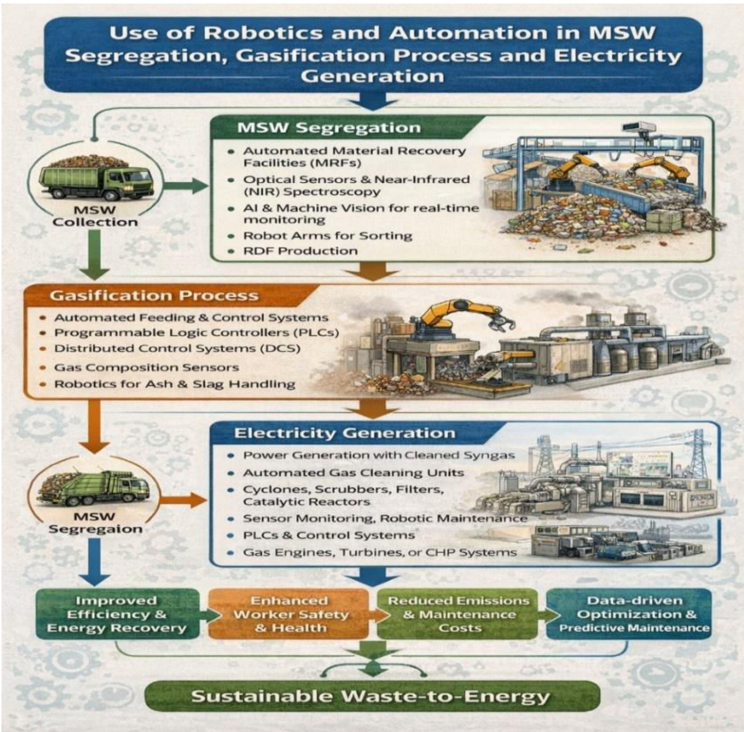

Fig 1. Different processes involved in the MSW to energy production system and involvement of robotics and automation

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E. Benefits of Robotics and Automation in MSW-Based Energy Systems

A high capacity advanced PLC like Mitsubishi Electric's iQ-R series has program capacity ranging from 10K to 1200K steps, processing speed from 1.96 to 31.3 nanoseconds, program memory of 640 KB, Data memory of 10 MB, signal flow memory of 5 MB, external memory support to 32 GB, local IO points from 4096 to 16384 and interrupt minimum interval of 50 microsecond. Such advanced PLCs can automate all three sections ie. MSW segregation, gasification and electricity generation which gives higher operational efficiency, improved energy recovery, enhanced worker safety, reduced emissions, and lower lifecycle costs. Automation enables real-time data acquisition, performance analytics, and predictive maintenance, supporting smarter decision-making and improved environmental compliance.

IV. RESULT AND DISCUSSION

Fig 2 shows the different sections in the power generating system with the amount of energy obtained and fuel/electricity output. MSW is shredded into 10-50 mm size particles to increase which makes uniform flow into gasifier, removes slagging and stabilizes the operation. This shredded matter is pre-treated at a temperature of 80–200°C to reduce moisture content below 20%, increase effective calorific value, improve ignition and reactivity, reduced auxiliary fuel requirement and stabilize gasifier temperature. In integrated systems, waste heat recovered from syngas engines or gas turbines is redirected to the thermal pre-treatment unit. So, this system does not require external fuel for drying, improves overall system efficiency, reduces operational costs and reduces greenhouse gas emissions. The combined effect of shredding and thermal pre-treatment results in higher H_2 and CO concentrations, reduced tar and particulate content, more stable syngas calorific value (4–6 MJ/Nm³) and improved compatibility with engines and turbines. MSW has lower heating value (LHV) of 10 MJ/kg giving energy potential of 356.4 MT organic MSW as 3,564,000 MJ. Syngas produced and the energy obtained from gasifier can be determined as [13] [21]:

Typical syngas yield from organic MSW gasification $2.2\ \text{Nm}^3/\text{kg MSW}$

Total Syngas Volume $V_{\text{syngas}} = 356{,}400 \times 2.2 = 784{,}080\ \text{Nm}^3$

Syngas Energy Density $\text{LHV}_{\text{syngas}} \approx 5\ \text{MJ/Nm}^3$

Syngas Energy content $784{,}080 \times 5 = 3{,}920{,}400\ \text{MJ}$

Syngas is used in IC engine / gas turbine under CHP mode Electrical Conversion Efficiency

$$\eta_{\text{el}} = 30\%$$

Electrical Energy Generated $E_{\text{electric}} = 0.30 \times 3{,}920{,}400 = 1{,}176{,}120\ \text{MJ or } 326{,}700\ \text{kWh}$

In CHP systems, thermal efficiency ≈ 50%, which gives:

Recoverable Waste Heat: $\eta_{\text{thermal}} = 50\%$

$$E_{\text{thermal}} = 0.50 \times 3{,}920{,}400 = 1{,}960{,}200\ MJ$$

Total Useful Energy Output $E_{\text{useful}} = E_{\text{electric}} + E_{\text{thermal}}$

$$E_{\text{useful}} = 1{,}176{,}120 + 1{,}960{,}200 = 3{,}136{,}320\ MJ$$

Overall CHP efficiency ≈ 88%

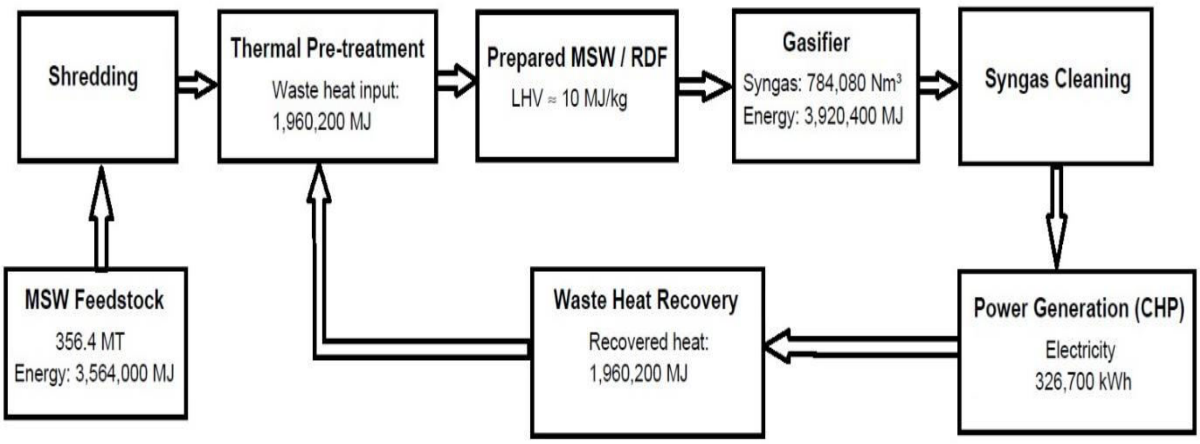

Fig 2. Different sections in the power generating system

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V. CONCLUSION

This study analysed the technical and operational feasibility of converting segregated 356.4 MT of organic municipal solid waste (MSW) out of 891 MT into useful energy through an integrated gasification-based power generation system supported by robotics and automation. Automated waste handling, preprocessing, and process control enhance system reliability, safety, and consistency of syngas production. The proposed combined heat and power (CHP) configuration generates 326,700 kWh of electricity while effectively recovering thermal energy, resulting in an overall system efficiency of approximately 88%. The approach simultaneously addresses waste management challenges, reduces landfill dependency, and contributes to sustainable urban energy supply, supporting circular economy and low-carbon development objectives.

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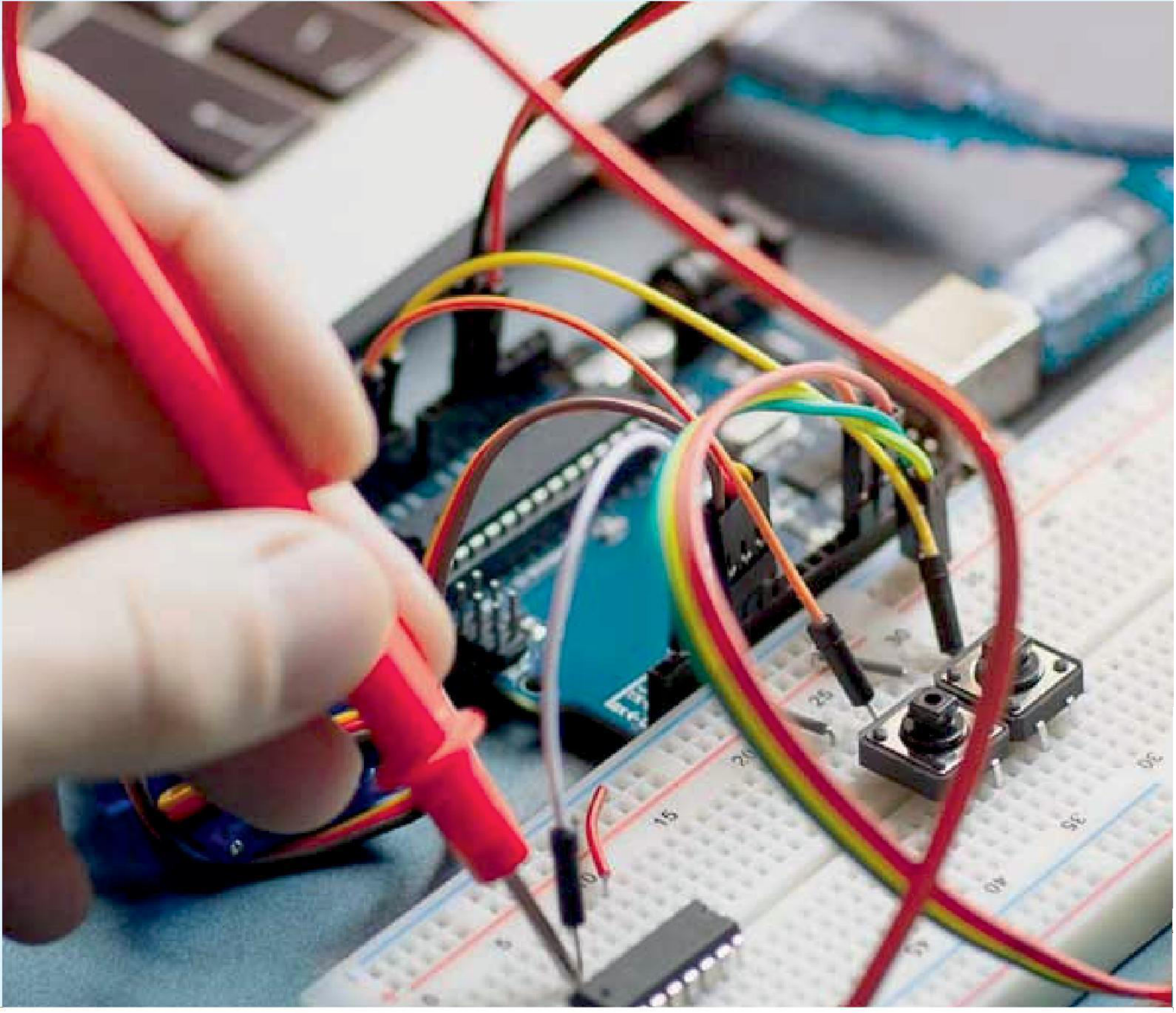

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