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Bio-Thermal Hybrid Storage (BTHS): Transforming Waste into Watts

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***Abstract* - The increased demand for sustainable energy has driven the development of more flexible mid-term energy storage solutions. The Bio-Thermal Hybrid Storage System (BTHS), which integrates Thermal Energy Storage (TES), waste incineration, and biogas generation, aims to enhance energy access in remote regions while solving the problem of waste management. Non-recyclable inorganic waste is combusted to generate additional heat, which is then stored in TES for later use. Organic waste is also converted into biogas, which can subsequently be used to generate electricity. This strategy helps to strengthen the energy economy by increasing the capture of usable energy while reducing dependence on landfills for waste disposal.**

Keywords: Bio-Thermal Hybrid Storage, Sustainable Energy, Waste-to-Power, Thermal Energy Storage, Decentralized Electrification, Energy Security.

I. INTRODUCTION

As a consequence of increasing energy consumption alongside the demand for decentralized and sustainable solutions, the requirement for reliable mid-term energy storage systems has sharply increased. Providing reliable energy is extremely challenging in rural areas due to their dependence on centrally located systems that tend to be inefficient and costly to expand. Traditional energy storage technologies, such as batteries and pumped hydro storage, are either too expensive or geographically limited, and these remote areas do not have the necessary conditions. In addition, poorly managed waste in rural areas contributes to environmental problems by giving rise to pollutes surrounding and carbon emissions. To solve these issues, an optimal approach is needed combining waste management, reliable energy storage, and renewable energy generation.

Combining waste-to-energy conversion, thermal storage, and biogas generation into a single system makes the Bio-Thermal Hybrid Storage System (BTHS) an innovative approach in providing reliable and affordable electricity for rural areas. BTHS creates a biogas using organic waste that powers generators, while also making use of non-recyclable inorganic waste to produce heat, achieving a dual energy flow that is directed into a thermal energy storage (TES) system.

The electricity stored can later be transformed to ensure uninterrupted power flow even in the lacking of urgent waste inputs. It is estimated that the system is capable of producing 35-40 kWh per day, which can be allocated toward household consumption as well as vital public infrastructure, including community centers, small businesses, and street lighting. It is a decentralized power generation architecture, which reduces consumption of transmission power, and lessens reliance on national networks. Furthermore, the technology promotes efficient waste disposal by using waste products generated in the community, thus lowering total energy costs for rural areas.

Several instances of similar usages can be used to showcase the effectiveness of BTHS. For instance, Biomass Power Plant in Punjab, India, utilizes agricultural waste for power generation. In Siltara, Raipur, Chhattisgarh, Godawari Power and Ispat Limited (GPIL) runs a 20 MW biomass power plant. To maximize energy efficiency, Gujarat's Solar Thermal Hybrid Plant incorporates solar energy with thermal storage. The Karcham Wangtoo Hydroelectric Plant in Himachal Pradesh works to maintain a turbine's optimum efficiency by integrating thermal storage with hydropower. These systems are being put in place to decrease dependence on traditional forms of energy production.

To sum up, BTHS provides an economical, ecologically friendly, and sustainable energy solution designed for rural electrification. This will play a crucial role in cutting down the dependency on the national grid to some extent, which in turn affects greatly on the transmission losses across large distances. The integration of thermal storage with bioenergy not only ensures energy security but also mitigates the environmental issues stemming from poor waste management practices. To study BTHS's strategy, its feasibility and

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benefits, this article attempts to BTHS's possibility emerges as a revolutionary shift towards self-sufficient sustainable energy in rural localities.

1.1 Objectives

Objective 1: Cut down on reliance on centralized grids: To improve local energy resilience together with grid independent power sources in order to promote electricity self-sufficiency in rural areas, and at the same time, reduce the cost of transmittal losses.

Objective 2: Create an adequate structure for thorough waste-to-energy: The garbage-to-Energy Plant aims to increase energy efficiency and facilitate the effective disposal of the garbage by combining biogas with the thermal energy produced by burning the waste.

Objective 3: Sustain the economy and environment: Lower the carbon emissions through waste to energy innovations while increasing employment by creating waste containment and maintenance jobs as well as lowering pollution with cleaner energy.

Objective 4: Optimize the usage and storage of energy:In rural regions enhance electricity supply reliability by making improvements on the efficiency of thermal energy storage (TES) to ensure electricity is available during peak hours.

These concepts aim to enhance the reliability and effectiveness of distributed energy production processes by applying various methods and approaches that will mitigate the challenges resulting from inefficiency of waste management systems as well as dependency on energy from the rural areas.

II. LITERATURE SURVEY

The shift towards renewable resources has resulted in the need for system modifications as well as energy storage capabilities. There has been a great deal of effort that has been put in relation to research on the different technologies for storage, their integration to the power system and system improvements with a view to formulating a workable and practicable sustainable energy system.

In the United States, this form of thermal energy storage is referred to as a charging tank and in defrost mode as a cold storage tank. Such storage equipment holds heat or cold for extended periods. Patel et al. (2022) describes this solution as providing short duration storage and aiding in the stabilization of the grid and were studied through flywheel energy storage devices [19]. Blakers et al. (2021) and Alva et al. (2018) have also studied and assessed the performance of pumped hydro storage PHS and thermal energy storage devices respectively.

New technologies which utilize gravity for energy storage are gaining popularity. Tong et al. (2022) [3] discussed Solid gravity energy storage which employs the use of heavy objects for electricity generation during peak hours. Hunt et al. (2020) provided suggestions for Mountain Gravity Energy Storage as a possible solution to the problem of balancing short-term and long-term storage demand, while Deep Ocean Gravity Energy Storage model of seasonal energy storage is claimed to be feasible by Hunts et al. (2020). [22], [23]. The employment of Gravity batteries was first suggested by AlZohbi (2023). demonstrating its potential to improve grid stability [21].

Technologies for battery storage are essential to India's switch to renewable energy. To eradicate coal-based power, Mohan et al. (2022) underlined that long-term cost reductions in solar PV and battery storage are required [4]. Battery storage was examined by Barbar et al. (2022) as a non-wire option for enhancing distribution networks [5], and their later study (2023) concentrated on its function in decarbonizing India's electrical sector in the face of growing demand [14]. Furthermore, in spite of resource and environmental problems, large-scale lithium-ion batteries, as reviewed by Arteaga et al. (2017), offer efficiency and scalability [24].

Smart grids are essential to contemporary electricity systems. In order to improve dependability and integrate renewable energy sources, TalharBelge et al. (2024) investigated India's adoption of smart grids [6]. While Jain et al. (2014) offered insights into India's particular smart grid programs [13], Aguero et al. (2017) talked about the wider prospects and problems in grid modernization [20]. In order to increase grid efficiency, Jha et al. (2022) examined hybrid power systems that combine solar and wind energy [12]. In order to promote greener networks, Jha et al. (2020) also suggested emission-aware energy storage scheduling [8].

The use of hybrid energy storage devices is growing in popularity. Sahoo and Timmann (2023) looked at how these technologies improve resilience and flexibility in contemporary power grids [16]. Converter topologies and control schemes for hybrid systems were examined by Babu et al. (2020) [17]. Emerging storage methods in grid modernization were further examined by Dhundhara et al. (2023) [18]. An overview of energy storage laws and policies influencing grid modernization was given by Sinha et al. (2023), with a focus on India's legislative environment [10].

Combining nuclear power and thermal energy storage is another grid stability tactic. This strategy was examined

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thoroughly by Faizan et al. (2024), who pointed out its possible advantages [25]. The significance of hybrid systems in attaining a stable and sustainable grid was emphasized by Rakib et al. (2024) [7]. For India specifically, Kumar et al. (2023) looked into cutting-edge grid-scale storage technology [9].

Micro-grids are also the target of modernization initiatives. A case study on improving micro-grid performance using solar PV units was carried out by Jaiswal et al. in 2022 [11]. A transactive architecture for dynamic energy storage allocation was presented by Dey et al. (2021) with the goal of efficiently managing essential loads [15].

Even if developments in energy storage and grid modernization show promise, obstacles including exorbitant prices, difficult integration, and regional restrictions still exist. In line with Indian and international energy goals, the examined research provides insightful information. Table 1 below lists out the drawbacks analyzed from existing system.

Table 1: Drawbacks in existing system

Drawback	Description
High initial costs	Modern storage and grid upgrades need large expenditures, which strains budgets in nations like India.
Geographic and environmental constraints	Systems like pumped hydro limit application in flat or metropolitan areas by requiring particular topographies.
Technological integration challenges	Including several energy sources into grids can be difficult and lower the efficiency.
Supply chain and resource limitations	Rare materials (e.g., lithium) expose environmental effect and supply problems.
Maintenance and operational complexity	In regions with little technical know-how, maintaining modern grids requires professional labour.
Energy losses and efficiency concerns	Energy can be lost during conversion and retrieval in certain techniques, such as Pumped hydro storage.

III. METHODOLOGY

The Bio-Thermal Hybrid Storage System (BTHS) enhances midterm energy storage by combining biogas generation, thermal storage, and waste combustion into a single functional unit. It effectively produces and stores power by using organic waste in rural and semi urban areas, also using non-recyclable and burnable waste, as shown in Figure 1.

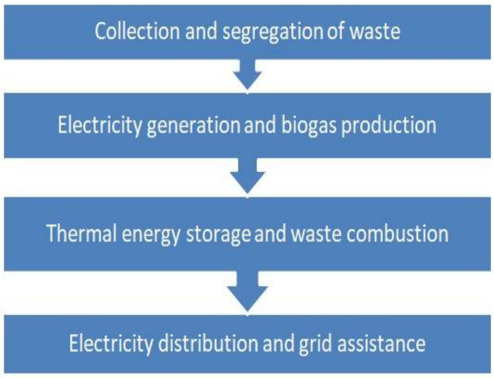

Figure 1: Integrated waste-to-energy process

Stage 1: Collection and segregation of waste

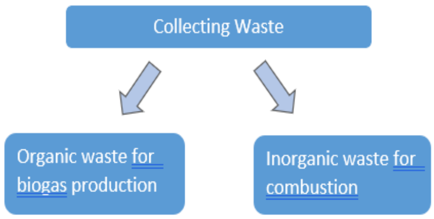

Figure 2: Waste segregation

Anaerobic digesters break down organic waste collected from villages, known to include food waste, livestock excreta, and crop residues. Burnable non-recyclable waste which includes some dry biomass and certain plastics is also collected and kept aside for burning as shown in figure 2.

Stage 2: Electricity generation and biogas production

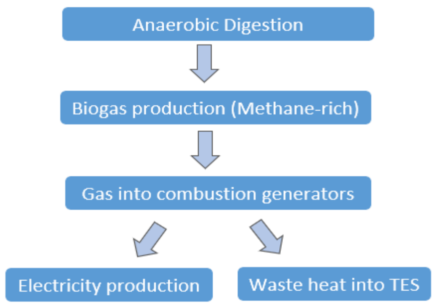

Figure 3: Power generation process and TES

As described earlier, Organic waste is processed in the anaerobic digestion procedure as shown in figure 3.The biogas produced is rich in methane and is then combusted in gas generators to produce electricity. This power can be stored in battery banks for later use, or directly supplied through micro grids. To complete the circular economy, the digestion residue can also be used as an organic fertilizer. To increase energy

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efficiency, waste heat is transported from the gas generators to the Thermal Storage unit, which is called contraction TES.

Stage 3: Thermal energy storage and waste combustion

Heat is produced by burning the non-recyclable garbage in a controlled chamber. TES units use molten salt or PCMs to store heat, also capturing waste heat from biogas generators. BTHS provides a midterm energy storage solution by allowing the application of steam turbines to electricity when needed. This is shown below in figure 4.

Stage 4: Electricity distribution and grid assistance

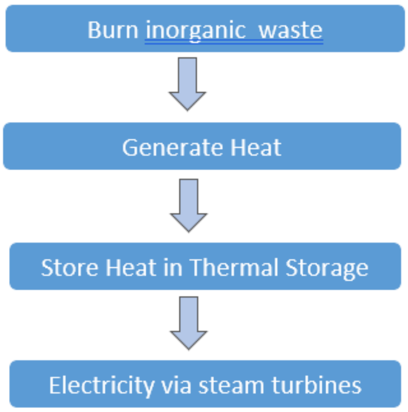

Figure 4: Power generation via TES

Both thermal and biogas-generated electricity are either stored for later use or delivered to nearby grids. This hybrid approach increases energy security and lowers reliance on conventional fossil fuel power plants in semi urban areas.

In order minimize waste, BTHS utilizes biogas along with thermal energy storage, which maximizes energy efficiency. Because of its greater flexibility regarding scaling, the system acts as a more economical option for medium-level energy storage in areas, where there is a high abundance of organic and combustible waste.

IV. RESULTS AND DISCUSSIONS

The results of the BTHS are shown in this section, with their implications for lowering reliance on the national grid while producing dependable, decentralized power from organic and burnable waste. Cost and efficiency comparison with other storage methods is shown below in Graph 1.

By combining thermal energy storage, waste combustion, and biogas production, the Bio-Thermal Hybrid Storage System. BTHS offers a viable mid-term energy storage option. In theory, a single village gives scale facility that processes waste, can sustainably generate energy which is enough to power small businesses, public infrastructure, and street lights. This amount of energy would not fully power a village but can aid as a backup power source to lessen dependency on the national grid while guaranteeing energy availability during droughts. Also, the system improves the electricity access in remote areas, acting as a decentralized generation system.

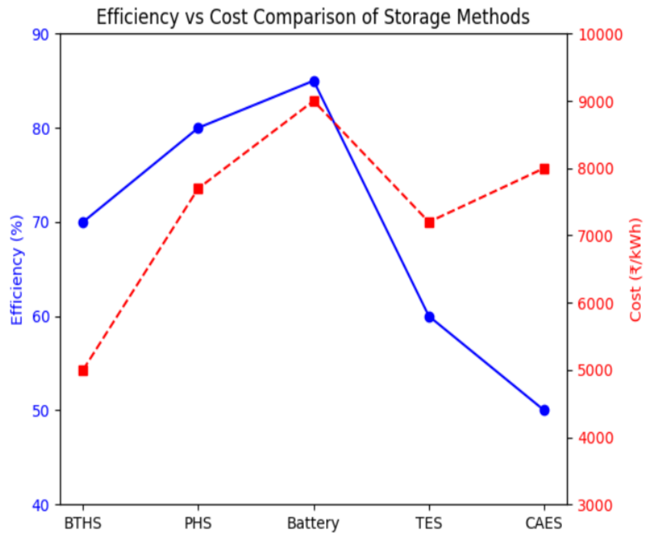

Figure 5: Graph: Efficiency vs Cost comparison with other systems

Addressing waste management issues is just the start. The combination of organic and combustible waste ensures a higher energy yield. Heat captured from clean biogas produced from anaerobic digestion is stored in a Thermal Energy Storage (TES) system along with the excess energy converted into electricity. Energy recovery is improved further with the burning of non-recyclable inorganic wastes which increases the heat energy stored in TES. Uncontrolled combustion of biogas rich in energy is burned when an excess of energy needs to be dissipated and its relation with waste makes it an ideal dispositional option due to the reduced dependency on landfills. There is a profound increase in effectiveness of the entire system with the integration and improved heat collection and storage techniques could increase energy recovery to over 60%.

One of the key advantages of this system is its cost-effectiveness over time. Although there is a large upfront cost concerning the electric infrastructure associated with anaerobic digesters, combustion chambers, and TES units, the operational cost is lower compared to other systems as this one relies on readily accessible organic and combustible waste. Moreover, the system's reliance on local resources and decentralized power production makes it ideal for rural areas, thus minimizing transmission losses and enhancing local energy autonomy. Additionally, the system enables rural residents to turn waste into energy, which helps offset their electricity expenses, making it more economical over time.

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can offset electricity costs, making the system more financially viable in the long run.

As depicted in graph 1, the proposed idea is very cost-effective in nature with a moderate efficiency, which makes it more efficient when compared to conventional methods in use.

Because we operate with a more compact unit that lowers energy dissipation and enhances output, the efficiency of TES is higher than Thermal Storages. The efficiency the system has over a sustained long period of time can be improved by better waste retrieval systems, more sophisticated filter systems, and more efficient thermal storage materials. In future, research might work on BTHS integration with other renewables like solar and wind for communities to develop sustainable hybrid energy systems.

The results of the Bio-Thermal Hybrid Storage System suggest one more option for mid-term energy storage that can be done in a sustainable, low cost, and scalable way.

It helps in waste management and stabilizing the grid, while allowing greater rural electrification through the use of biodegradable and combustible waste. Even in the backup role, BTHS improves local energy security and reduces dependency on the national grid. In developing nations, BTHS has the potential to transform the concept of decentralized energy storage with further optimization.

V. CONCLUSION

The Bio-Thermal Hybrid Storage System (BTHS) combines storage of thermal energy and production of biogas alongside waste incineration for medium energy storage purposes. The BTHS facilitates some degree of national grid modification, promotes economic activity in rural areas, and offers some waste management solutions. Although there are challenges such as the scope of the dumping and system maintenance, these issues can always be suppressed. Provided the proper measures are taken with the help of the authorities, improvements can be made to BTHS so that it functions as an economical, self-sustaining power generator for rural areas. This not only improves the environment and economy, but also stands to mitigate the energy gap considerably.

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