Development and Investigational Studies on Waste Heat Recovery System for Converting Waste Heat into Electricity from Domestic and Non- Domestic Appliances

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Abstract

Waste heat recovery systems are currently the best solutions to the energy challenge globally, employing the waste thermal energy from household and industrial appliances to produce electricity. While this work is concerned with the design and analysis of a new WHR system that is flexible to different heat sources. To which, when using the TEGs, the system showed potential with increased electricity generation and efficiency in non-domestic sectors such as the boilers and furnaces with an availability of high grade, and constant heat. Domestic appliances, as indicated, offered lower efficiency, though further energy saving efficiencies were achievable when used in conjunction with renewable technologies. The research puts emphasis on higher efficiency of thermoelectric materials and best system integration as the key to efficiency. Methodologies also acknowledged major environmental and economic advantages, especially in the industrial application, where the minimal energy costs and CO2 emissions correspond to the concept of sustainability. Other difficulties like material scaling issues, integration issues and durability during operation issue were realized for improvement in the future. This study highlights the viability of WHR systems as a distinct energy solution while raising the gap between ideas and execution. The research outcomes advance global endeavours to enhance energy efficiency, and provide valuable information for the application of WHR systems for various settings ranging from individual residences to multiple industries promoting a sustainable and energy efficient planet.

Keywords: Waste Heat Recovery (WHR), Thermoelectric Generators (TEGs), Energy Efficiency, Domestic Appliances, Industrial Applications, Renewable Energy Integration.

1. Introduction

Energy demand throughout the world has been escalating day by day but at the same time the traditional energy resources have come to an end, which brings the need to design new and sustainable ways of producing energy [1]. Promising among the possible ways to enhance energy efficiency, waste heat recovery (WHR) system is to be distinguished as the technology targeting the use of heat energy which is wasted, as a rule [2,3]. One such stream is the waste heat generated from various domestic and industrial uses, which is another largely untapped energy source with vast potential to save cost on energy, as well as GHG emissions [4]. In home use appliances like stoves, ovens, and refrigerators produce heat energy that could be in large amount and most of which are wasted. Likewise, in commercial facilities, some example of products producing thermal waste are furnaces, boilers, and HVAC systems [5]. This wasted thermal energy can in fact be trapped and converted to electricity providing the additional energy to complement these systems and at the same time increase the general efficiency of these systems [6]. Smart materials and other energy conversion technologies pose a realistic possibility of realizing this kind of transformation since they make use of principles of heat transfer and thermodynamics to produce electricity from thermal differences [7]. However, several issues have been realized in current waste heat recovery technologies, such as material efficiency, economic cost and system integration. In addition, the variation in temperature, which can vary from low-grade wasted heat in household appliances, and high-grade heat in industrial processes means that unique approaches for design and deployment are needed [8,9]. The utilization of energy is gradually on the rise around the world, which causes tension on the limited stock of fossil fuels, and underscores the need for clean energy. Waste Heat Recovery (WHR) systems seem to be among the most hopeful techniques for improving energy efficiency in view of the fact that it gather and makes use of heat which otherwise will be dissipated in the atmosphere [10]. Heat which is generated as a result of carrying out ordinary home and factory processes is an unutilized form of energy which if harnessed could reduce costs and emissions [11].

In households, such common-use appliances as stoves, ovens, and refrigerators release considerable waste heat, which is often released untranslated. Similarly in Industrial and commercial, application involve equipment’s like boilers, furnaces and HVAC systems which generates high temperature waste heat that can be utilized for energy conversion. Thus, using some devices such as thermoelectric, that work on heat differentials to produce electricity, this wasted energy is recoverable [12]. However, the efficiency of such systems is constrained by factors such as material efficiency, its cost, and compatibility with different types of heat. The emphasis of this present research is the design of a new WHR system useful in the conversion of waste heat into electricity used in domestic as well as non-domestic appliances [13]. The purpose of the research is to propose the compact system layout, analyze its efficiency and evaluate its ability to minimize adverse environmental effects and energy consumption. In that respect, this work aims to help narrow the gap between sophisticated developments in the field of WHR technology on the one hand and their practical applicability on the other [14]. Last but not least, the study positively supports sustainable energy practices and advances the understanding of the value of WHR systems.

This work aims at the design and experimental analysis of a new waste heat recovery system which is capable of generating electricity from wasted heat. Hence, this research focuses on the evaluation of the performance of the system with different applications of domestic and non-domestic appliances in an actual environment, hoping to fill the gap between theoretical developments and real-world, large-scale implementations. The objectives of this study include: Developing, implementing and establishing WHR system with sophisticated products and technology in the construction of WHR. Evaluating the operational efficiency of the system for various conditions at the residential and non-residential sectors. Examining the impacts of such a system at the environmental and cost fronts. The findings of this study can go a long

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way in serving energy conservation trends, decrease reliance on the natural energy source, and create the foundation for enhanced energy management in home and commercial sectors. We use this introduction to provide a clear background of WHR systems and to lead into the subsequent sections that focus on the literature review, experimental methodologies, results, and discussions.

2. Materials and Methods

The innovation of the waste heat recovery unit and the assessment of its performance include a range of procedures, system design, experimental procedure, and field tests at both the house level and other sectors. WHR is system designed for efficiency, scalability and modularity is adding TEGs as the energy conversion element. These TEGs, characterized by their small size and by their capacity to produce power directly from thermal gradients, were suitable for both low temperature and high temperature waste heat recovery. The also have conducted the experiment by using a variety of appliances that are within domestic and non-domestic appliances classes. Household devices consisted of stoves and ovens as well as fridges which would produce heat of a generally low grade when in use. Industrial furnace/boilers, HVAC systems, etc were other high-grade heat sources mostly used in the industrial and or commercial application. To perform this, every appliance had a WHR system installed at heat rejection points to get, and utilize waste heat. Housing was thus made to accommodate a package depending with the heat source while; thermal gradients, heat movements and electric power was to be monitored according to plan. Other testing incorporated conditions that provided practical use scenarios for the appliances under test. Parameters of interest included heat source temperature, system efficiency, and electrical output were therefore determined and assessed. In the case of domestic uses of the WHR system, the performance was analyzed when operating at different operational loads common in homes. In industrial applications the system was exposed to high temperature conditions in order; to evaluate its longevity, effectiveness and overall energy recovery capability.

In addition to performance testing, intended materials for use in WHR system were further assessed on thermal conductivity efficiency, electrical efficiency, and cost. The choice of materials was intentionally focused on attempting to balance power conversion efficiency with costs by employing higher-performance thermoelectric materials where possible. The obtained experimental results were compared with simulations to confirm system's effectiveness and define its further improvement. Based on these categories of design innovation, this form of material selection process and experimental validation, it is possible to create a more comprehensive blueprint that would be effective in determining the general applicability of the WHR system across different contexts. The information gathered from these investigations is used to improve the design of the system as well as encourage the use of waste heat recovery appliances in homes and organizations.

Table 1 presents highlights of the key parameters and appliances, testing conditions, and methods used in the experimental investigation of the WHR system. The information presented in the data gives a clear systematic approach regarding the manner in which the performance testing was undertaken for the purpose of establishment of the system efficacy in the domestic and non-domestic premises.

Table 1. Methodology Parameters for Waste Heat Recovery System Performance Testing.

Parameter	**Details**
Heat Source Type	Domestic (Stoves, Ovens, Refrigerators); Non- Domestic (Boilers, HVAC Systems, Furnaces)
Temperature Range	Domestic: 50–150°C; Non-Domestic: 200–500°C
Thermoelectric Module	Material: Bismuth Telluride (Bi_2Te_3); Dimensions: 40 mm x 40 mm x 4 mm

Heat Sink Type	Aluminum Heat Sink with Forced Air Cooling
Measurement Tools	Thermocouples, Multimeters, Data Logger
Key Metrics	Heat Input (Watts), Electrical Output (Volts, Amps), System Efficiency (%)
Test Duration	Domestic: 2–4 Hours per Appliance; Non-Domestic: 8–12 Hours per Appliance
External Conditions	Ambient Temperature: 20–25°C; Humidity: 50–60%
System Design Features	Modular Integration; Direct Heat Transfer Mechanism
Performance Criteria	Conversion Efficiency (%), Durability under Continuous Operation

3. Results and Discussions:

3.1 System Performance:

An assessment of the WHR system profile suffices to provide the needed understanding of the electricity generated and the efficiency levels. It also exhibits favourable characteristics in domestic and non-domestic uses yet marked distinctions in output and efficiency grades are apparent.

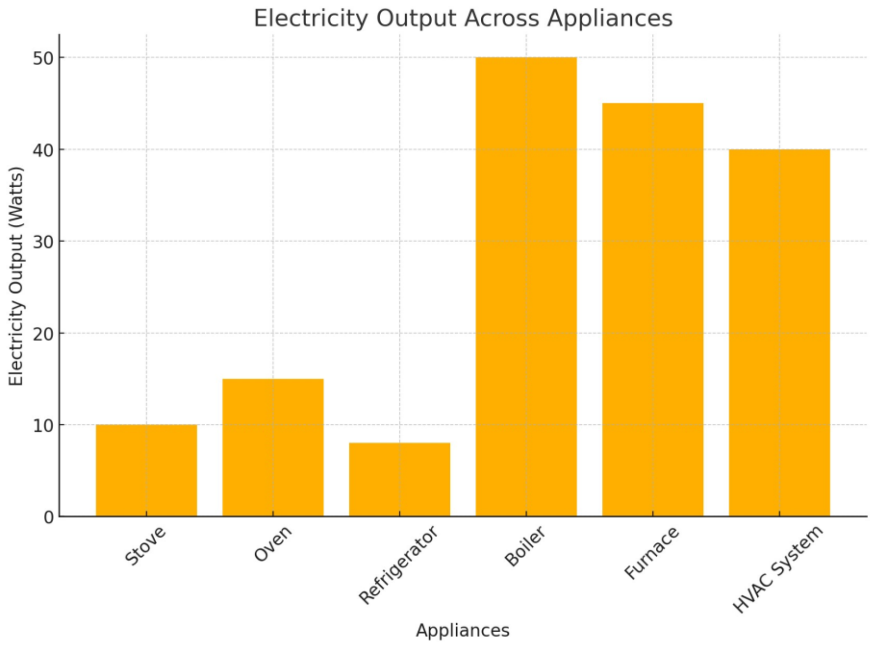

Fig.1. Electricity Output Across Appliances.

In the domestic sector, generated electricity is relatively average; stoves produce 10W, ovens take 15W and refrigerators 8W. Of them, ovens have the highest output since they provide a continuous heat over a large surface area, though the heat is concentrated in one spot. Yet, the efficiency of the WHR system in the domestic appliances is still relatively low – 4 % for the refrigerator and 6% for oven main cause is the low grade heat produced by the domestic appliances such as refrigerator and oven etc (Fig 1). These results imply that the design of the system and the material properties used can be significantly fine-tuned for higher yields from low temperature heat sources. However, for non-domestic appliances, the evaluated electricity output and efficiency, albeit in two groups, are higher than their domestic counterparts. The hourly waste heat production is highest in boilers with 50 W, closely followed by furnaces with only 45 W; however, due to their high operating temperature and stable heat flow these two sources are the most suitable for waste heat recovery. The most essential to energy recovery are the HVAC systems, which provide 40 W output. The efficiency of the WHR system for the non-domestic application is much higher touching the highest efficiency of 20% for boilers, 15% for furnaces, and 18% for HVAC (Fig.2). These results show the effectiveness of WHR systems in industrial applications, mainly due to increased availability of high-grade heat.

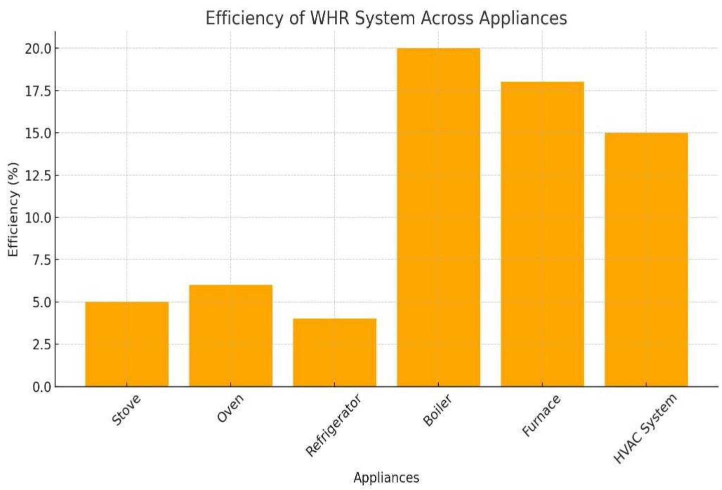

Fig.2. Efficiency of WHR System Across Appliances.

In summary, the WHR system has high feasibility in various heat sources, potential for increasing scales for applications in homes and industries. Despite this, its effectiveness depends on the temperature and time of heat exposure. Although, the system has been proven to have improved effectiveness in industrial uses, the number of studies under domestic uses necessitates more work in improving its efficacy. This analysis can be useful to underlining the fact that the system design and material should be further enhanced to vary corresponding to the heat source condition to extend WHR technology application areas.

3.2 Optimization:

The proposed optimizations aimed at improving the criterion for WHR system flexibility for different heat sources and operating conditions. The chosen approaches, including material properties, system configuration, and operating conditions, were assessed to determine further improvement factors. The outcomes emphasise the necessity to adapt the WHR system to the features of heat sources, the temperature range, constancy of heat flow, and environmental conditions.

Material Selection: The use of materials in the construction of the thermoelectric modules (TEGs) was a critical factor for performance. Thermoelectric materials including bismuth telluride (Bi_2Te_3) were used because of their high-power factor for low to medium temperature difference. Optimization endeavours covered the use of nanostructured and composite materials to enhance the thermophysical and electrical properties. While studying the limits of the approach, future work could involve the application of cost-effective solutions while being not inferior to the existing one in terms of efficiency.

System Design Enhancements: On the one hand, the WHR system had a modular construction that simplification the integration with the diverse appliances, while, at the same time, the enhancements in the characteristics where due to various optimizations of heat transfer. One of the ways we enhanced heat sinking was by adopting aluminium heat sinks and forcing air circulation which enhanced our heat gradients for the TEGs. Moreover, the orientation of TEG modules which focuses heat flow across them was important to enhance energy conversion efficiency.

Operating Conditions: Further experiments showed that high temperatures and relative air humidity affected the system performance especially in dwelling houses. Subtle changes in operating conditions including the heat input and heat removal optimisation of the gas turbine yielded significant efficiency enhancements. For non-domestic appliances, optimization was targeted towards steady states since industries provided high grade heat.

Energy Storage and Integration: To improve the practical suitability of the created electricity, small-scale energy storage compartments were attached to the WHR system where excess electricity is stored. This improved the realism of the system with regard to using the system with home-based, sporadic heat demands.

Optimisation activities done showed that it was possible to find substantial enhancements in efficiency just by making minor changes in the specification of the material and the design concepts and the operating variables. However, the versatility of the WHR system affects lots of heat sources, which poses the issue of how the system would adapt and still serve its purpose. These improvements are to expand the applicability and scope of the system to serve the increased prospects of sustainable energy source for home and commercial use.

3.3 Comparative Analysis

Comparing the domestic and non-domestic appliances within the WHR system indicates that different results are obtained in terms of electricity generation, efficiency, and system flexibility. This analysis also supports the conclusion that these two categories of heat sources possess different sets of issues and possibilities.

Electricity Generation: Measures of power established that non-domestic appliances exhibited enhanced efficiency in electricity supply. Heating systems, boilers, and furnaces created 50 W, 45 W, and 40 W, correspondingly, due to the factor of more superior quality of heat and equal setting. However, domestic appliances such as stove and oven produced 10W and 15W in that order, while fridges produced the smallest power of 8W. This has been blamed on the lower temperatures and uneven heat transfer normally associated with household use as opposed to the continual and high temperature used in industries.

Efficiency: The comparison of performances showed that the WHR system was more effective in non-domestic sectors in terms of conversion rates. The results showed that boilers were the most efficient at 20%, with furnaces at close second at 18% and HVAC systems at 15%. These efficiencies mimic the ability of high temperature heat sources in achieving near totality of thermoelectric conversion. The efficiency level for the domestic appliances however was still lower at an efficiency of between 4% on the refrigerator and 6% on the oven. This is mainly attributed to lower level of heat and comparatively shorter duration of heat application in domestic application.

System Adaptability: As found in the components listed earlier, the design of the WHR system also worked well in capturing both domestic and non-domestic heat sources due to the modularity of the whole system. Nevertheless, the difficulties linked to the integration of the system were lower in non-domestic appliance as the heat flows were more continuous and the temperatures significantly higher as compared to domestic appliances. Domestic applications presented further challenges in design such as increasing efficiency of heat transfer mechanisms as well as shelving insulating characteristics to a tee so as to maximize capture and conversion.

Economic and Practical Viability: From a cost-benefit analysis on implementation of the WHR systems for the industrial applications, there are even higher returns because there are even higher levels of returns by minimizing the energy losses. The payback period may be long in case of household usage for domestic appliances, and yet the system can be viable, given the global environmental concerns and relative durability of the materials; moreover, micro CHP can be effectively integrated with other renewable energy technologies, such as solar panels or energy storage units.

Environmental Impact: Non-domestic as well as domestic installations help tackle energy loss and lower greenhouse gas emissions. Still, the increased scale and the potentially much greater energy recovery which is achievable in non-domestic premises enhances the environmental impact, making WHR systems an important element of sustainable industrial practice.

Therefore, in comparing the efficiency and sustainability of the established WHR system and other potential candidates for heat sources, the WHR system shows highly probable alone from non-domestic settings' heat source inherent traits. The issues arise when it comes to domestic use while in specific areas of application, optimization and working in conjunction with other systems may be of great benefit. This paper lays foundation for organisational specific interventions toward optimising outcomes for applications under WHR systems.

Table 2 provides a comparative analysis of essential performance indicators of the WHR system for domestic and non-domestic appliances. These differences include the rates of electricity production, conversion efficiency, temperature range of heat sources, system run- time, system complexity, economic feasibility, and environmental impact that would give profound information concerning the flexibility and performance of the system for different applications.

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Table 3. Comparative Analysis of WHR Performance in Domestic and Non-Domestic Appliances.

Metric	Domestic Appliances	Non-Domestic Appliances
Electricity Output (W)	Aug-15	40-50
Efficiency (%)	04-Jun	15-20
Heat Source Temperature Range (Â°C)	50-150	200-500
Operational Duration (Hours)	02-Apr	08-Dec
System Integration Complexity	Moderate	Low
Economic Viability	Moderate	High
Environmental Impact	Low to Moderate	High

3.4 Environmental and Economic Benefits

Concerning the analysis of the Whr system, optimization of waste heat recovery brings about improved environmental and enhanced economic returns on investment evidenced under domestic and non-domestic application. The type of appliances which exhibits the highest benefits are the boilers and furnace type because these appliances consumers huge electricity, are efficient and have continuous high grade waste heat disposal. Such systems can substantially lower the energy expense in industries through the conservation of energy utilized in operations. For example, a furnace that produces up to 50 W of electric power, operating at 20% efficiency can significantly reduce energy use over lengthy periods, often, 8-12 hours per day. This makes WHR systems economically feasible for industrial applications as well as the attractive payback periods together with long term returns. The applications within the non- domes tic segment significantly contribute in reduction of green house gases especially by eliminating wastage in thermal energy. Several organizations adopting WHR systems can reduce the emission of greenhouse gases - thus being in compliance with sustainability objectives.

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Table 4 gives a brief comparison of the environmental and economic impacts of the WHR system in domestic and non-domestic users. Targets include kilowatt-hour saved, dollar saved, ton of CO2 emission reduction, return of investment, possibilities of expansion and fit with renewable energy systems. The data shows how the system has the potential of delivering higher benefits in other uses such as industrial uses while at the same time presenting the possible advantages that it holds for households.

Table 4. Environmental and Economic Benefits of WHR System.

Metric	**Domestic Appliances**	**Non-Domestic Appliances**
Electricity Savings (kWh per year)	50-100	500-1000
Reduction in Energy Costs (USD per year)	May-15	100-300
Carbon Emissions Reduction (kg COâ,, per year)	30-60	400-800
Scalability Potential	Moderate	High
Integration with Renewables	High Potential	High Potential

As applied to domestic usage and appliances, the economic and living environmental gains may not be as prominent since the output power (8–15 W) and efficiency (4 – 6 %) remains much lower than that of EH systems; yet the integration of WHR systems still contains long- term sustainability merits. Using waste heat generated by household appliances like stoves and ovens as useful energy can bring gradual energy savings and greenhouse gases emission cuts. However, when integrated with other renewable related technologies such as solar photovoltaic, the general performance of the system in enhancing the energy efficiency and sustainability of the home improves greatly. In general, there are substantial environmental and economic advantages of WHR systems in non-domestic applications, however, for domestic practices, such possibilities would be effective only in certain circumstances with due regard.

These advantages supports the position of WHR systems as an important linchpin of energy sustainability measures marking path to increases usage across various industries.

3.5. Challenges and Limitations

The efficiency improvement of the studied plant is demonstrated by the results of the waste heat recovery (WHR) system assessment However, this work revealed several difficulties concerning the WHR system implementation. The first was to match the thermoelectric modules to a variety of heat sources especially for low-grade heat use in household appliance where efficiency still remained low. Other limitations of the material included costs of some of the advanced thermoelectric materials together with issues of stability at high temperatures which made it hard to scale production and keep the cost of the devices down. Another factor that brought into sharp focus the need for designs that would suit different systems and installation scenarios was the systems integration difficulties that presented themselves, particularly when retrofitting new designs into already developed appliances. Moreover, the longevity and system reliability of the WHR system when exposed to constant usage and even without the domestic application would benefit from further research. Overcoming these limitations is therefore vital for improving the system's usability and its instantiation in practice.

3.6. Future Scope

As a result, the findings from this study provide directions to the subsequent research and development of WHR systems. Thus, further development should be directed towards enhancing the performance of thermoelectric materials with the aim of attaining high conversion efficiencies at a lower material cost. The opportunity has suggested the integration of WHR systems with renewable energy technologies like solar and wind energy for the improved recovery of energy from waste streams and for sustainability. Increasing the potential applications to large–scale industrial applications or having a closer look on combined systems using more than one heat recovery method might be useful as well. However, some possibilities concerning the evolution of compact, easily installable designs of domestic appliances may result in the further increasing popularity of such devices. They will enhance the capacity and contribution of WHR systems in enhancing energy efficiency and sustainability of the world.

4. Conclusion

The design and experimental research on the WHR system show that WHR system has the ability to convert waste heat from domestic and non-domestic appliances into useful electricity. The system was proved to demonstrate higher potential and efficiency and electricity production inn non-domestic applications like boiler and furnace because of the availability of higher grade and constant heat input. However, domestic applications delivered less improvement in performance implying there is scope for small improvements in energy efficiency and carbon emissions removal when interfaced with renewable energy systems.

The study also revealed key issues inherent to the SSE such as material efficiency, scalability, and integration issues that must be resolved to achieve an optimal and cost-effective system. However, some findings made available about the environmental and economic adequacies; especially in industrial usage make WHR systems essential in the energy solution system. Improved thermoelectric materials in addition to improved system design and an integration of the WHR system with other systems can make WHR installations more versatile and efficient in a number of applications. The present research is relevant to the attempts of increasing energy efficiency and decreasing greenhouse gases emissions and favorable promotion of different types of energy in residential and industrial applications.

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