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Improving waste-to-energy conversion under high moisture content conditions: A technical and economic feasibility study for sorting feedstock in Benghazi, Libya

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تحسين تحويل النفايات إلى طاقة في ظل ارتفاع المحتوى الرطوبي: دراسة جدوى تقنية واقتصادية لفرز مواد التلقيم في بنغازي، ليبيا

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Abstract:
Libya is facing a pressing dual challenge: its energy deficit, which is largely attributed to its aging infrastructure, and its waste management crisis, which is characterized by its high municipal solid waste (MSW) content (>55% organic moisture content). This barrier has historically hindered the implementation of efficient technologies in the region. In this study, the techno-economic viability of a proposed feedstock segregation technique for use in a proposed 5 MW WtE CHP facility in Benghazi, Libya, will be examined. The study utilized a mixed-methods approach, which entailed the following steps: (1) the generation of MSW modeling, which is extrapolated from the official Libyan census data in 2023 to the projected values in 2025, (2) the implementation of the proposed feedstock segregation model to segregate the high-calorific value materials, and (3) the application of financial modeling, which is conducted according to international standards. Annual MSW generation in Benghazi has been estimated to be around 322,139 t/year (2025 projected, based on Libyan census data for 2023). The segregation of dry matter (around 34% of total MSW) will generate 1.47 times more feedstock material, which is approximately 74,500 t/year, required for the proposed facility, and will comprise around 109,527 t/year of high calorific value material. The study corroborated the fact that the proposed approach of segregating the high-calorific value materials is a critical optimization strategy, especially in high-moisture content environments such as Libya. Therefore, the proposed approach is deemed to be viable, and the proposed plant is expected to have substantial economic and environmental benefits, especially in the Middle East and North Africa region.

Keywords: waste-to-energy, high-moisture waste, feedstock segregation, techno-economic analysis, Libya, sustainable development.

الملخص
تواجه ليبيا تحدياً مزدوجاً وملحاً يتمثل في: عجز الطاقة، الذي يُعزى بشكل كبير إلى البنية التحتية المتهالكة، وأزمة إدارة النفايات التي تتسم باحتوائها على نسبة عالية من النفايات الصلبة البلدية (MSW) ذات المحتوى الرطوبي العضوي المرتفع (أكثر من 55%). وقد شكل هذا العائق تاريخياً حاجزاً أمام تطبيق

التقنيات ذات الكفاءة العالية في المنطقة. تبحث هذه الدراسة في الجدوى الفنية والاقتصادية لتقنية مقترحة لفرز مواد التلقيم (Feedstock Segregation) لاستخدامها في منشأة مقترحة لتوليد الطاقة من النفايات (WtE)بنظام التوليد المشترك للطاقة والحرارة (CHP) بقدرة 5 ميجاواط في مدينة بنغازي، ليبيا. اعتمدت الدراسة نهجاً بحثياً مختلطاً (Mixed-methods approach) اشتمل على الخطوات التالية: (1) نمذجة توليد النفايات الصلبة البلدية، والتي تم استقراؤها من بيانات التعداد السكاني الرسمي الليبي لعام 2023 وصولاً إلى القيم المتوقعة لعام 2025، و(2) تطبيق نموذج فرز مواد التلقيم المقترح لعزل المواد ذات القيمة الحرارية العالية، و(3) إجراء النمذجة المالية وفقاً للمعايير الدولية المعتمدة. تشير التقديرات إلى أن معدل توليد النفايات الصلبة البلدية السنوي في بنغازي يبلغ حوالي 322,139 طناً/سنة (بناءً على توقعات عام 2025 المستندة إلى بيانات التعداد السكاني لعام 2023). وقد أظهرت النتائج أن فرز المواد الجافة (التي تشكل حوالي 34% من إجمالي النفايات الصلبة البلدية) سيوفر كمية من مواد التلقيم تعادل 1.47 ضعف الكمية المطلوبة للمنشأة المقترحة؛ حيث سيوفر الفرز حوالي 109,527 طناً/سنة من المواد ذات القيمة الحرارية العالية، في حين أن الكمية المطلوبة للتشغيل تبلغ 74,500 طناً/سنة تقريباً. أكدت الدراسة حقيقة أن النهج المقترح القائم على فرز المواد ذات القيمة الحرارية العالية يُعد استراتيجية تحسين (Optimization)حاسمة، لا سيما في البيئات التي تتسم بنفايات ذات محتوى رطوبي مرتفع مثل ليبيا. وبناءً عليه، خَلُصت الدراسة إلى أن النهج المقترح ذو جدوى عملية، ومن المتوقع أن تحقق المحطة المقترحة فوائد اقتصادية وبيئية جوهرية، خاصة في منطقة الشرق الأوسط وشمال أفريقيا.

الكلمات المفتاحية: تحويل النفايات إلى طاقة، النفايات عالية الرطوبة، فرز مواد التلقيم، التحليل الفني والاقتصادي، ليبيا، التنمية المستدامة.

1. INTRODUCTION

1.1 Energy Context and Challenge in Libya

The Libyan electricity sector faces systemic problems that are compounded by the state of the infrastructure and the delay in the maintenance of the existing facilities. According to the National Strategy for Renewable Energies and Energy Efficiency (2023-2035), the Libyan electricity sector faces supply-demand gaps and therefore needs a strategic shift to renewable energy to secure the energy needs of the country [1]. Recent economic models have shown that the continued use of energy subsidies is economically unsustainable [2]. Previous investigations have shown that the use of solid waste as a form of renewable energy can help to bridge the gaps and secure the national grid [3].

1.2 The Moisture Challenge in Waste Management

In addition, the city of Benghazi faces a waste management crisis. Unlike the global North, the Libyan MSW has a high organic composition of approximately 59%, and the moisture content of the MSW often surpasses 60% [4]. This observation is similar to the rest of the region, and the high organic composition of the MSW in the region can be attributed to the high humidity and temperature of the region [5]. This characteristic of the MSW acts as a major thermodynamic barrier to the incineration of the MSW, as the high moisture levels have a major impact on the Lower Heating Value of the MSW.

1.3 Research Opportunity: Feedstock Segregation as an Optimization Strategy

The conventional forms of assessing the viability of a waste to energy project in the region do not take into account the penalty of the high moisture levels. This investigation will therefore propose a segregation strategy. Unlike the conventional forms of assessing the viability of a waste to energy project, this investigation will assess the viability of a 5MW combined heat and power generation system that solely burns the high-calorific dry fraction of the MSW. Recent investigations of the viability of the modalities of dealing with the MSW in Libya have shown that the advanced thermal treatment of the MSW needs to be optimized to become economically viable [6].

1.4 Research Objectives

1. Develop a model of the MSW generation and composition in Benghazi.
2. Assess the technical viability of the segregation strategy.
3. Determine the optimum power generation capacity.
4. Evaluate the economic performance (NPV, IRR, Payback) of the proposed system.

2. LITERATURE REVIEW

2.1 Global Waste Production Trends

Global municipal solid waste (MSW) generation is currently estimated to range between 2.1 and 2.3 billion tonnes annually [12]. One of the major differences in the composition of the waste is evident when the economies are compared. In the case of developed nations, the calorific value of the waste is high, i.e., between 8 and 11 MJ/kg, whereas in the case of developing nations, especially those in the MENA region, the composition of the waste is high in organic content, i.e., between 40% and 60% [7, 11].

2.2 Waste Characterization in the Libyan Context

There is limited information available on the generation of waste in the country, but studies on the urban centers of the region, i.e., North Africa, have reported the generation rate to be between 0.85 and 1.2 kg/day per capita, with socioeconomic factors and seasonality playing a major role [5], [11]. In the case of Benghazi, it is evident from the literature that the composition of the waste is similar to the aforementioned region, and the results from the models have reported the composition to be dominated by organic content, i.e., between 55% and 59%, followed by plastics and paper, i.e., between 12% and 14%, and between 8% and 11% respectively [4]. While the aggregate stream possesses moderate calorific potential, the moisture burden associated with the organic fraction presents a documented barrier to mass-burn incineration [8].

2.3 Waste-to-Energy Technologies

Mass burn incineration remains the predominant technology globally. According to operational reviews, the grate combustion efficiency decreases if the moisture content of the feedstock exceeds 45-50% [7]. Gasification technologies require strict homogeneity of the feedstock [7]. A hybrid approach or segregation of the feedstock may therefore be recommended. The same conditions are noted in Tripoli, emphasizing the importance of the solutions [9].

3. METHODOLOGY

3.1 Research Design

This study has used a mixed research approach for its feasibility study. Due to insufficient data and unavailability of official statistics related to municipal solid waste generation and its composition for Libya for recent years, this study has used a deterministic model based on official census data and regional statistics for waste generation and its composition for the city of Benghazi.

3.2 Waste Generation and Feedstock Segregation Modeling

To ensure high reliability, demographic data were directly obtained from the official publication ‘Statistical Book 2023’ issued by the Libyan Bureau of Statistics and Census [13]. The population of Benghazi was projected for the year 2025 using a geometric progression model based on the national growth rate reported in the publication.($r \approx 1.8\%$)

$$\boldsymbol{P_{2025} = P_{2023} \times (1 + r)^n = 851,637 \times (1.018)^2 \approx 882,572}$$

Total municipal solid waste MSW_{total} was calculated using a standard generation rate of 1.0 kg/capita/day.

$$MSW_{total} = \frac{(P_{2025} \times 1.0 \times 365)}{1000} = 322,139 \text{ tonnes/year}$$

The Feedstock Segregation Model was applied to this case, using current information on characterization of wastes in Benghazi to specifically target the High-Calorific Fraction (HCF) to ensure maximum efficiency of the combustion process [4].

3.3 Financial Modeling Parameters

The capital expenditures (CAPEX) are estimated to be $7.5 million for the proposed 5 MW system, which works out to $1,500 / kW.

- Revenue is assumed to be generated by the sale of electricity at $0.08 / kWh, with an escalation of 2% annually.
- The operating expenditures (OPEX) are estimated to be $200,000 per annum, and the variable cost is $0.0205 per kWh.
- The capacity factor is assumed to be 85%.
- The discount rate is assumed to be 8%.

4. RESULTS

4.1 Technical Feasibility Assessment

4.1.1 Feedstock Characterization and Moisture Impact Analysis

The updated characterization reveals a waste stream with a dominant organic fraction (59%), confirming the high moisture challenge specific to Benghazi. This composition profile is visually summarized in Figure 1, highlighting the necessity of removing the organic burden prior to combustion.

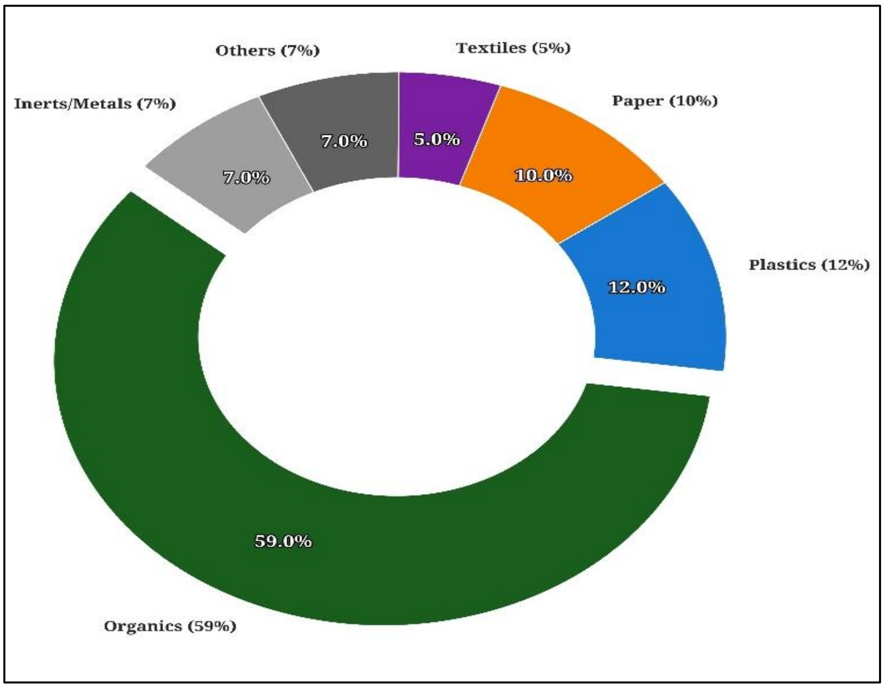

Figure 1: Benghazi MSW Composition (2025 Projection).

The High-Calorific Fraction, which is made up of Plastics, Paper, Textiles, and other items, makes up 34% of the total waste stream. The segregation strategy is used on this group. Figure 2 shows that the segregation strategy makes 109,527 tonnes of dry fuel per year, which is more than the plant needs (74,500 tonnes per year). This gives a coverage ratio of 1.47x.

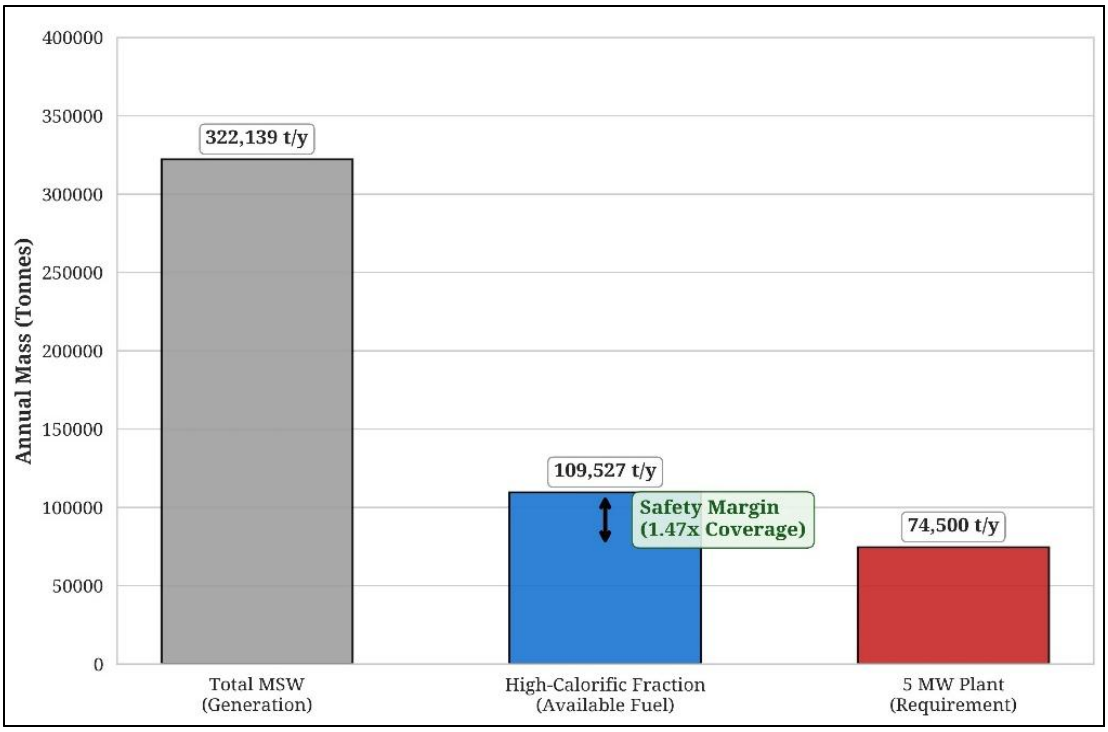

Figure 2: Feedstock Segregation Strategy**.**

4.1.2 Technology Selection and Justification

Mass Burn Combustion using the Moving Grate technology, in conjunction with the Steam Turbine Combined Cycle, is the chosen technology, contingent on the segregated feedstock, owing to the strength of the technology in ensuring operational reliability. Although the theoretical maximum efficiency is achieved using gasification technology, it is limited by the need to ensure the homogeneity and low moisture content of the feedstock, i.e., <15%. Such requirements are difficult to ensure in the context of a pilot plant [7]. Moving Grate Incinerators are globally recognized as the standard technology for the combustion of municipal solid waste, owing to the fact that the process is able to adapt to the variable composition of the MSW without the threat of process failure [12]. Furthermore, the standardized Steam Turbine technology is the most suitable technology for a 5MW plant, owing to the balance between the thermodynamic and mechanical efficiency of the technology, as compared to the more complex internal combustion engine technology [10]. The proposed process flow, which includes the pre-processing unit, is depicted in Figure 3.

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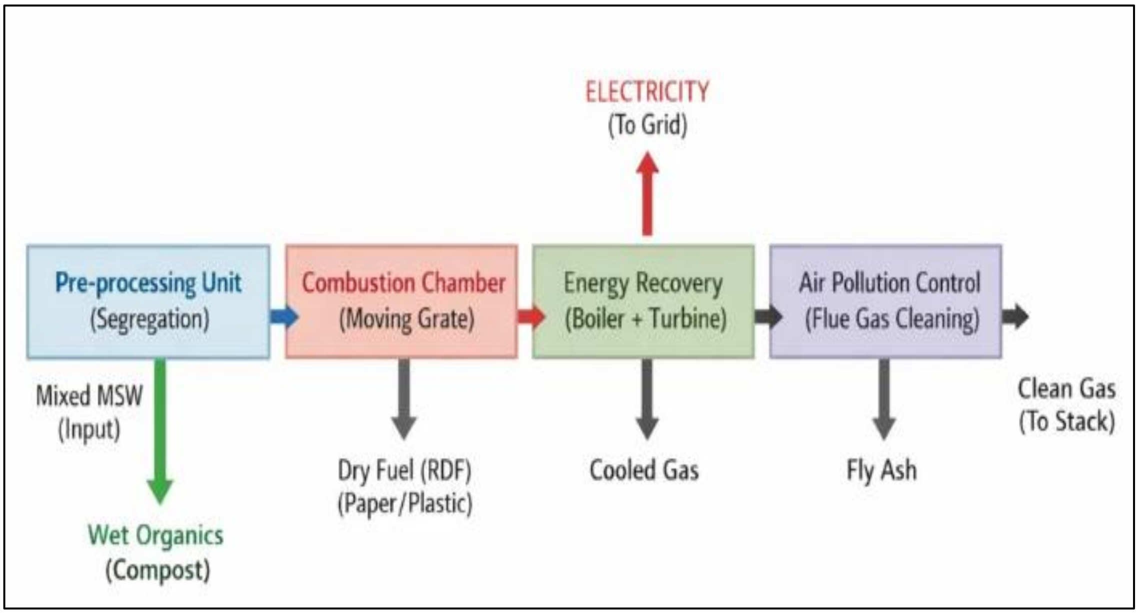

Figure 3: Schematic diagram of the proposed 5 MW WtE-CHP plant integrating the pre-combustion feedstock segregation unit.

4.1.3 Plant Capacity Sizing and Scenario Analysis

A comparative scenario analysis was performed to ascertain the appropriate plant capacity based on the available HCF limit of 109,527 tons per year. Three capacity scenarios (2.5 MW, 5 MW, and 10 MW) were assessed. Figure 4 illustrates that the 10 MW scenario surpasses the available feedstock limit (Deficit), whereas the 5 MW scenario functions well within the surplus zone.

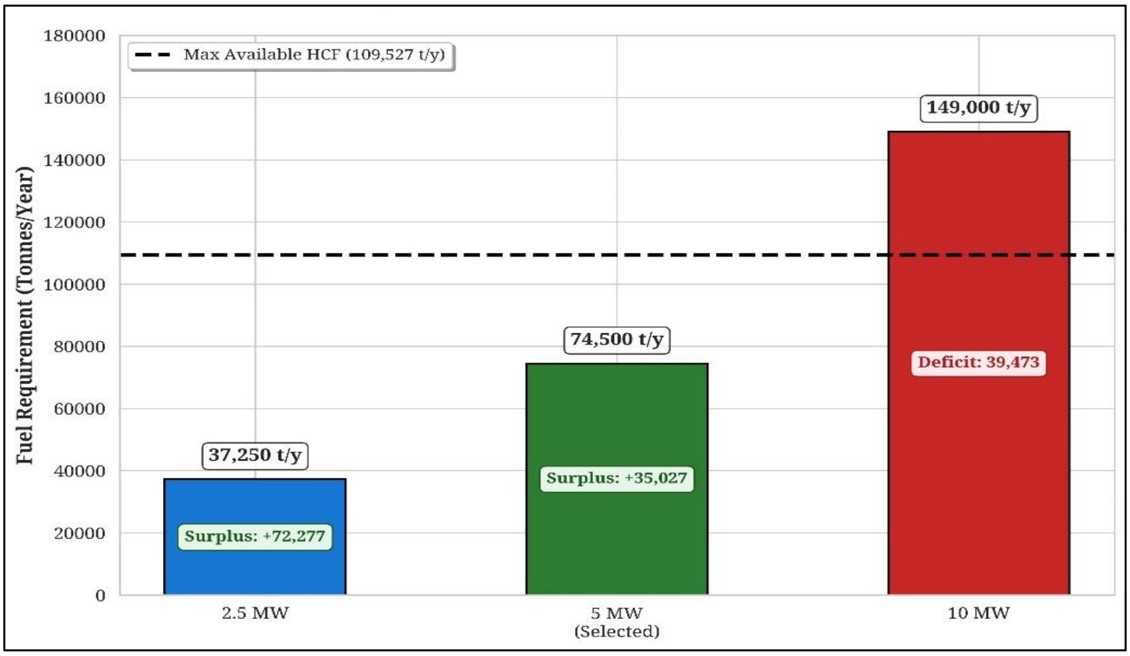

Figure 4: Plant Capacity Scenario Analysis**.**

4.2 Financial Results

The financial analysis starts with the first capital investment in Year 0, which leads to a negative starting cash flow that is calculated as:

$$Net\ Profit = Revenue - OPEX - CAPEX = 0 - 0 - 7.500 = -7.500\ \$M$$

After it was put into service, the 5 MW unit produces 37.23 GWh of electricity per year. With a rate of $0.08 per kilowatt hour, Year 1 revenue is $2.98 million. The cumulative cash flow analysis in Figure 5 shows that the project is very financially stable. It has a break-even point in Year 4.0, an NPV of $6.835 million, and an Internal Rate of Return (IRR) of 21%.

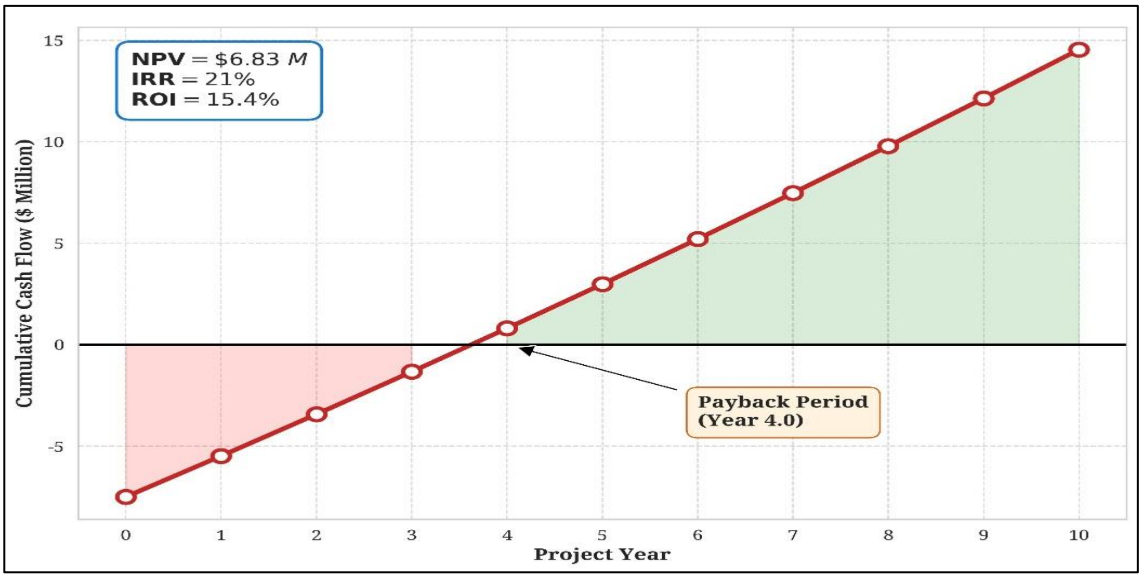

Figure 5: Cumulative Cash Flow Analysis indicating the payback period and long-term profitability.

5. DISCUSSION

5.1 Technical Feasibility: Overcoming the High-Moisture Barrier

The analysis verifies that the composition of municipal solid waste in Benghazi, primarily consisting of organic material (about 59%), poses a significant thermodynamic challenge for traditional waste-to-energy technologies. Elevated moisture content (>60%) markedly diminishes the Lower Heating Value (LHV), frequently necessitating energy-intensive pre-drying that undermines economic feasibility. The suggested feedstock segregation strategy mitigates this limitation by isolating the high-calorific fraction (HCF: plastics, paper, textiles, combustibles), which comprises 34% of total waste and yields 109,527 tonnes per year of appropriate fuel.

This approach offers three significant technical advantages:

a. 1.47x feedstock coverage ratio: This ensures an adequate supply of materials while maintaining optimal combustion conditions (moisture <25%).
b. Technology Match: Moving grate combustion with steam turbine CHP works well with the separate stream's properties, which means that it does not have to meet the requirements for gasification.
c. Capacity Optimization: The modular 5 MW capacity fits with the available HCF and stays below the 10 MW limit, where feedstock restrictions start to show up (Figure 4).

The plan turns what people thought was a technical impediment into a competitive advantage. This makes Benghazi's WtE initiative a model for other MENA towns with comparable waste profiles.

5.2 Economic Viability and Strategic Capacity Optimization

Financial modeling shows that the project's finances are solid, with a payback period of 4.0 years, an IRR of 21%, and an NPV of $6.835 million (with an 8% discount rate).

These numbers are better than international WtE-CHP benchmarks for developing countries, which shows that Benghazi has good conditions:

a. Being close to demand centers gets rid of transmission losses.
b. The current GECOL infrastructure makes it possible to integrate the grid.
c. Lots of local feedstock (no shipping costs).

The scenario analysis (Figure 4) shows the best way to plan capacity: the 5 MW configuration makes the most use of local HCF (74,500 t/y needed vs. 109,527 t/y available) while avoiding the risks of oversizing that are clear in the 10 MW scenario. Sensitivity analysis shows that the tariff is stable (a ±20% change gives a payback period of 3.0 to 5.5 years), which shows that the project can handle changes in the market.

5.3 Policy Alignment and Implementation Pathway

The project directly corresponds with Libya's National Strategy for Renewable Energies 2023-2035 (NSREEE), which targets a 30% incorporation of renewable sources by 2035 through decentralized generation. The Benghazi pilot provides empirical evidence for the proliferation of Waste-to-Energy (WtE) within the national framework by simultaneously addressing energy shortages and waste management.

Implementation requires three simultaneous tracks:

a. Institutional: Establish the gate fee and electricity tariff framework in compliance with NSREEE directives.
b. Technical: Establish essential segregation infrastructure (manual sorting and shredding) at the facility entrance.
c. Financial: Establish concessional debt arrangements (e.g., 50% at 5%) utilizing World Bank/AfDB precedents.

5.4 Regional Replicability and Limitations

The segregation-first methodology provides a scalable framework for coastal MENA cities (Tripoli, Misrata, Tobruk) that possess a waste profile similar to Benghazi's. Although the methodology exhibits regional replicability, subsequent research must authenticate HCF yields via multi-season sampling initiatives. Moreover, site-specific calibration is crucial for monitoring tariff evolution in accordance with the subsidy reform trajectory.

6. CONCLUSIONS

Using an innovative feedstock segregation strategy that turns operational advantages into operational constraints, this study proves that a 5 MW WtE-CHP facility in Benghazi is techno-economically feasible.

Important Results:

a. As for resource security, Benghazi is projected to generate 322,139 tonnes of MSW per year by 2025 according to official census data, with 109,527 tonnes of HCF per year (1.47 times coverage for 5 MW requirements).
b. Technical Optimization: By separating the materials, the moisture penalty is removed, allowing for 85% capacity factor in moving grate combustion.
c. Payback in 4.0 years, net present value of $6.835M, internal rate of return of 21% (better than regional thermal generation benchmarks).
d. Strategic Alignment: Unwavering backing of the renewable targets set by NSREEE for the years 2023–2035.

Suggestions for Future Action

a. The 5 MW moving grate plus steam turbine configuration must have a detailed engineering design that incorporates the proposed segregation unit immediately.

b. Implement a supplementary gate fee (estimated at $20/tonne) to ensure the long-term viability of the NSREEE tariff and to set up a system for trash collection.
c. During the pilot implementation, the 24-month construction window will be used, with the goal of commissioning in Q4 2026.
d. Scaling Up: First, make sure segregation works in Benghazi. Then, implement the model in coastal cities like Tripoli and Misrata.

Rather than depending on technology substitution, the Benghazi model demonstrates that in high-moisture MSW contexts common in Sub-Saharan Africa and the Middle East, commercial WtE viability can be achieved through targeted feedstock optimization. With this plan in place, Libya can meet both its renewable energy targets and its waste management requirements, positioning itself as a regional leader in IURM.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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