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Review on Waste Oil Powered Thermal Electric Energy Generation System

Prof. V.H. Shivsharan[1], Rhishikesh Sanjay Mahadik[2], Ajay Malhari Riswadkar[3], Vikas Pawar[4]

Research Guide, Department of Mechanical Engineering, Sahakar Maharshi Shankarrao Mohite-Patil Institute of Technology and Research Shankarnagar, Akluj[1]

Research Student, Department of Mechanical Engineering, Sahakar Maharshi Shankarrao Mohite-Patil Institute of Technology and Research Shankarnagar, Akluj[2,3,4]

Abstract: The global demand for clean, affordable, and sustainable energy has driven researchers toward innovative methods of harvesting energy from unconventional and waste sources. This paper presents a comprehensive literature review on the design and implementation of a Waste Oil Powered Thermoelectric Energy Generation System, which integrates a Peltier module (thermoelectric generator), a waste oil burner as the heat source, an aluminium cooling block as the cold-side heat sink, and a complete operational circuit comprising a 6V battery, LED lights, a 9V water pump, and a supporting tank frame structure.

Waste cooking and lubricating oils, being abundant by-products of industrial and domestic activity, represent a significant untapped energy reservoir. When combusted, these oils generate substantial thermal gradients which can be directly converted into electrical energy via the Seebeck effect, as exploited in Peltier/thermoelectric modules. The proposed system offers a compelling low-cost, decentralised energy solution particularly suited for rural electrification, off-grid communities, and emergency power applications.

This review synthesises current research across thermoelectric generator (TEG) performance optimisation, waste oil combustion characteristics, heat exchanger and cooling system design, and practical low-voltage application integration. Key findings indicate that system efficiency is strongly governed by the quality of the thermal gradient maintained across the Peltier module, the effectiveness of the cooling block design, and the calorific properties of the waste oil fuel. The paper concludes with identified research gaps, future directions, and a consolidated understanding of how this integrated system can contribute to sustainable and decentralised energy solutions.

Keywords: Waste Oil, Seebeck Effect, Thermoelectric Generator, Peltier Module

1. INTRODUCTION

The rapid depletion of fossil fuel reserves, escalating energy costs, and the severe environmental consequences of conventional energy production have catalysed global interest in alternative and renewable energy systems. Thermoelectric generation — the direct conversion of heat into electricity — has re-emerged as a particularly attractive technology owing to its solid-state nature, absence of moving parts, silent operation, scalability, and ability to utilise a wide spectrum of thermal sources, including industrial waste heat, solar thermal energy, geothermal heat, and combustion-derived heat.

In parallel, the growing volumes of waste oils — including used cooking oil (UCO), spent lubricating oil, and other petroleum by-products — present both an environmental hazard and an untapped energy resource. Improper disposal of waste oils leads to severe soil and water contamination. However, when properly combusted in controlled burners, waste oils exhibit calorific values comparable to or exceeding those of standard diesel fuel, making them an efficient and cost-effective fuel source.

The integration of waste oil combustion with thermoelectric generation modules presents a unique opportunity: the thermal energy released by waste oil combustion can be harvested via a Peltier module to produce usable electrical power. The cold side of the thermoelectric module is maintained by an aluminium cooling block — often water-cooled — to sustain the essential temperature differential that drives electricity generation via the Seebeck effect.

2.SYSTEM OVERVIEW

The system described in this literature review consists of the following integrated components:

- Waste Oil Burner: The primary thermal energy source that combusts waste/used oil to generate high-temperature heat.

- Peltier Module (TEG): A thermoelectric generator positioned at the junction of the hot and cold surfaces to convert the temperature differential into DC electrical voltage.
- Aluminium Cooling Block: Attached to the cold side of the Peltier module, this heat sink maintains the low-temperature differential necessary for efficient power generation; a 9V water pump circulates coolant through this block.
- 6V Battery: Stores the electrical energy generated by the Peltier module for buffered, stable delivery to loads.
- LED Light: A practical, low-power load demonstrating the viability of the generated electricity for lighting applications.
- 9V Water Pump: Circulates cooling water through the aluminium cooling block to enhance heat dissipation and maintain temperature differential.
- Tank and Frame Structure: The mechanical housing and support structure integrating all components into a coherent, portable unit.

This configuration represents a self-contained, waste-fuelled micro-generation system that addresses both energy poverty and waste oil disposal challenges simultaneously. The literature review that follows examines each component domain in depth, analysing previous research, design innovations, performance benchmarks, and identified limitations.

3.OBJECTIVE

The primary and secondary objectives of this literature review and the associated research into the Waste Oil Powered Thermoelectric Energy Generation System are articulated below:

3.1 Primary Objectives

- To conduct a systematic review of existing literature on thermoelectric generator (TEG) systems with a focus on Peltier module-based power generation, identifying key performance parameters, efficiency benchmarks, and optimisation strategies.
- To survey research on waste oil combustion — including used cooking oil and spent lubricating oil — as a viable thermal energy source, analysing combustion efficiency, calorific values, emission profiles, and burner design considerations.
- To examine literature on heat exchanger and cooling system design, specifically aluminium cooling blocks and liquid cooling configurations, as applied to TEG cold-side heat management.
- To review integration studies combining thermoelectric generation with waste/biomass fuel combustion systems, identifying practical design approaches, power output ranges, and application contexts.
- To assess the suitability of the generated power for low-voltage applications such as LED lighting, small water pumps, and battery charging.

3.2 Secondary Objectives

- To identify technical and practical gaps in existing research that limit the real-world deployment of waste oil powered TEG systems.
- To analyse advantages and disadvantages of the proposed system configuration relative to conventional energy alternatives.
- To propose a framework of future research directions that can improve system efficiency, scalability, and commercialisation potential.
- To consolidate knowledge from disparate research domains — thermoelectric, combustion engineering, heat transfer, and low-power electronics — into a unified reference for researchers and practitioners in this field.

4.Scope of Research

This literature review encompasses a broad but focused scope designed to address all critical dimensions of the Waste Oil Powered Thermoelectric Energy Generation System. The scope is defined along the following axes:

4.1 Temporal and Geographic Scope

The review prioritises literature published from 2005 to 2024, with particular emphasis on work from 2015 onwards to capture recent advances in thermoelectric materials, nano-engineered Peltier devices, and waste oil combustion technologies. Research from both developed and developing nations is included, recognising that the target application context — decentralised, off-grid energy generation — is of heightened relevance to emerging economies in South Asia, Sub-Saharan Africa, and Southeast Asia.

4.2 Technical Scope

The technical scope encompasses the following domains:

- Thermoelectric generation fundamentals, including the Seebeck effect, figure of merit (ZT), and Peltier module specifications.

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- Combustion science applied to waste and used oil fuels, including calorific value determination, flame temperature analysis, burner design, and emission control.
- Heat transfer and thermal management, specifically conductive and convective heat exchange in aluminium cooling blocks and water-cooled systems.
- Power electronics for low-voltage TEG output conditioning, including DC-DC boost converters, maximum power point tracking (MPPT), and battery charge management.
- Mechanical and structural design considerations for portable, integrated system packaging.

4.3 Application Scope

The application focus is on low-power, decentralised electricity generation for:

- Rural and off-grid household lighting (LED systems).
- Small-scale water pumping for agriculture and domestic supply.
- Battery charging for portable electronics and communication devices.
- Emergency power systems for disaster relief and remote installations.

4.4 Exclusions

This review does not cover large-scale industrial thermoelectric systems, high-temperature waste heat recovery from industrial furnaces or exhaust systems (beyond reference comparison), photovoltaic systems, wind energy, or hydroelectric generation. Additionally, detailed electrochemical analysis of battery chemistry is outside the scope, with the 6V battery treated as a standard energy storage buffer.

5. LITERATURE REVIEW

5.1 Thermoelectric Generation: Fundamentals and Peltier Module Research

The theoretical foundation of thermoelectric generation rests on the Seebeck effect, discovered by Thomas Johann Seebeck in 1821, which describes the generation of an electromotive force (EMF) in a conductor or semiconductor subjected to a temperature gradient. The efficiency of a thermoelectric generator is characterised by the dimensionless figure of merit $ZT = S^2\sigma/\kappa$, where S is the Seebeck coefficient, σ is the electrical conductivity, and κ is the thermal conductivity (Goldsmid, 2010).

Bismuth telluride (Bi_2Te_3) based Peltier modules remain the dominant commercial thermoelectric material for near-ambient temperature differentials (up to approximately 250°C), owing to their ZT values approaching unity at room temperature (Rowe, 2006). Commercially available modules such as the TEC1-12706 and TEC1-12715, operating in generator mode, are capable of producing between 2W and 15W under optimal temperature differentials of 60–100°C (Chen et al., 2012). For higher temperature applications, lead telluride (PbTe) and skutterudite-based TEGs are preferred, though at significantly higher cost.

Significant research has been directed toward TEG array configurations and thermal interface optimisation. Yazawa and Shakouri (2011) demonstrated that maximising power output from TEG arrays requires careful impedance matching between the generator and load, and that the use of thermal interface materials with conductivities exceeding 5 W/mK substantially reduces contact resistance losses. Mori (2013) reviewed nano-structured thermoelectric materials showing ZT values above 1.5, attributing improvements to phonon scattering at grain boundaries.

For low-grade heat recovery applications — the category into which waste oil combustion at 200–400°C falls — studies by Hsu et al. (2011) and Kaibe et al. (2011) demonstrated power densities of 10–100 mW/cm² in flat-panel TEG configurations. These power densities, while modest per unit area, become practically significant when TEG arrays of sufficient size are employed. In the context of this system, a stack of four to eight TEC1-12706 modules has been demonstrated by similar projects to generate between 8W and 40W depending on waste oil flame temperature and cooling efficiency.

5.2 Waste Oil as a Thermal Energy Source

Waste cooking oil (WCO) and spent lubricating oil constitute significant categories of industrial and domestic waste. Global production of waste cooking oil is estimated at over 34 million tonnes annually (IEA, 2022). The calorific value of WCO typically ranges from 37 to 40 MJ/kg, comparable to commercial diesel (approximately 42 MJ/kg), making it an energy-dense and viable combustion fuel (Lam et al., 2010).

Research by Sajjad et al. (2019) characterised the combustion performance of a waste oil gravity-feed burner, achieving flame temperatures of 600–900°C under controlled air-to-fuel ratios. The study identified that pre-heating the oil feed to 60–80°C significantly reduced viscosity, improved atomisation, and enhanced combustion stability — a finding corroborated by Ndindeng et al. (2020) in their work on small-scale waste oil heating systems in Sub-Saharan Africa.

Waste lubricating oil presents greater challenges due to contaminant loading — including metallic particles, oxidation products, and water content — which can adversely affect burner nozzle performance and increase particulate emissions (Williams et al., 2008). However, simple filtration through a 100-micron mesh filter has been shown to

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sufficiently clean waste oil for use in drip-feed burners without nozzle atomisation, which is the burner type most commonly employed in DIY and small-scale thermoelectric systems reviewed herein.

The drip-feed or gravity-feed waste oil burner, as used in the proposed system, operates on the principle of controlled oil dripping onto a heated cast-iron or steel combustion bowl, where pyrolysis and subsequent combustion occur. Studies by Thomas (2016) confirmed that such burners can sustain temperatures of 400–650°C on the combustion bowl surface, providing an adequate hot-side temperature for Bi_2Te_3-based Peltier modules, whose maximum operating temperature is approximately 200–250°C. Heat transfer via a steel or copper heat exchanger plate is therefore necessary to prevent module degradation.

5.3 Aluminium Cooling Block and Thermal Management

The cold-side thermal management is as critical to TEG performance as the hot-side heat supply. The temperature differential (ΔT) across the Peltier module is the primary driver of power output, and the cooling block's effectiveness in removing heat from the cold side directly determines ΔT sustainability under load.

Aluminium is the preferred material for cooling blocks in small-scale TEG systems due to its high thermal conductivity (approximately 205 W/mK), low density, corrosion resistance, machinability, and low cost. Tao et al. (2017) demonstrated that a finned aluminium heat sink with forced water cooling achieved cold-side temperatures of 20–35°C under hot-side temperatures of 200°C, maintaining ΔT values above 150°C — well within the operating envelope of standard Bi_2Te_3 modules.

Water-cooled aluminium cold plates have been shown to outperform air-cooled heat sinks by a factor of 4–8× in thermal resistance reduction (Liu et al., 2018). For the proposed system, where a 9V water pump circulates cooling water at flow rates of 1–3 litres per minute, literature suggests that a well-designed microchannel or serpentine-channel aluminium cooling block can reduce thermal resistance to below 0.05°C/W per module, ensuring effective heat removal even at continuous operation.

Research by Min and Rowe (2006) established that for optimised TEG systems, the ratio of the thermal resistance of the heat source to the cold sink should be maintained at approximately 1:1 for maximum power transfer. This principle informs the physical sizing and channel geometry of the aluminium cooling block design. In practical implementations reviewed, cooling blocks measuring 100mm × 100mm × 15mm with 3mm-diameter internal channels have proven effective for module arrays of up to four TEC1-12706 units.

5.4 Power Conditioning, Battery Storage, and Low-Voltage Applications

The raw DC output of a Peltier-based TEG is characterised by low voltage (typically 1–5V per module under partial load) and variable output depending on thermal conditions. Power conditioning circuitry is therefore essential for practical application.

DC-DC boost converters, specifically the MT3608-based and XL6009-based modules, have been widely adopted in small TEG systems to step up the raw 2–6V TEG output to regulated 5V or 12V for battery charging and load driving (Kim et al., 2014). Research by Ramde et al. (2011) on thermoelectric rural electrification in Ghana demonstrated that a 12W TEG output, after boost conversion and rectification, was sufficient to charge a 6V, 4.5Ah sealed lead-acid battery to 80% capacity in approximately 3 hours of operation, subsequently powering LED lighting for 6–8 hours.

LED technology has revolutionised the economics of off-grid lighting. Modern high-efficiency LEDs achieve luminous efficacies of 100–200 lm/W (Tsao et al., 2010), compared to 10–15 lm/W for incandescent bulbs. A 1W LED, for instance, provides illumination equivalent to a 10–12W incandescent bulb, making LEDs the ideal load demonstration technology for low-power TEG systems. Multiple studies have confirmed that 4–8W of TEG power output can supply adequate household lighting (3–5 LED lamps) for rural off-grid applications.

The 9V water pump, used in this system for cooling water circulation, consumes approximately 2–5W depending on flow rate. Research by Huang et al. (2015) on closed-loop water cooling for TEG systems confirmed that the energy expenditure of the cooling pump is more than offset by the 3–5× improvement in TEG power output compared to passive air cooling, resulting in a net energy gain from forced liquid cooling. The pump is typically powered directly from the battery buffer, ensuring consistent cooling even during transient TEG output variations.

5.5 Integrated Waste-Fuelled TEG Systems: Case Studies

Several research groups have reported integrated systems combining waste or biomass fuel combustion with thermoelectric generation, providing direct comparisons to the proposed system.

Champier et al. (2011) developed a biomass stove-based TEG system using eight TEC1-12706 modules with a water-cooled cold plate, achieving 9.5W of electrical output under steady-state combustion conditions. The system powered LED lighting and a radio, demonstrating practical viability for rural electrification. The study reported overall thermal-to-electrical efficiency of 2.3%, consistent with the theoretical limits of Bi_2Te_3 modules under the prevailing ΔT.

Nuwayhid et al. (2005) designed and tested a thermoelectric module mounted on a wood-burning stove, generating 4.2W from a single-module configuration. The work highlighted the importance of module clamping pressure

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and thermal interface material quality in achieving rated performance, noting that poorly installed modules exhibited 30–40% lower power output than optimally mounted units.

In a study directly analogous to the proposed system, Brito et al. (2012) constructed a waste oil-fired TEG test rig using six Bi_2Te_3 modules and a copper heat exchanger plate, achieving hot-side temperatures of 180–220°C and cold-side temperatures of 25–40°C via a water-cooled aluminium block. The system generated 18–32W of electrical power, sufficient to charge a 12V lead-acid battery at 1–2A and operate a 10W LED array continuously.

Research from India (Patil et al., 2020) demonstrated a jatropha oil-powered TEG system in a rural village setting, producing 15W of power to operate a 12V, 5W LED lamp and charge mobile phones. Community acceptance was high, with 87% of surveyed households preferring the system over kerosene lanterns due to reduced smoke, lower operating cost, and the dual benefit of waste oil disposal.

5.6 Frame and Structural Design Considerations

The mechanical integration of burner, heat exchanger, TEG modules, cooling block, pump, and battery into a coherent, portable, and safe unit is a critical but often under-reported aspect of small-scale TEG system design. Structural requirements include thermal isolation between the hot combustion zone and electrical components, vibration resistance for the water pump and TEG stack, and weather resistance for outdoor deployment.

Steel angle iron frame construction, as used in many prototype systems reviewed, provides adequate mechanical rigidity at low cost. Ceramic fibre insulation or vermiculite board panels are commonly employed to isolate the burner chamber from the TEG and electrical assembly (Thomas, 2016). Studies have noted that inadequate thermal isolation can elevate ambient temperatures around electronic components by 30–60°C, reducing battery and LED driver lifespan by 40–60% (Sundaram et al., 2019).

Portable system weight is a design constraint for rural deployment applications. Reviewed systems of comparable output (10–30W) typically weigh 8–25 kg, with the fuel tank and battery constituting the largest mass fractions. Stainless steel fuel tanks with capacity of 5–15 litres provide 3–8 hours of continuous operation at typical waste oil consumption rates of 0.5–1.5 litres per hour (Ndindeng et al., 2020).

6.FUTURE SCOPE

The field of waste oil powered thermoelectric generation presents numerous promising avenues for future research and development, spanning material science, engineering design, systems integration, and policy implementation:

6.1 Advanced Thermoelectric Materials

The most transformative potential improvement lies in the adoption of next-generation thermoelectric materials with ZT values significantly above unity. Materials such as tin selenide (SnSe) single crystals (ZT ~ 2.6 at 923K, Zhao et al., 2014), half-Heusler alloys, and skutterudite-based composites offer substantially higher conversion efficiencies. Future research should investigate the economic viability and manufacturing scalability of these materials for use in waste-fuelled small-scale TEG systems.

6.2 Maximum Power Point Tracking (MPPT) Integration

Advanced power electronics incorporating MPPT algorithms, analogous to those used in solar PV systems, can continuously optimise the electrical load presented to the TEG array to extract maximum power under variable thermal conditions. Research into MPPT topologies specifically designed for the low-voltage, variable-output characteristics of small TEG systems represents a high-value area for future work.

6.3 Improved Burner and Heat Exchanger Design

Future research should explore catalytic combustion of waste oil at lower temperatures, which could enable more direct hot-side coupling with higher-temperature TEG materials. Computational fluid dynamics (CFD) modelling of heat exchanger geometries can identify configurations that maximise heat transfer to the TEG hot face while minimising combustion gas temperature losses.

6.4 Hybrid Energy Systems

Integration of the waste oil TEG system with solar thermal collectors, phase change material (PCM) thermal storage, or small wind turbines could create hybrid systems capable of 24-hour operation with reduced fuel consumption. Research into such hybrid architectures, including optimal control strategies for multi-source energy management, represents a compelling future direction.

6.5 Waste Oil Pre-Treatment and Fuel Standardisation

Research into low-cost, small-scale waste oil filtration, dewatering, and blending technologies could standardise fuel quality and improve combustion performance. Studies on the optimal blending ratios of waste cooking oil, waste lubricating oil, and bio-ethanol for TEG burner applications would contribute significantly to system reliability and emission reduction.

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6.6 IoT-Enabled Remote Monitoring

Future systems should incorporate low-power sensors and IoT connectivity to enable remote monitoring of fuel level, combustion temperature, TEG output, battery state, and coolant temperature. Data-driven predictive maintenance and performance optimisation, enabled by machine learning algorithms, could substantially improve system availability and lifespan.

6.7 Community-Scale Deployment Studies

Rigorous field deployment studies in target communities — measuring energy access improvement, economic benefit, health impact from reduced indoor air pollution, and lifecycle environmental performance — are essential for building the evidence base necessary for policy support and development finance mobilisation.

7.CONCLUSION

In conclusion, the Waste Oil Powered Thermoelectric Energy Generation System represents a technically sound, practically feasible, and socially valuable contribution to the decentralised energy landscape. Continued research investment in the identified future directions has strong potential to transform this from a promising prototype concept into a commercially deployable and widely adopted off-grid energy solution, particularly for underserved communities in developing nations where both waste oil availability and energy poverty are prevalent.

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