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Bridging Architecture and Energy Recovery: Waste-to-Energy Solutions for Yaoundé

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Abstract: As Yaoundé grapples with the dual crises of growing waste production and increasing energy demands, Waste-to-Energy (WtE) presents a viable solution. This article explores the design of a WtE plant in Yaoundé, integrating both architectural innovation and environmental sustainability. The study analyzes the current waste management and energy landscape in Cameroon, revealing the potential for energy valorization through waste incineration. The proposed plant features four incineration lines, capable of producing up to 419,000 MWh of electricity annually. Beyond its functional role, the plant's design incorporates community engagement features such as climbing walls and educational pathways, transforming the industrial complex into a public asset. This article examines how WtE plants can be designed to mitigate environmental impact, contribute to urban development, and promote community well-being.

Keywords: *Municipal Solid Waste; Waste-to-Energy; Public Engagement; Yaoundé.*

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I. INTRODUCTION

In cities like Yaoundé, the rapid urbanization has led to an overwhelming waste management challenge, with municipal solid waste (MSW) collection systems often strained [1]. Traditional methods of waste disposal, including landfilling, are proving to be environmentally unsustainable due to land scarcity and pollution risks. Simultaneously, Yaoundé faces energy shortages, with much of its electricity sourced from hydropower, which is susceptible to seasonal variability [2]. WtE technology offers a promising solution, addressing both waste and energy concerns. WtE facilities not only reduce the volume of waste sent to landfills but also generate renewable energy in the form of electricity or heat. This dual-purpose technology has gained traction worldwide as an alternative to traditional waste management methods. The challenge, however, is ensuring that such facilities are not only functional but also aesthetically and socially integrated into the urban fabric.

II. ANALYSIS OF YAOUNDE'S MSW POTENTIAL

➢ *Waste Generation*

Yaoundé, as a rapidly growing urban center, produces a significant amount of MSW. The waste generation rate is on an upward trend, driven by factors such as population growth, urbanization, and economic development. This increasing volume presents challenges for the city's existing waste management systems, which are often overwhelmed, leading to issues like improper disposal and environmental degradation.

- *According to Latest Estimates, we Have the Following Figures:*

Waste generation rate population: In Yaoundé, the average per capita waste generation is around 0.5 to 0.7 kg/person/day. And has a population of approximately 4.6 million people as shown in Figure 1.

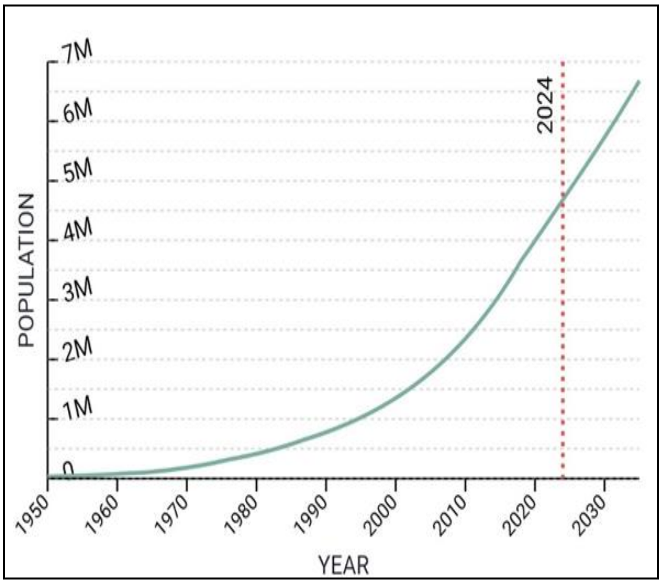

Fig 1 Yaounde population 2024
(Source: World Population Review)

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- *Daily Waste Generation:*
  - ✓ Lower estimate: 4.6 million people * 0.5 kg/person/day = 2,300,000 kg/day or 2,300 tons/day
  - ✓ Upper estimate: 4.6 million people * 0.7 kg/person/day = 3,220,000 kg/day or 3,220 tons/day

- *Annual Waste Generation:*
  - ✓ Lower Estimate: 2,300 tons/day * 365 days = 839,500 tons/year
  - ✓ Upper Estimate: 3,220 tons/day * 365 days = 1,175,300 tons/year

➢ *Waste type*

Yaoundé, like many urban areas in developing countries, generates various types of waste. Based on studies and reports, the primary types of waste in Yaoundé are:

- *Organic Waste:*

Includes food scraps, yard waste, and other biodegradable materials. Organic waste often constitutes a significant portion of MSW in Yaoundé, typically around 50-60 %.

- *Plastics:*

Includes various types of plastic packaging, bottles, bags, and containers. Plastics typically make up about 10-15 % of the waste stream.

- *Paper and Cardboard:*

Includes newspapers, office paper, cardboard boxes, and packaging materials. Paper and cardboard waste usually account for around 10-15 % of the total waste.

- *Metals:*

Includes aluminum cans, metal containers, and other scrap metals. Metals generally comprise about 2-5 % of the waste stream.

- *Glass:*

Includes bottles, jars, and other glass products. Glass waste typically makes up about 2-5 % of the total waste.

- *Other Waste:*

Includes textiles, rubber, wood, electronic waste, and miscellaneous items. This category can account for 5-10 % of the waste stream.

- *Waste Collection and Disposal*

From an interview held with the technical director of HYSACAM, not all of the waste generated daily in Yaoundé is collected by the city's waste management system. A significant portion of the waste remains uncollected, contributing to environmental pollution in various parts of the city.

The waste that is collected is transported to the Nkolfoulou landfill, where it undergoes decomposition, producing large amounts of biogas. This biogas is released into the environment through incineration, a practice that poses serious risks to the environment due to the release of harmful gases and pollutants into the atmosphere.

The current waste management practices highlight the urgent need for improved solutions that minimize the environmental impact of waste disposal.

- *Waste Suitability*

To determine the suitability of the waste for incineration in a WtE plant, we need to consider the calorific value, moisture content, and composition of the waste.

- *Calorific Value:*

The calorific value (CV) of waste is a measure of the energy content. Higher CV indicates better suitability for incineration.

- ✓ Organic Waste: Generally has a lower CV due to high moisture content but can be improved with proper pre-treatment.
- ✓ Plastics: Have a high CV and are excellent for incineration.
- ✓ Paper and Cardboard: Have a moderate CV and are suitable for incineration.
- ✓ Metals and Glass: Do not contribute to the calorific value but can be separated and recycled.

- *Moisture Content:*

High moisture content in waste reduces the efficiency of incineration.

- ✓ Organic Waste: Typically has high moisture content, which can be reduced through drying or mixing with drier waste types.
- ✓ Plastics, Paper, and Cardboard: Usually have lower moisture content and are suitable for incineration.

- *Composition:*

The presence of non-combustible materials like metals and glass can affect the incineration process. These should be separated before incineration.

The waste generated in Yaoundé, primarily organic waste, plastics, and paper/cardboard, is generally suitable for a WtE plant. However, the high moisture content of organic waste necessitates pre-treatment to improve its suitability for incineration. The inclusion of plastics and paper/cardboard enhances the overall calorific value of the waste stream, making it more efficient for energy recovery.

➢ *Energy Potential*

Based on the waste composition and quantities, it is possible to estimate the energy that could be generated from Yaoundé’s MSW. According to Best Available Techniques (BAT) of waste incineration [3], 1 ton of waste is capable of yielding approximately 0.5 MWh. Therefore, using the estimated waste quantities obtained above, we have:

- Lower Estimate:839,500 tons/year* 0.5 MWh = 419,750 MWh/year

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- Upper Estimate: 1,175,300 tons/year * 0.5 MWh = 587,650 MWh/year

The total energy potential from Yaoundé's MSW could therefore make a significant contribution to the city's energy mix, reducing dependence on non-renewable energy sources and enhancing energy security. This energy could be fed into the local grid or used to power the waste treatment facilities themselves, creating a sustainable loop of waste-to-energy conversion.

III. SITE ANALYSIS

➢ *Location and Context*

- *Geographic Location:*

The selected site for the Waste-to-Energy (WtE) plant is located in Nomayos, near the Cimencam cement plant, on the outskirts of Yaoundé Figure 2, Cameroon. This site is situated approximately 12 kilometers from the city center, providing a strategic location that is both accessible and sufficiently removed from densely populated areas.

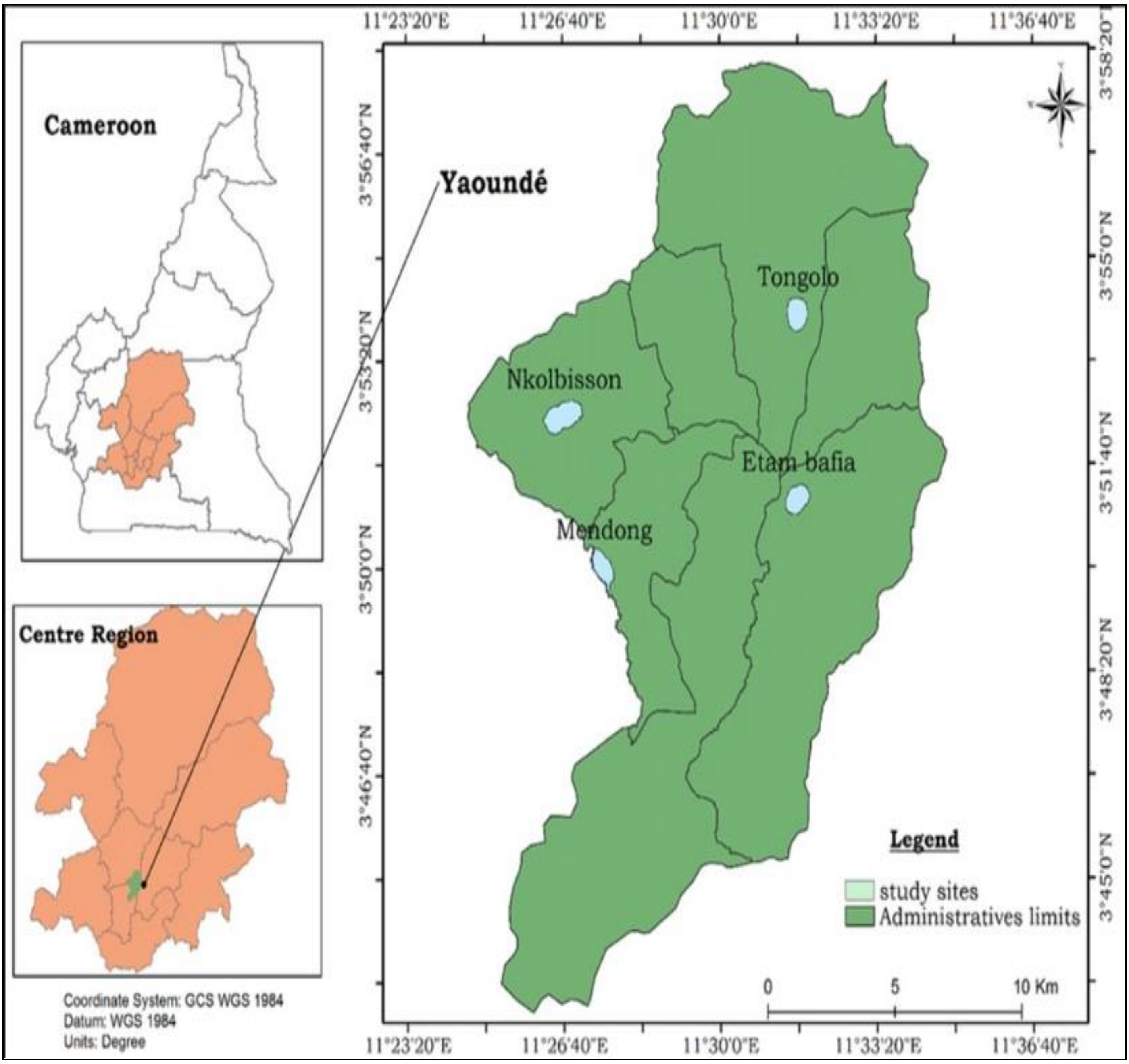

Fig 2 Geographical Location of Yaounde

- *Surrounding Environment:*

The area is predominantly industrial, with the Cimencam cement plant being the most prominent feature in the area. The site is also bordered by undeveloped land, characterized by low-density vegetation and minimal residential presence as seen in Figure 3. The surrounding area includes a mix of industrial and rural land uses, with nearby small-scale agricultural activities.

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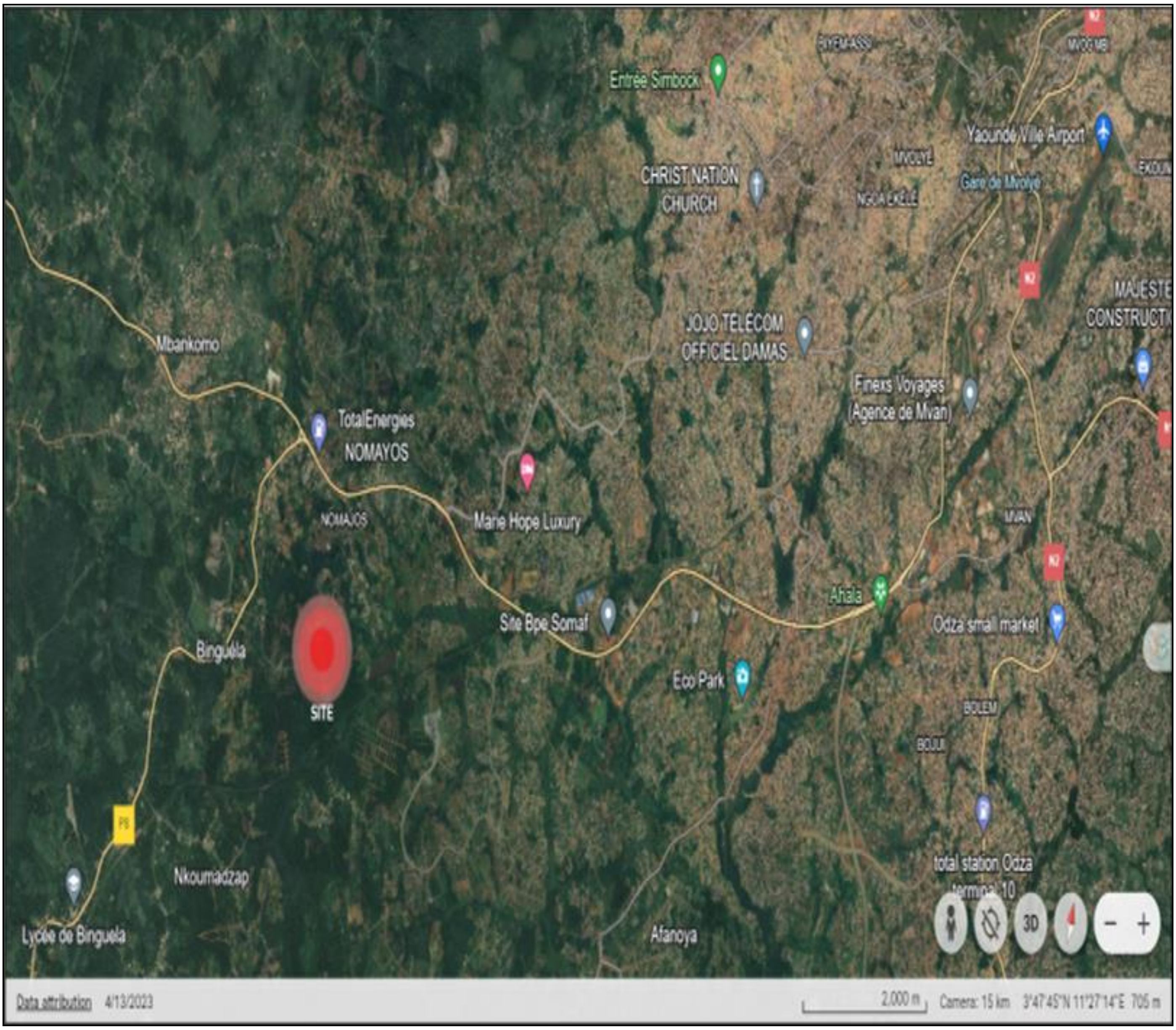

Fig 3 Site Location

➤ *Cultural and Historical Analysis*

- *Cultural Context:*

Nomayos and its surrounding areas are inhabited by diverse communities with rich cultural heritage. Traditional practices, local crafts, and communal living are integral aspects of life in this region. The development of the WtE plant will need to respect and integrate cultural sensitivities, potentially incorporating local architectural styles or motifs into the design.

- *Historical Significance:*

Historically, the area around Nomayos has been predominantly rural, with gradual industrialization influenced by the presence of the Cimencam cement plant. The WtE plant represents a continuation of this industrial development, contributing to the area's economic growth while also addressing modern waste management challenges.

➤ *Climate Analysis*

Yaoundé has an equatorial climate. Its geographical location gives it a particular climate known as the "transition type", characterized by four seasons of unequal duration, mainly: A long dry season from December to February; A short rainy season from March to June; A short dry season from July to August; A long rainy season from September to November.

Maximum and minimum temperatures in Figure 4, are respectively 33 ºC in February and 16 ºC in July, August and November. The average annual temperature varies between 20 and 25 ºC. Rainfall in Yaoundé is irregular and abundant, averaging 1,700 mm/year. Over the past ten years, rainfall has continued to fluctuate, alternating between deficit and surplus years due to climate change.

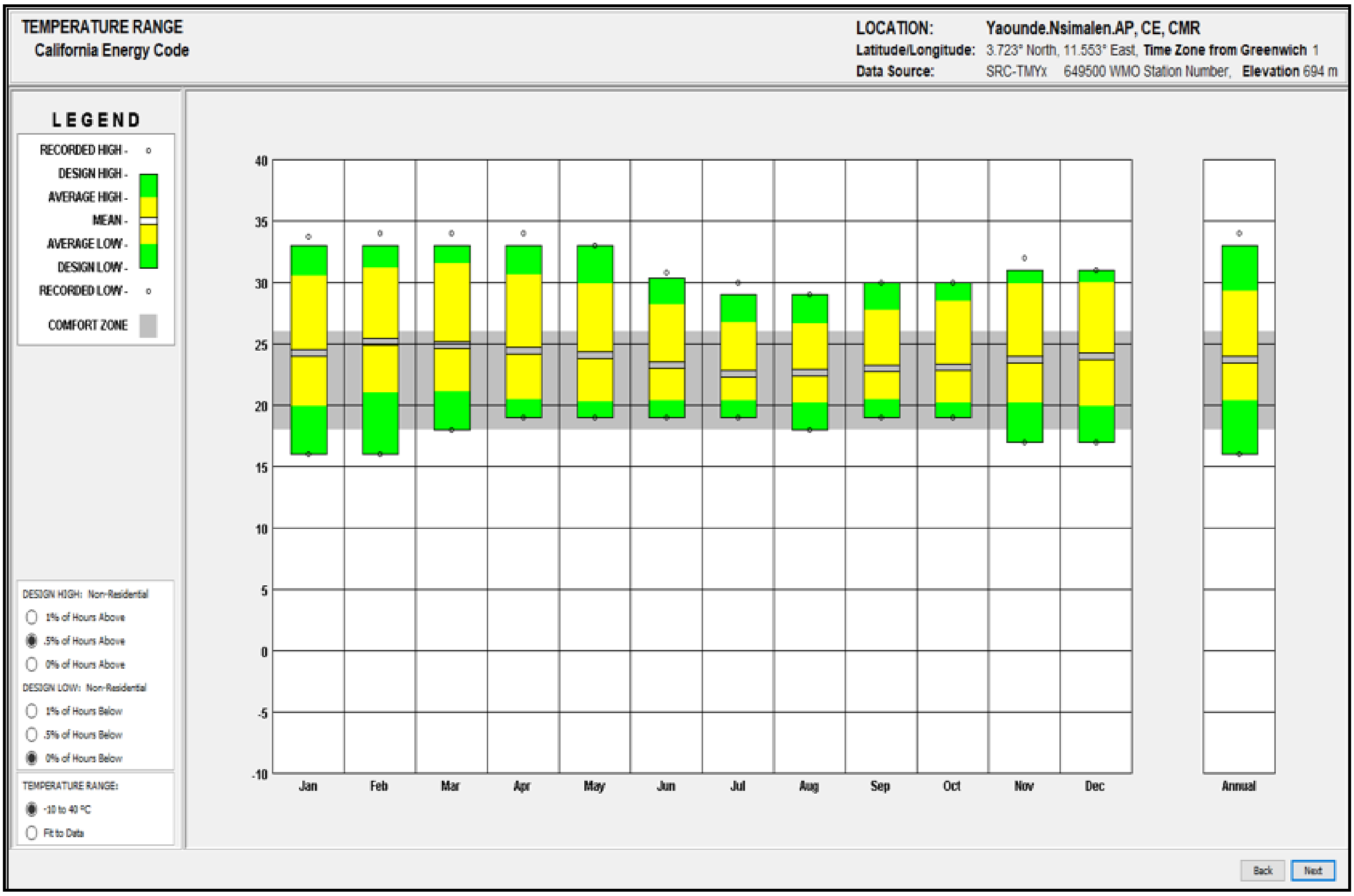

Fig 4 Maximum and Minimum Temperatures in Yaounde

Average humidity is 80 %, varying between 35 % and 98 % during the day. Winds are frequently humid and blow from the southwest. Strong winds in Figure 5 are from the southwest. Solar radiation is around 360 to 400 w/m2/h.

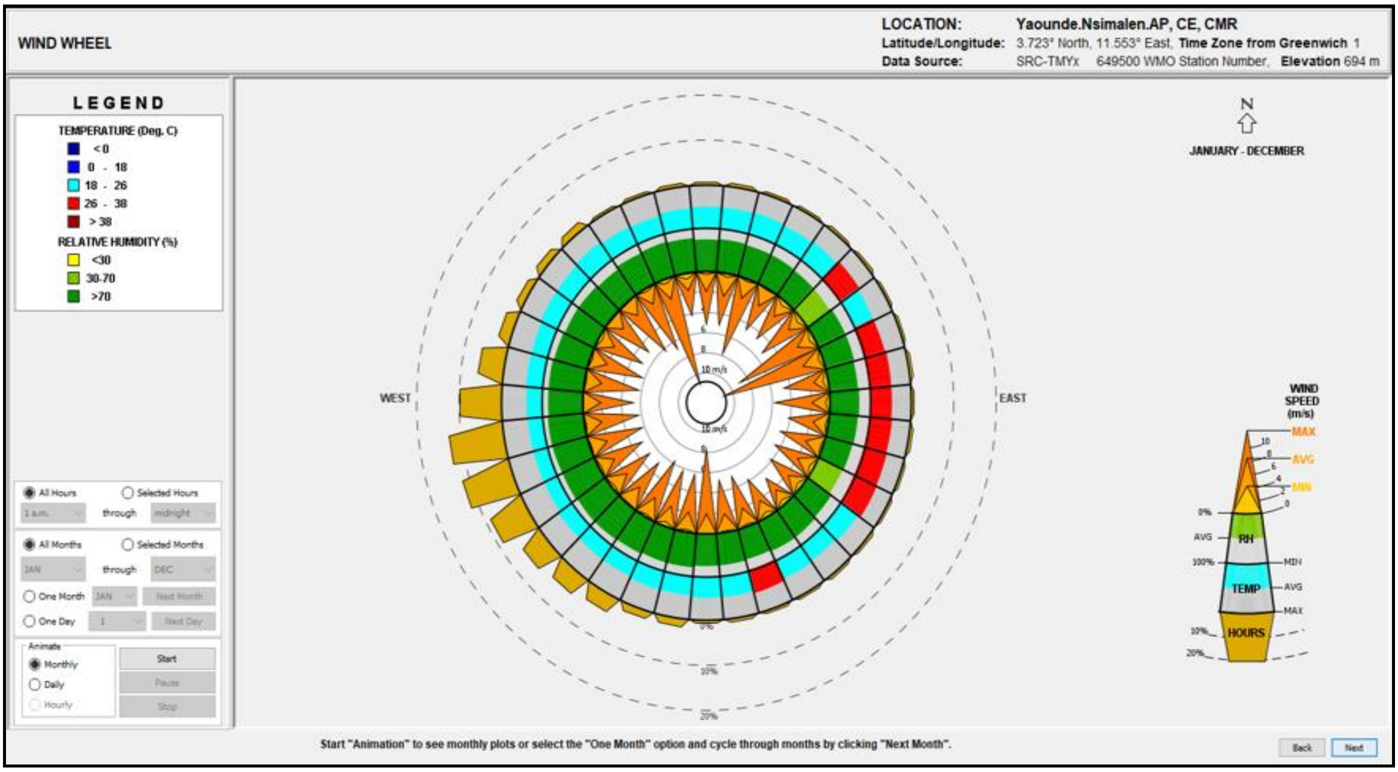

Fig 5 Wind Direction in Yaoundé

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➢ *Topography and Land Characteristics*

* *Topography:*

The site features gently undulating terrain. The natural slopes are mild, making the site suitable for large-scale industrial development with minimal need for extensive grading or land alteration.

* *Land Area:*

The total surface area of the site in Figure 6, is approximately 24 hectares, providing ample space for the development of the WtE plant, associated facilities, and potential future expansions. The site's size allows for the inclusion of green spaces, public areas, and buffer zones to minimize any potential impact on the surrounding environment.

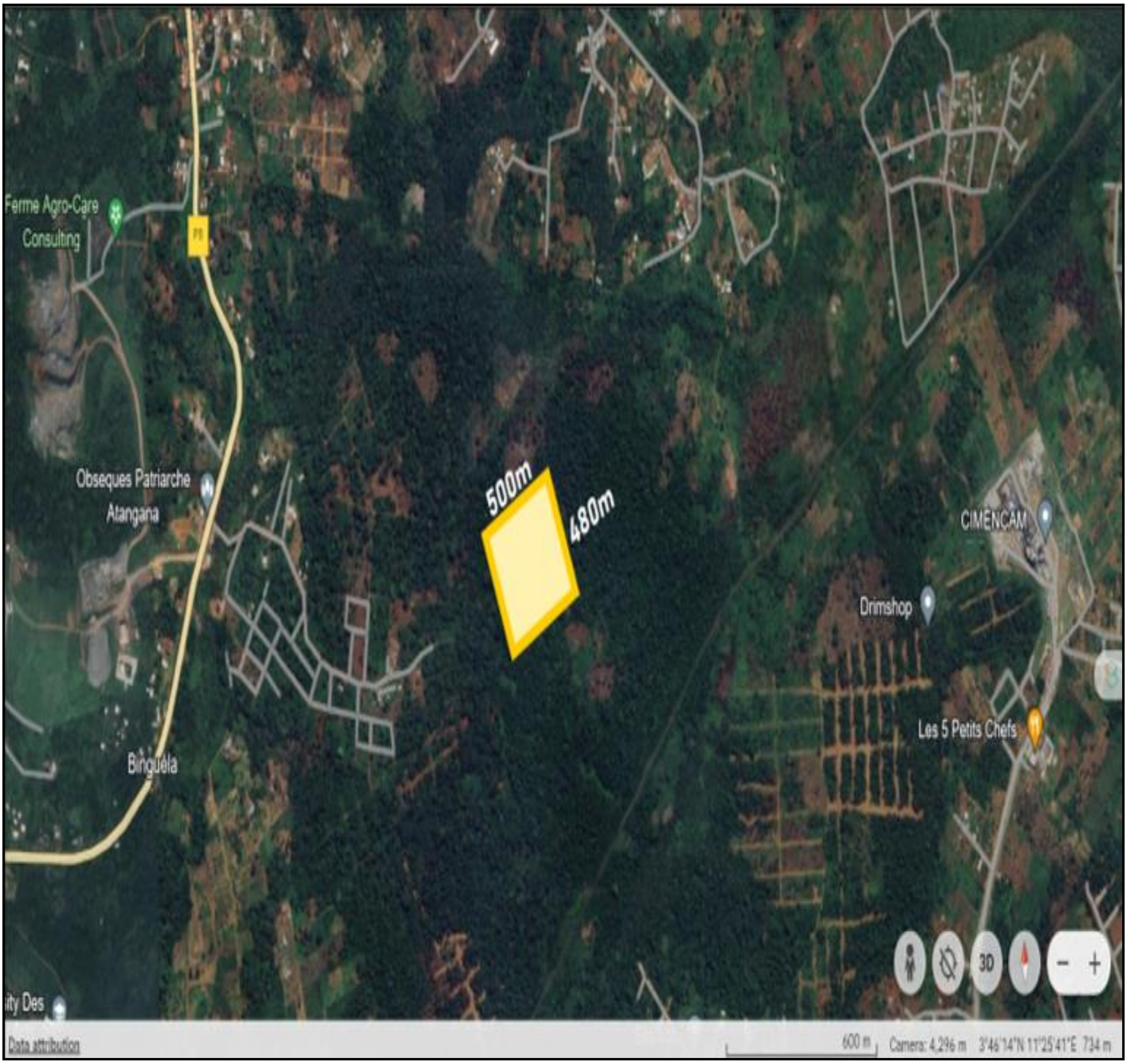

Fig 6 Site Dimensions

➢ *Infrastructure and Accessibility*

* *Road Access:*

The site is accessible via a major road (National Road 3) and a secondary road as seen in Figure 7, which connect Nomayos to the main urban areas of Yaoundé. The road network in the area is well-developed, facilitating the transportation of waste to the plant.

* *Utilities:*

Basic utilities such as water, electricity, and telecommunications are available at or near the site, with infrastructure development being relatively straightforward. The proximity to the Cimencam plant also means that there is existing industrial infrastructure that can be leveraged.

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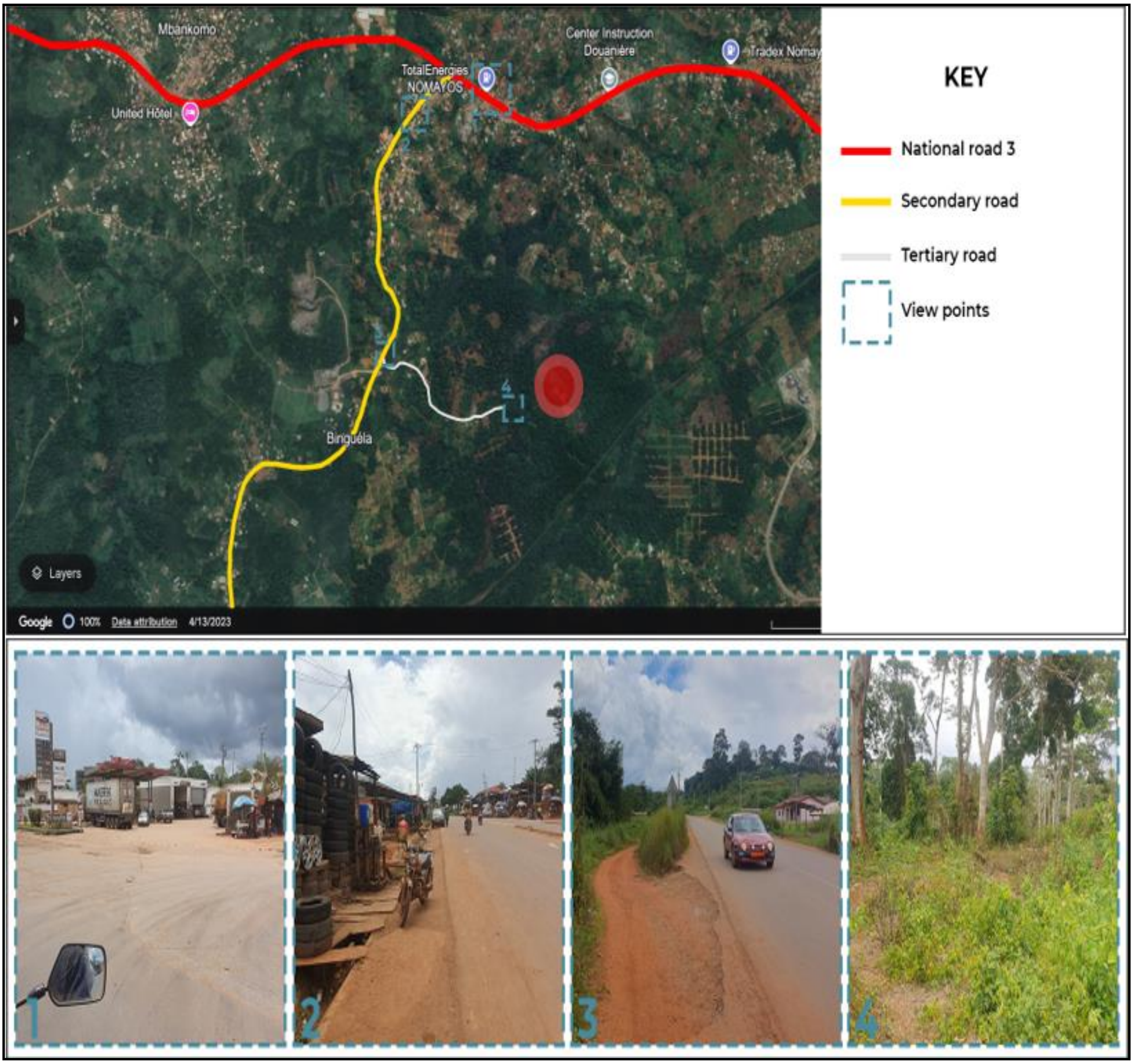

Fig 7 Site Infrastructure and Accessibility

➢ *Zoning and Regulatory Compliance*

The site is located in an area zoned for industrial use, which is suitable for the development of a WtE plant. Local zoning regulations support the establishment of facilities that contribute to energy production and waste management, aligning with the strategic goals of the city of Yaoundé.

IV. PROJECT DESIGN

➢ *Architectural Program*

Insights from WtE plants in Copenhill, Shenzhen, and Roskilde informed the spatial organization of our plant, ensuring efficient integration of industrial functions with public spaces [4][5][6]. The plant is divided into zones for waste processing, energy recovery, and public engagement, ensuring industrial operations are efficient and public areas are safe and accessible.

➢ *Below are Key Components of Our WtE Facility:*

- *Incineration Facility:*

Here we have to determine the capacity in terms of number of incinerations lines, needed by the plant. It is done by using the formula below; Number of incineration lines = (Total waste generated per day)/(Waste handled per line per day).

Based on the available data from Yaounde, let's assume the city generates approximately 2,300 tons of waste daily. Incineration lines vary in capacity, but a common range is

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between 120 to 720 tons per day. Let's assume that each incineration line can handle about 550 tons of waste per day.

- ✓ Therefore: Number of incineration lines = (2300 tons)/ (550 tons/line) ≈4.18 lines

Based on this calculation, our plant should include 4 incineration lines. And each of these lines is composed of a; tipping hall, waste bunker, combustion chamber and a boiler room.

- *Energy Recovery Section:*
- ✓ Steam Turbine Room: A space for the steam turbines that convert steam into electricity.
- ✓ Generator Room: Area for the generators that produce electricity from the turbines.
- ✓ Heat Exchange Area: To capture and utilize residual heat for district heating or other purposes.

- *Air Pollution Control Area:*
- ✓ Flue Gas Treatment: Includes filters and scrubbers to reduce emissions.
- ✓ Stack: A double, well-designed stack that combines emissions from the four incineration lines.

- *Wastewater Treatment Facility:*
- ✓ Manages and treats wastewater generated during the incineration process.

- *Administrative and Operations Buildings:*
- ✓ Control Room: Centralized control of plant operations.
- ✓ Offices: Spaces for administrative staff.
- ✓ Maintenance Workshop: Area for maintenance equipment and activities.
- ✓ Staff Facilities: Includes locker rooms, rest areas, and meeting rooms.

- *Public Engagement Areas:*
- ✓ Visitor Center: A facility for educating the public about waste management and energy recovery processes. Includes exhibition spaces, meeting rooms, and an auditorium.

- ✓ Recreational Areas: Includes a climbing wall located on the exterior facade of the plant; an accessible green roof with paths for jogging and walking; a visitor's pathway designed to guide visitor safely through the plant for educational tours.

Table 1. Illustrates the overall surfaces of the key components of our WtE facility and Figure 3.x is a functional diagram illustrating the relation between different parts of the project.

Table 1 Surface Program of Our Wte Facility

Level	Zone	Area (m^2)
Ground Floor	Incineration facility	35136.18
	Energy recovery section	1000
	Condenser room and water treatment	2350.6
	Pre-treatment center	4733
	Technical room	4763.92
	Offices	4733
	Restrooms	558.64
First floor	Tipping hall	4751.24
	Restaurant	4733
	Restrooms	558.64
Second floor	Visitors center	4733
	Technical room 1	4733
	Technical room 2	2350.6
	Restrooms	558.64
Roof	Roof	61407.7
Total Area		**137101.16 m^2**

➢ *Functional Diagram*

A functional diagram is an essential tool for visualizing and understanding the organization and interactions of various components within a system or project. It provides a clear and structured representation of information flows, relationships between functions, and key processes. To optimize space, improve circulation, clarify objective needs, and ensure coherence and cohesion between different functions, we have proposed the functional diagram illustrated in Figure 8.

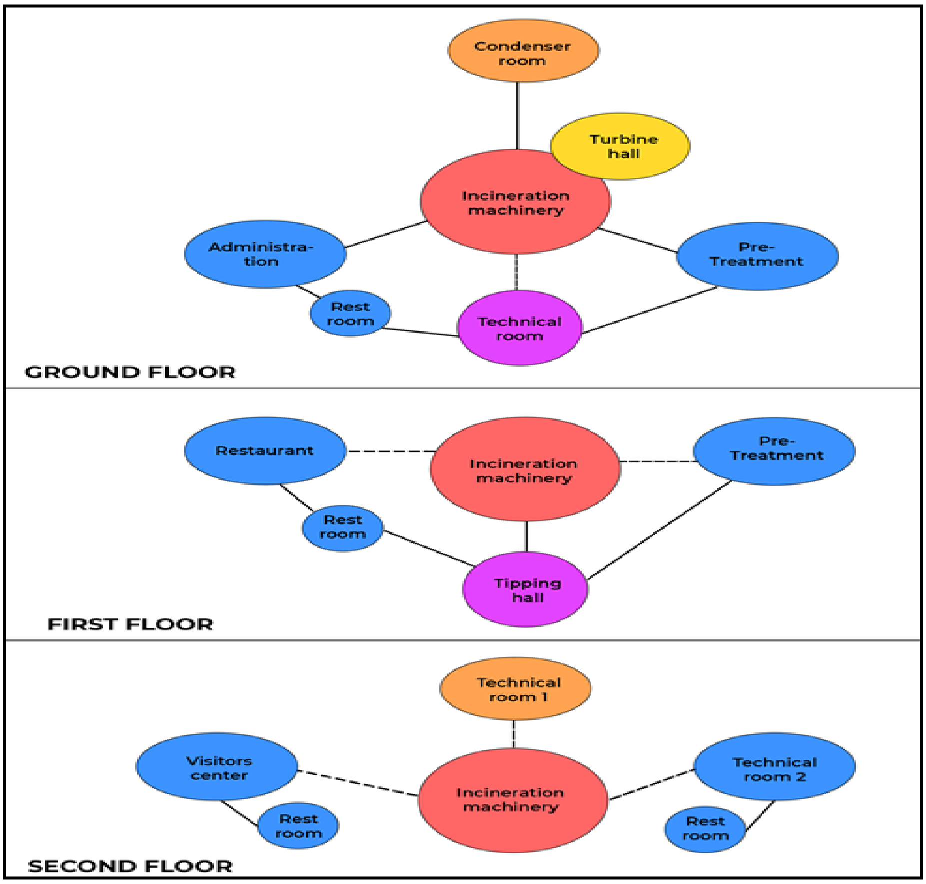

Fig 8 Functional Diagram

➢ *Architectural Concept*

In the pursuit of sustainable solutions for waste management, the design of a WtE plant offers an opportunity to merge advanced technology with architectural excellence. The design concept emphasizes compactness and efficiency, addressing land use constraints while maintaining a balance between industrial functionality and aesthetic appeal.

Our project aims to embody the principle of equilibrium, linking the waste generated to the energy produced, thereby maintaining a delicate balance. This equilibrium is metaphorically represented through the use of a triangle, which is one of the most balanced structures in nature, serving as the form of the building, with curved angles. This design choice not only symbolizes stability and balance but also introduces a modern and harmonious aesthetic to the facility. Figure 9, Figure 10, Figure 11, Figure 12 and Figure 13 illustrate our design concept:

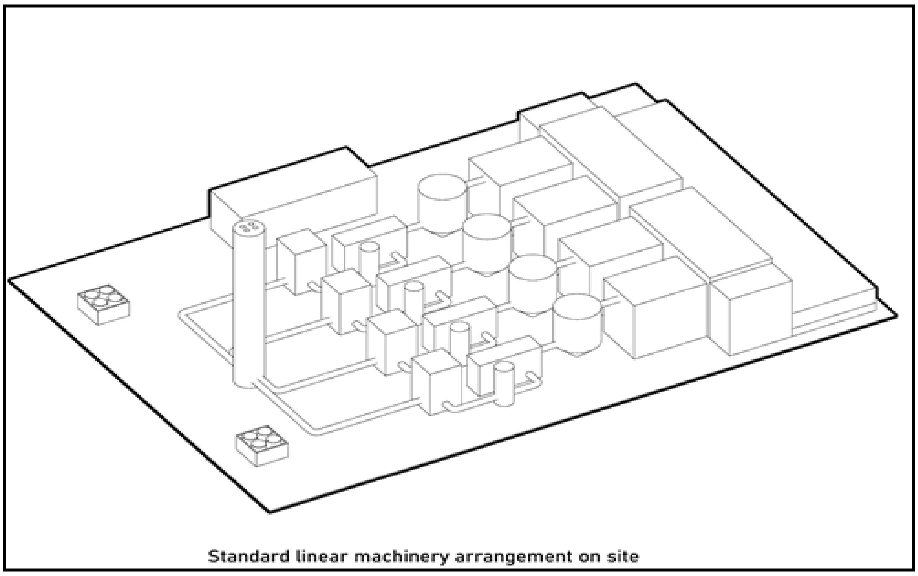

Fig 9 Concept Diagram 1

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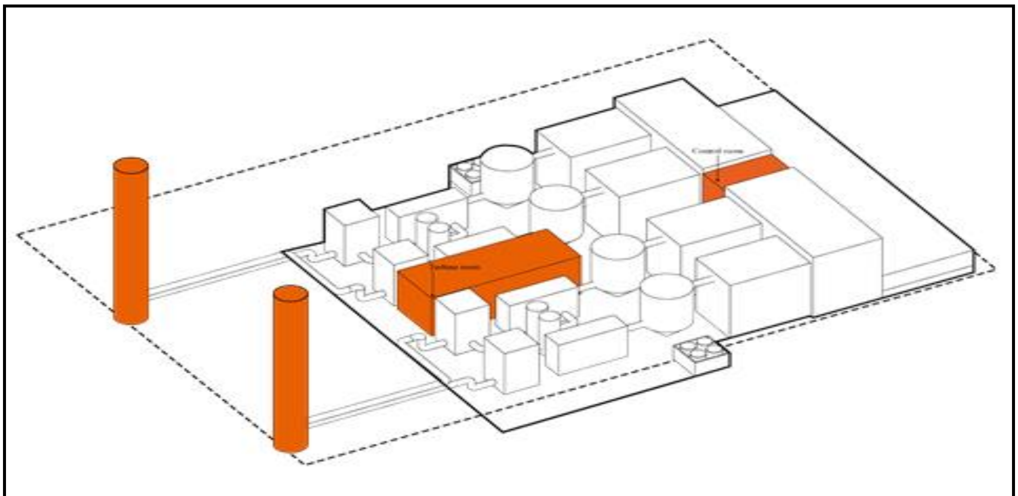

Fig 10 Concept Diagram 2

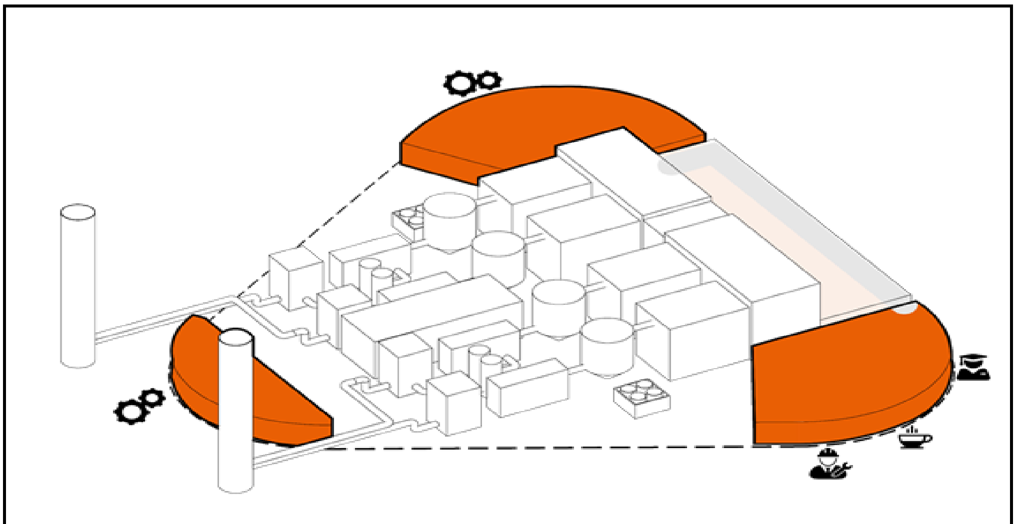

Fig 11 Concept Diagram 3

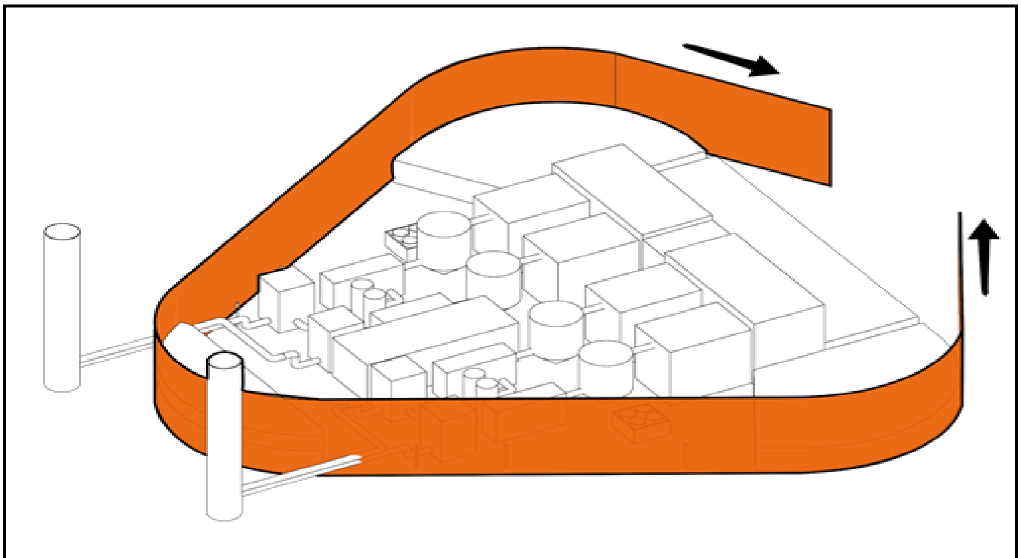

Fig 12 Concept Diagram 4

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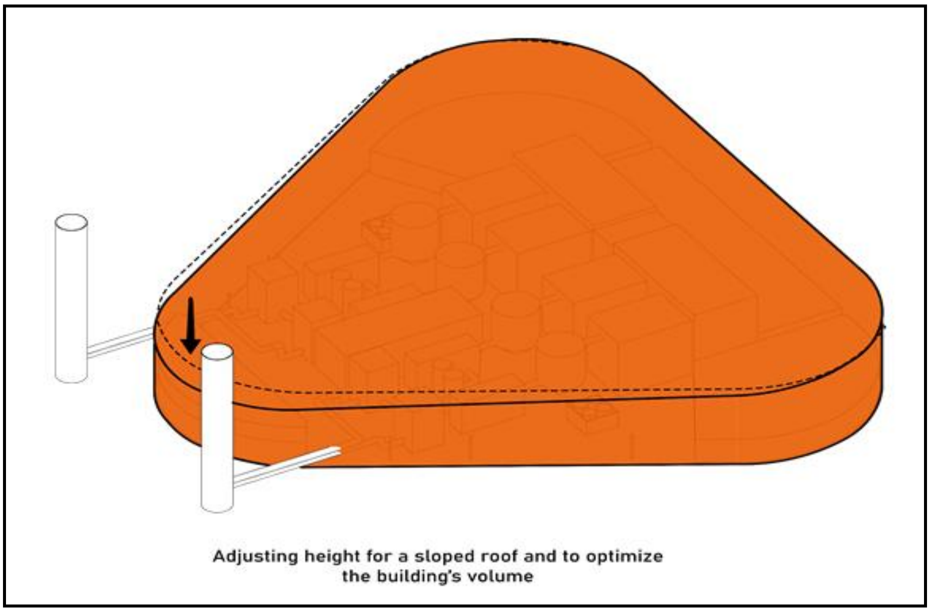

Fig 13 Concept Diagram 5

The building's triangular form not only provides a visually striking design but also optimizes spatial organization, aligning with the concept of equilibrium that balances functionality with aesthetic appeal.

V. DESIGN STRATEGY

In our WtE plant project, each of these design approaches contributes to the sustainability, functionality, and aesthetic appeal of the facility. Below is an explanation of each design approach and how we implemented them:

➢ *Model Orientation*

In our project, the building was oriented along the North-South axis as seen in Figure 14, to maximize exposure to natural light while minimizing direct sunlight during peak hours, reducing the need for artificial cooling. The orientation also takes into account wind patterns from South-West, to enhance natural ventilation, improving the plant's energy efficiency.

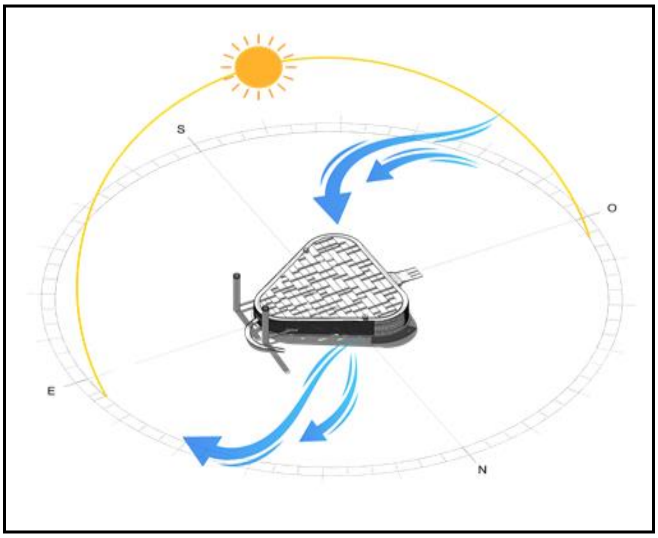

Fig 14 Building Orientation

➢ *Natural Lighting*

Skylights integrated into the roof design as seen in Figure 15, allows for ample daylight to penetrate the interior spaces. The facade's transparency further enhances natural lighting, creating a bright, open environment within the plant.

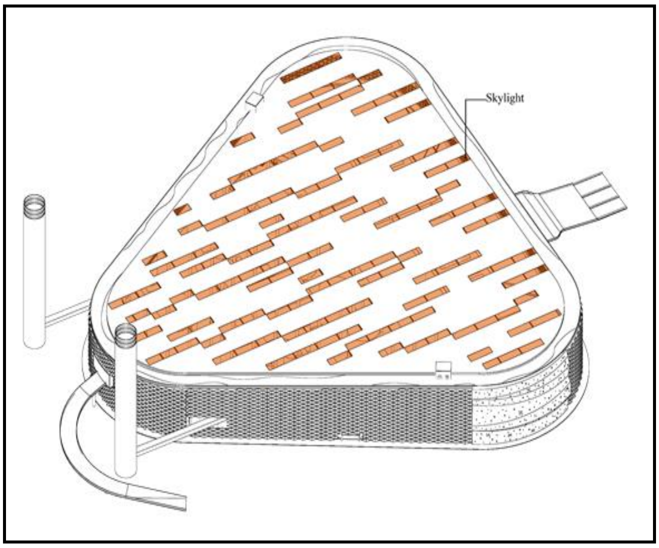

Fig 15 Natural Lighting System

➢ *Natural Ventilation*

The facade design allows for natural airflow to enter the building as seen in Figure 16, reducing the reliance on mechanical ventilation systems. The triangular panels on the facade are designed to promote cross-ventilation, ensuring a steady flow of fresh air throughout the facility.

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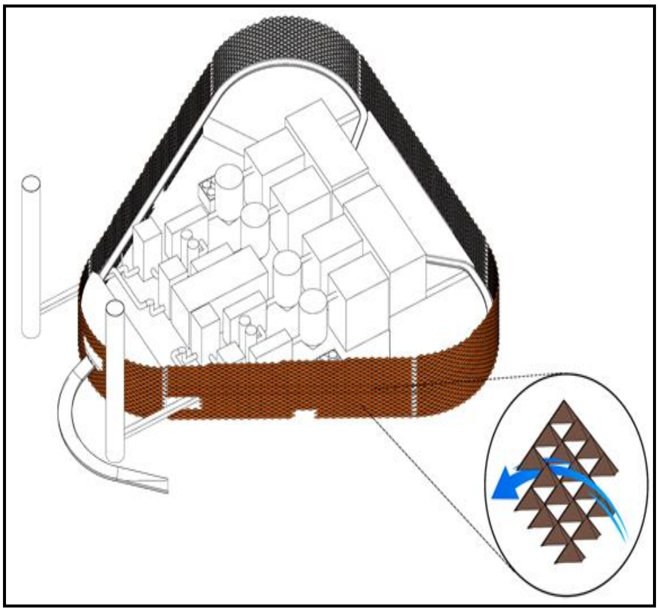

Fig 16 Living Module 9m²

➢ *Renewable Energy*

Incorporated solar panels on the roof of the building as seen in Figure 17, generates renewable energy to partially power the plant's operations. This system complements the energy produced from waste incineration, making the plant more energy-independent.

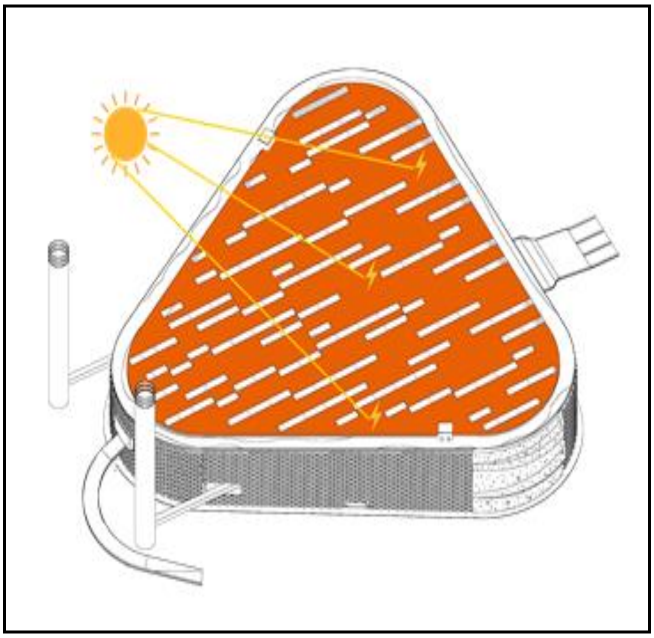

Fig 17 Solar Panels System

➢ *Rainwater Management*

The main roof features a system of water collection integrated into the design as seen in Figure 18. The collected rainwater is stored for various uses within the plant, such as for landscaping or non-potable processes, reducing the demand for municipal water supplies.

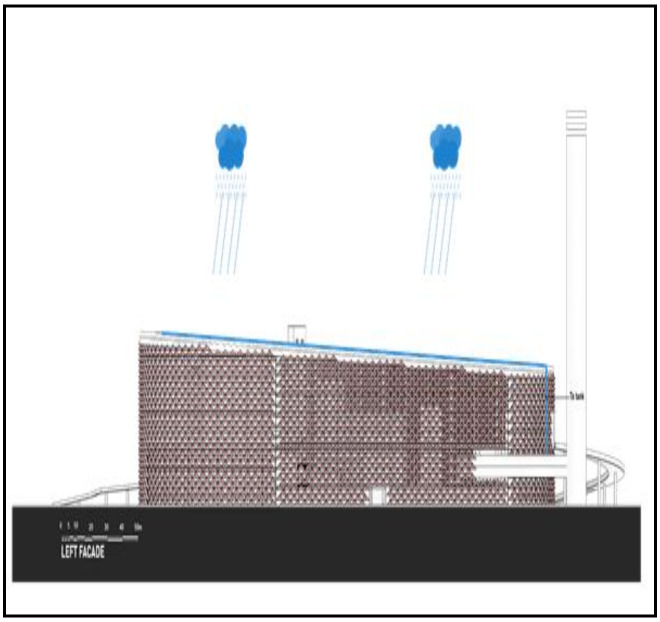

Fig 18 Rainwater management

➢ *Noise and Smell Pollution Management*

For noise proofing, we used acoustic insulation in the turbine hall to minimize noise pollution. To control odors, especially in the waste bunker, the building incorporates smell-proof facades and advanced ventilation systems with air filtration to contain and filter out foul odors before air is expelled from the facility. It is illustrated in Figure 19.

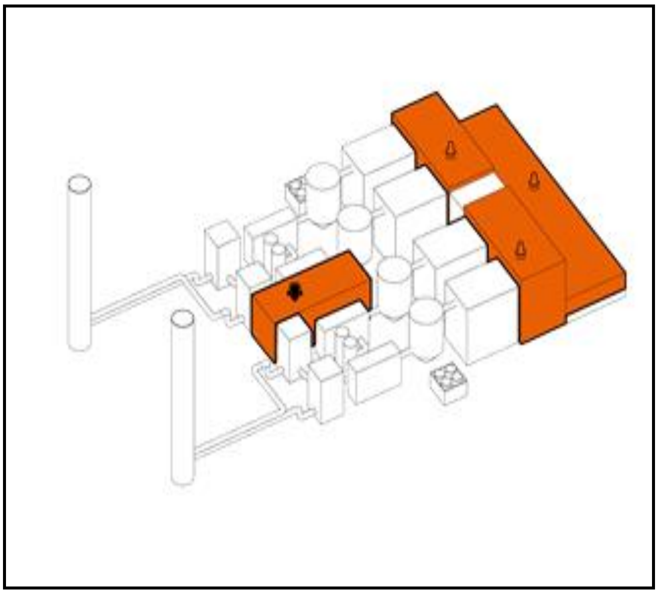

Fig 19 Noise and Smell Proofing

➢ *Construction Materials*

We selected recycled plastics for the facade panels, steel for the building's main structure, and reinforced concrete for supporting factories. These materials as seen in Figure 18, were chosen for their durability, recyclability, and their ability to contribute to the transparency and openness of the building.

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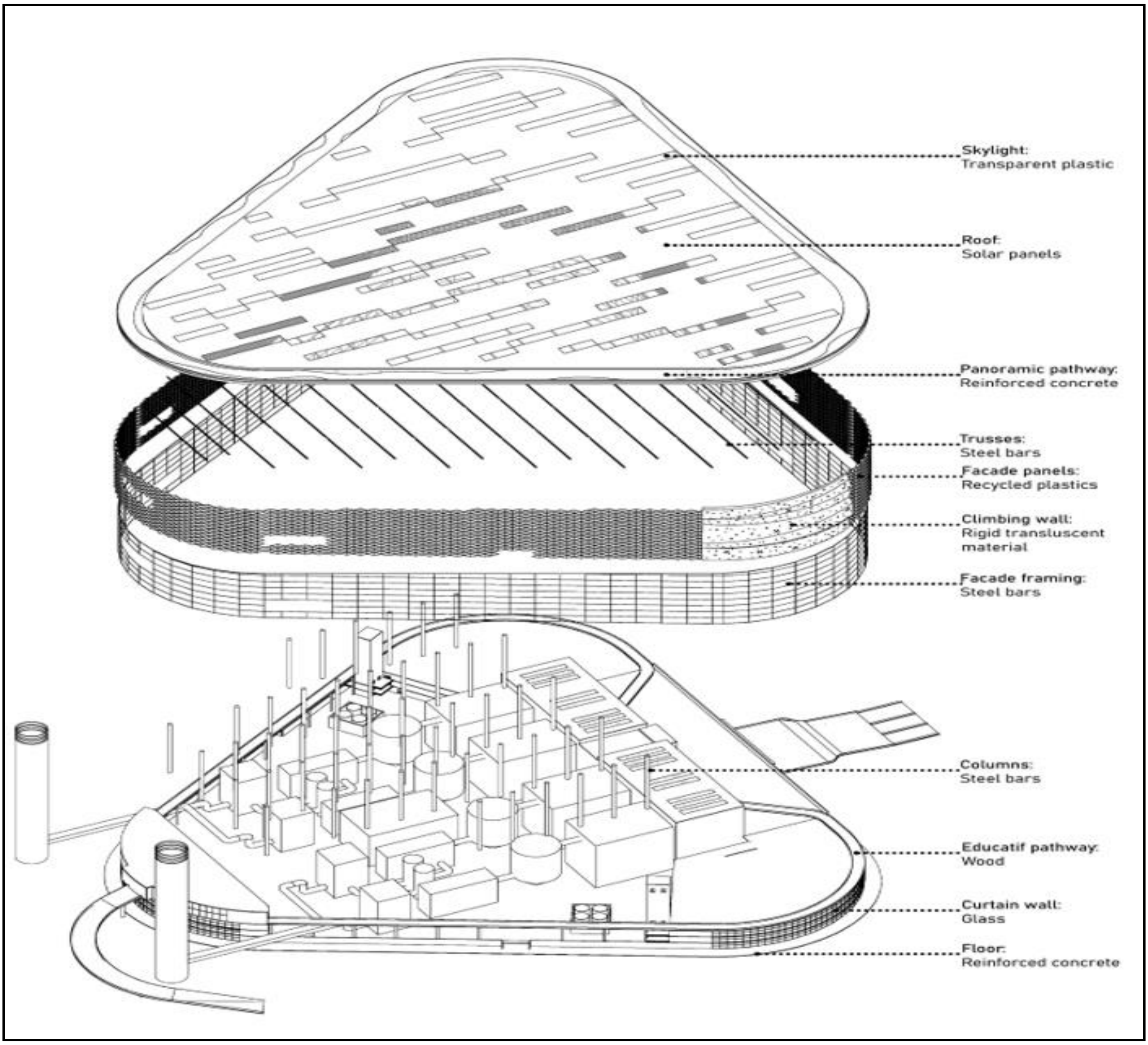

Fig 18 Exploded Axonometry

➢ *Public Engagement*

Public engagement enhances the plant's integration into the community, making it more than just a functional industrial building. The plant includes a visitors' pathway for educational purposes as seen in Figure 19, allowing the public to learn about the waste-to-energy process. The recreational features, such as the climbing wall and accessible roof, engage the public, making the plant an integral part of the community.

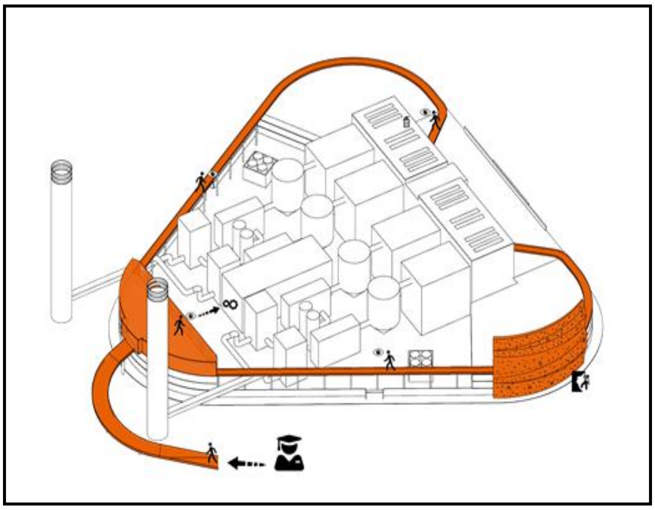

Fig 19 Public Engagement Implementation

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➢ *Landscaping*

We designed the landscape with alternating strips of green areas as seen in Figure 20, water bodies, parking spaces, and walkways. This not only improves the plant's visual appeal but also creates a harmonious interaction between the facility and its natural surroundings. The green spaces help in carbon sequestration and provide a buffer between the industrial plant and nearby areas.

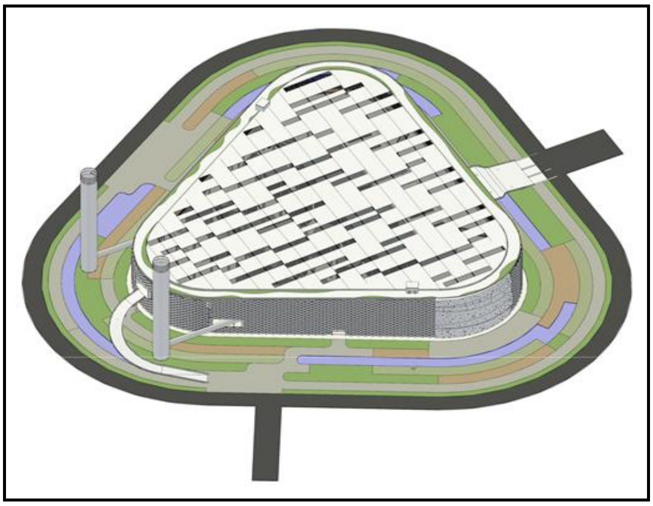

Fig 20 Landscape Layout

VI. PROJECT IMPACT ASSESSMENT

The impact assessment for the proposed Waste-to-Energy (WtE) plant in Yaoundé evaluates its socio-economic and environmental implications on the local community and surrounding environment. This analysis guides decision-making to maximize benefits while minimizing negative effects.

➢ *Socio Economic Impacts*

- Employment Opportunities: The plant will create direct jobs in operations and indirect jobs in related sectors such as construction and local services, contributing to economic growth and reducing unemployment.
- Economic Growth: The project will boost the local economy by stimulating infrastructure development and increasing business activities.
- Community Benefits: The WtE plant will offer educational programs on waste management and renewable energy, as well as recreational facilities (e.g., climbing walls, panoramic paths), enhancing public awareness and well-being.
- Accessibility and Social Equity: The design includes accessible public spaces to ensure that the plant’s benefits are shared across all social groups, promoting social inclusion.

➢ *Environmental Impacts*

- Air Quality: Advanced flue gas cleaning technologies will minimize harmful emissions, ensuring compliance with air quality standards and protecting public health.
- Noise Pollution: Acoustic measures such as noise barriers will be implemented to reduce noise pollution, minimizing disturbances to nearby communities.
- Water Management: Green infrastructure, such as vegetated swales, will manage stormwater runoff and prevent water contamination, protecting local water resources.
- Ecological Preservation: The plant’s design will preserve natural habitats, supporting biodiversity and minimizing ecosystem disruption.
- Waste Management: The plant will significantly reduce the city’s reliance on landfills by diverting waste for energy conversion, contributing to sustainable waste management practices.

VII. PHOTOREALISTIC IMAGES

High-quality visualizations of the plant, showcasing day views were produced with the help of D5 render software.

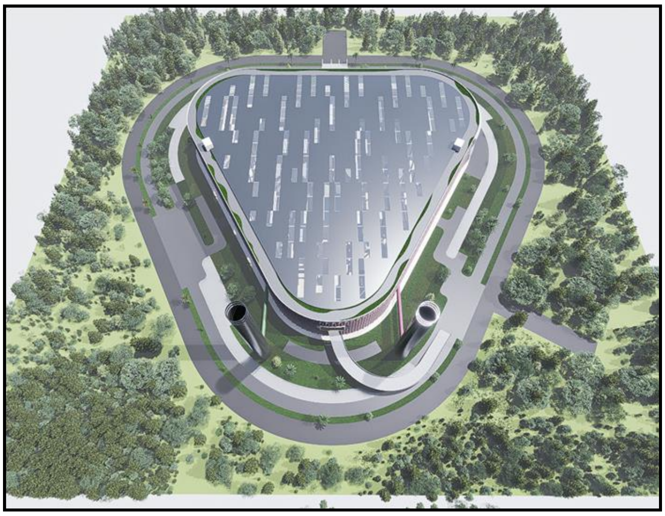

Fig 21 Exterior 1

Fig 22 Exterior 2

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Fig 23 Interior

VIII. CONCLUSION

The implementation of a Waste-to-Energy plant in Yaoundé represents a significant step toward addressing the city's waste management and energy challenges. By combining waste reduction and energy production in one facility, the plant offers a sustainable and efficient solution. The integration of architectural design principles enhances the plant’s functionality and transforms it into an asset for the urban environment, promoting public engagement and sustainable urban development.

Future projects should continue to explore the potential of WtE technology, with an emphasis on creating facilities that are not only functional but also contribute to the well-being of the surrounding community. In the long term, incorporating more renewable energy sources and expanding public engagement will be key to ensuring the sustainability and success of such projects.

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