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Investigating Potential Uses of Exhaust Waste Heat from Thermal Power Plants in Africa: A Case of Hakan Quantum Power Plant in Rwanda

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ABSTRACT:This study investigates the untapped potential for utilizing waste heat from thermal power plants in Rwanda to enhance energy sustainability. Hakan Quantum(HQ)Power plant is located in Mamba sector of Gisagara District in the southern rural part of Rwanda and serves as a representative thermal plant for this study. Purposive sampling was used to select three (3) interviewees from HQ Power plant. Next, purposive sampling was used to select three (3) respondents from each of the sixteen (16) potential future waste heat users. Results indicate that HQ Power plant wastes approximately 170 megawatts of heat when producing 80 megawatts of electricity, amounting to 1.955 x 10^12 joules or 1.955TJ per hour. Respondents expressed concerns about environmental impact of waste heat release into the environment, confidence in thermal power plant heat reliability, and interest in its use if commercially available. Results showed that tea processing, coffee drying, and the food and beverage industries are perceived as having the most benefits from waste heat utilization. Limited technological infrastructure, financial constraints, and economic feasibility were identified as key challenges to waste heat utilization in Rwanda. Results also indicate that supportive policies are deemed crucial for advancing waste heat utilization. Consistency of results between HQ Power Plant (as a waste heat producer) and potential users underscores shared perspectives on waste heat utilization in Rwanda.

KEYWORDS: Energy sustainability, Rwanda, thermal power plant, waste heat recovery, waste heat utilization.

I. INTRODUCTION

Waste heat is the excess heat generated during industrial processes or energy production that is typically not put into any practical use and is lost or discharged into the environment (Jouhara et al, 2018). Utilizing the exhaust waste heat produced by thermal power plants has the potential to significantly improve sustainability and energy efficiency on a worldwide scale. Technological advancements, such as Heat Recovery Steam Generators (HRSG) and Organic Rankine Cycles (ORC), have enabled the effective utilization of waste heat (IEA, 2018; Ragupathi, Debabrata, Pradeep, Lakshan, 2018).

Combined Heat and Power (CHP) systems and district heating networks are successful solutions that generate electricity while capturing excess heat for heating applications (Lund et al., 2018). For example, the Kymijärvi II Power Plant in Finland successfully utilizes waste heat through an HRSG system, contributing to improved energy efficiency and reduced emissions (Granatstein, 2002). These examples demonstrate the economic and environmental benefits of waste heat utilization.

According to the International Finance Corporation (IFC) (2014) and the Industrial Productivity (IIP) (2014), Waste Heat Recovery (WHR) technologies are implemented in various sectors other than power plants. In the cement industry for example, WHR has a great deal of potential in Latin America and Asia. There are also significant opportunities in a few Middle Eastern and African nations. Although WHR viability varies depending on the particular cement plant, Latin America and East and South Asian nations often have good enabling conditions. A variety of favourableconditions exist in Africa and the Middle

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East, major among them being political stability and industrial electricity prices (IFC&IIP, 2014).

Thermal power plants in Africa generate substantial waste heat, presenting an opportunity for increased energy efficiency. Implementing technologies like HRSG and ORC can help capture and utilize waste heat effectively (IEA, 2018). Successful case studies from other regions, such as the Kymijärvi II Power Plant in Finland, demonstrate the potential for waste heat utilization in Africa. By drawing insights from these examples and tailoring them to the African context, waste heat recovery and utilization can be promoted.

Some African countries have successfully integrated CHP systems in their energy infrastructure. In Nigeria, the Olorunsogo Power Plant is a combined-cycle power plant that utilizes natural gas for electricity generation (Okedu, Kenu, Idowu and Uhunmwangho, 2018). Another example is the Ain Beni Mathar Integrated Solar Combined Cycle Power Plant in Morocco that combines solar thermal energy with a natural gas-fired combined-cycle power plant, utilizing waste heat from the gas turbines for steam generation and further electricity production (Alqahtani and Patiño-Echeverri, 2016).

The idea of using waste heat from thermal power plants has not been investigated in Rwanda. The current installed capacity to generate electricity in Rwanda is 276.068 MWe, according to the Rwanda Energy Group. 51% of the generated electricity comes from thermal sources, with 4.2% coming from solar and 43.9 % from hydro sources. (Rwanda Energy Group, 2024).Additionally, Rwanda is making significant strides towards its energy future, including achieving net-zero emissions by 2050 while satisfying forecasted demand for electricity.

Technological advancements, including HRSG and ORC, can be implemented to capture and utilize waste heat efficiently, therefore helping Rwanda to achieve its development targets. Successful case studies from around the world, such as the Kymijärvi II Power Plant in Finland, demonstrate the potential economic and environmental benefits of waste heat utilization (Granatstein, 2002). Rwanda could apply the lessons from successful projects to its own context. By implementing waste heat recovery systems, Rwanda can enhance energy efficiency, reduce emissions, and contribute to its sustainable energy goals.

This study aims to examine the waste heat loss from HQ Power plant and identifying opportunities and challenges associated with utilizing exhaust heat from thermal power plants in Rwanda. It holds significance for Rwanda's energy, environment, and economy, offering insights to optimize energy generation, reduce emissions, and unlock economic opportunities.

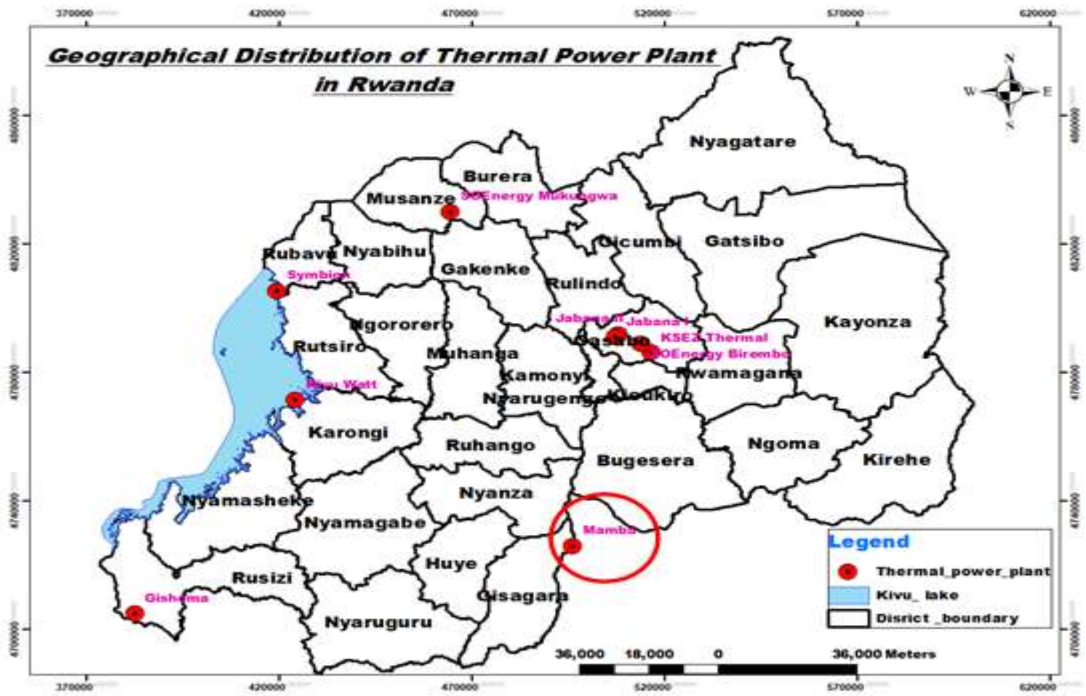

Figure 1:Geographical Distribution of Thermal Power Plants in Rwanda (HQ Power plant is denoted as Mamba) Source: Researcher, 2023. Map data source: Rwanda Energy Group (REG).

II. UTILIZATION OF HEAT IN VARIOUS INDUSTRIAL PROCESSES

2.1. Use of heat in the tea processing

Heat is important in different steps of tea processing. The processing involves many important steps that turn newly picked tea leaves into the tasty beverage that is enjoyed across the world. After harvesting, the leaves undergo withering to remove moisture and enhance pliability. Subsequent rolling breaks down cell walls and initiates oxidation, a vital process for flavour development. Controlled oxidation follows, often with regulated heat application to influence flavour profiles. The oxidation process is halted through fixing or firing, where heat stabilizes the flavour. Finally, drying reduces moisture content for long-term preservation, with heat aiding in moisture removal and preventing spoilage (Naheed, Barech, Sajid, Khan & Hussain,2007).

2.2. Use of heat in coffee processing

The use of heat plays a crucial role in both coffee drying and processing, influencing the quality and characteristics of the final product. During coffee drying, heat is employed to reduce the moisture content of the beans, a critical step in preventing mold growth and ensuring preservation. This process typically involves exposing the beans to controlled temperatures, either through sun drying or mechanical drying methods (Sandeep et al., 2020).

Heat is used to facilitate many steps of coffee processing, including roasting, grinding, and brewing. Roasting, in particular, is a critical phase in which green coffee beans are treated to high temperatures, resulting in chemical changes that impact flavour, aroma, and colour of the beans. (Alessandrini et al., 2008). Furthermore, heat plays an important role in the brewing process, where hot water extracts soluble compounds from ground coffee beans, resulting in the formation of thebrewed beverage. The temperature and duration of brewing have a direct impact on the extraction efficiency and flavour intensity of coffee. (Batali et al., 2020).

2.3. Use of heat in brick processing

In brick processing, heat plays a pivotal role in transforming raw materials into long-lasting building materials. The controlled application of heat in brick production is essential for producing high-quality bricks that fulfill building codes and endure environmental conditions. Clay, sand, and water are mixed to form a malleable mixture, which is then shaped into bricks. These bricks are then dried to remove excess moisture, usually by exposure to natural sunlight or artificial heat sources (Alaa & Ali, 2013). Once dried, the bricks undergo firing in kilns or ovens, where they are subjected to high temperatures ranging from 871 ºC to 1316 ºC. This intense heat causes chemical changes in the clay minerals, resulting in the fusion of particles and the formation of a hardened, ceramic-like structure (Brick Manufacturing Association, 2006). The firing process also drives off remaining water and organic matter, further strengthening the bricks and increasing their durability (Alaa & Ali, 2013).

2.4. Use of heat in plastic products manufacturing

The use of heat plays a crucial role in various chemical processing plants, including those involved in the manufacturing of plastic products. In plastic product manufacturing such as Polyvinyl Chloride (PVC) tanks, heat is essential for shaping and molding PVC materials into the desired forms. This involves processes such as compression and injection molding, blowing, extruding, thermoforming, and stamping, where heat is applied to soften the PVC materials, allowing it to be shaped into tanks or other products (Deshpande,1996). The precise temperature and duration of heating are critical factors in achieving the desired properties and quality of the final product (Marques, Fagali de Souza, Miranda & Yadroitsau, 2015).

2.5. Use of heat in food production

The use of heat is essential in food and beverage companies at various phases of production, processing, and preservation. Heat is used for a variety of functions, including cooking, pasteurization, sterilization, and preservation. Heat is used during food processing to enhance flavours, improve texture, and ensure food safety by eliminating harmful pathogens. (Gopalakrishnan, Konnadath, Kumkum, Rani & Meemansha, 2022).

Pasteurization, a heat treatment process, is widely used in beverage production to extend shelf life and eliminate harmful bacteria while preserving the beverage's nutritional value. Furthermore, sterilization procedures such as canning involve the application of heat to kill bacteria and other microorganisms, enabling for long-term preservation of food products (Gopalakrishnan et al., 2022).

2. 6. Use of heat in cement manufacturing

Heat is used extensively in cement production operations to help turn the raw materials into the final product. During the production of cement clinker, raw materials such as limestone, gypsum are subjected to high temperatures in a kiln. This process, known as calcination, involves heating the raw materials to temperatures around 1450°C, causing chemical reactions that lead to the formation of clinker nodules. Additionally, heat is utilized in the grinding and mixing stages to pulverize clinker and other additives into fine powders, which are then mixed to produce different types of cement (Stanislav, 2018).

2.7. Use of heat in metal processing

Heat is an important tool in metal processing since it shapes and refines metals for a variety of uses. The process of metal processing often begins with heating raw materials to high temperatures to cause desired changes in the metallurgical structure and consequently in the properties of metal components. Once melted, metals undergo a series of heat treatment techniques to modify their mechanical properties. For instance, annealing involves heating metal to specific temperatures and then slowly cooling it to relieve internal stresses and improve ductility. Quenching, on the other hand, is the quick cooling to harden metals, while tempering serves to reduce brittleness and improve toughness (Sverdlin & Ness, 2006).

III. MATERIAL AND METHODS

3.1. Examination of waste heat loss

To examine the heat loss of HQ Power plant, the researcher performed calculations based on the plant's performance data including plant efficiency and net heat rate.

3.2. Interview with HQ Power plant experts

The researcher conducted a semi-structured interview for three (3) experts from this power plant, which helped to capture a broader range of perspectives, experiences, and expertise related to the power plants' operations, processes, and waste heat recovery and utilization therefore enhancing the reliability and validity of the research findings. The data were then analysed using descriptive statistics.

3.3. Questionnaire for potential waste heat users

To identify opportunities and challenges of using exhaust heat from thermal power plants in Rwanda, data were collected from respondents in 16 potential future waste heat users using a questionnaire, then were analysed using descriptive statistics to generate meaningful findings.The sixteen (16) potential future users (companies) of waste heat were sampled using purposive sampling as below:

- Four (4) tea processing companies, each with three respondents: Gisakura Tea Company, Mushubi Tea Company, Nyabihu Tea Factory and Rubaya Tea Factory.
- Three (3) metal processing companies: SteelRwa, Imana Steel Rwanda Ltd and S&H Industries Ltd
- Three (3) chemical processing companies: Sulfo Rwanda Industries Ltd, ROTO Ltd and Royal for Investment & Industrial Ltd.
- One (1) brick processing company: RULIBA Clays Ltd
- One (1) cement manufacturing company: Prime Cement Ltd
- Four (4) food and beverage companies: Kwetu Bakery Ltd, Bender Exports Ltd, Cooperative Kawa Nyarubaka and Gihanga Coffee.

A total of forty-eight (48) respondents were selected from the sixteen companies, with each company contributing three respondents. The research opted for three respondents from each company due to the relatively novel nature of waste heat utilization in Rwanda, which might not be widely understood by a large number of individuals within an individual company.Among these respondents, there were 37 males, accounting for 77.1% of the sample, and 11 females, comprising 22.9% of the sample.In terms of educational attainment, 48 individuals representing 91.7% of the sample, possessed university-level education. Additionally, two (2) respondents (4.2%) completed secondary education, while another two (4.2%) completed primary education. These literacy levels among respondents indicate a robust dataset, with the majority holding at least a university degree. This higher level of education enhances the reliability and credibility of the research findings, as it suggests an informed participant group capable of providing insightful contributions.

IV. RESULTS AND DISCUSSIONS

4.1. Waste heat loss

The gross efficiency of the HQ Power plant is 32% as revealed during data collection. Additionally, according to HQ Power Plant's records, this efficiency is consistent with a declared net heat rate of 11,500 kJ/kWh, signifying the amount of heat required to produce one kilowatt-hour of electricity.Further analysis deduces that with a gross efficiency of 32%, the plant, theoretically operating at 100% efficiency, would produce 250 MW when generating 80 MW of electricity. Consequently, 68% of the heat is not converted into electricity, corresponding to 170

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MW of potential electrical output that is lost. This underscores the significance of optimizing efficiency in power generation processes.

Wasted Energy (Electrical) = Total input – Total output

= 250 MW– 80MW = 170 MW

Knowing that the net heat rate of this power plant is 11,500 kJ/kWh, meaning that one kWh of electricity requires 11,500 kJ of heat to be produced, it is possible to determine the amount of heat (in Joules) that would be required to produce the wasted 170 MW for a period of one hour as follows:

- 1 KWh (Electricity) ------->11,500 kJ (Heat)
- 170 MWh (Electricity) ------------- $> \frac{11500 \text{ kJ x } 170 \text{ x } 10^6 \text{Wh}}{1 \text{ x } 10^3 \text{ Wh}}$

After simplification of units:

- 170 MWh (Electricity) -------------> 1955 x 10^9 J

Therefore, at a gross efficiency of 32%, HQ Power plant theoretically wastes approximately 170 megawatts worth of heat when producing 80 megawatts of electricity. This is wasted heat is equal to 1955 x 10^9 joules or 1.955 x 10^{12} joules or 1.955TJ every hour.

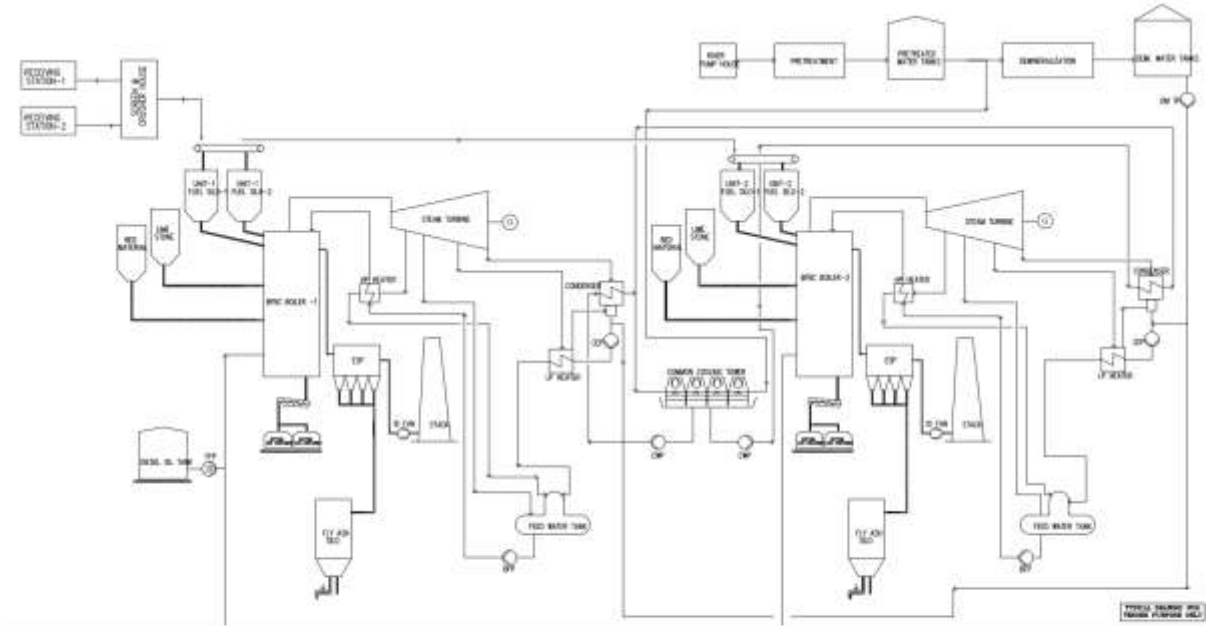

Figure 2**:** Main flow diagram for HQ Power plant**.** Source: HQ Power plant manual

The plant already uses various heat recovery systems whereby the recovered heat is used for air preheating and feed water heating in economizers. To increase the efficiency of the power plant, HQ Power Plant should invest in research and development to investigate innovative technologies and methods, such as advanced combustion technologies, innovative heat recovery systems, and optimized turbine design. It is also important to note that not all waste heat is necessary released in exhaust form and therefore may not be recoverable. The primary exhaust waste heat stream consists of flue gas, which is discharged into the environment through stacks at temperatures below 100°C.

4.2. Opportunities and challenges of using exhaust heat from thermal power plants

4.2.1. Temperature ranges used by surveyed potential waste heat users

Temperature range necessary for the heating processes within the sixteen (16) surveyed facilities/plants identified as having the potential to leverage waste heat from thermal power plants such as HQ Power plant are presented in Table 1.

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Table 1:Temperature ranges used by surveyed potential users of waste heat

		Frequency	Percent
Valid	Low: Below 100°C	13	27.1
	Moderate: 100°C - 300°C	22	45.8
	High: Above 300°C	13	27.1
	Total	48	100.0

Source: Primary Data (2023)

Results indicate that 27.1% of the surveyed potential waste heat users indicated that their heating processes involve low temperatures, specifically below 100°C (Table 1).Additionally, 45.8% of respondents reported that their heating processes fall within the moderate temperature range of 100°C to 300°C, while another 27.1% use high temperatures above 300°C. The researcher's conclusion is drawn from the majority response, with 45.8% of respondents highlighting a preference for moderate temperatures in their heating processes, specifically within the range of 100°C to 300°C. This means that only 27.1% of potential waste heat users use temperatures that are very close to the temperature of the main exhaust waste heat steam at HQ Power plant (Below 100°C). The findings about waste heat temperatures at HQ Power plant align with the research conducted by Forman, Muritala, Pardemann & Meyer (2016) which indicated that the majority (63%) of the examined waste heat streams originate at temperatures below 100°C, in which electricity generation had the largest share followed by transportation and industry. And information regarding the flow rate of the primary waste heat stream from HQ Power Plant.

4.2.2. Opportunities and challenges of using exhaust waste heat, according to HQ Power experts

With regards to opportunities and challenges of using exhaust heat from thermal power plants in Rwanda, participants from HQ Power Plant identified the most significant obstacles to utilizing waste heat in Rwanda. Notably, 33.3% of interviewees highlighted limited technological infrastructure, 22.2% emphasized financial constraints (big investments), 33.3% pointed to economic feasibility, and 11.1% mentioned lack of awareness as key challenges.

4.2.3. Opportunities and challenges of using exhaust heat, according to potential waste heat users

On the side of potential future waste heat users, respondents were provided with a range of options to choose from to express their viewpoints. They were given the option to select multiple answers, and the frequency of each selected answer was calculated (Table 2).

Table 2: Perception on the most significant obstacle of utilizing waste heat in Rwanda

		Frequency	Percent
Valid	Limited technological infrastructure	19	30.6
	Financial constraints (big investments)	21	33.9
	Lack of awareness	8	12.9
	Economic feasibility	7	11.3
	Lack of awareness	7	11.3
	Total	62	100.0

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Source: Primary Data (2023)

Results show that30.6% identified limited technological infrastructure as a primary challenge, while 33.9% highlighted financial constraints, emphasizing the challenge of substantial investments.

4.2.4. Potential waste heat users' opinions on waste heat utilization

Potential waste heat users from the surveyed sixteen (16) companies shared their opinions on waste heat utilization (Table 3

Table 3: Potential waste heat users' opinions on waste heat utilization

Statement	n	SA		A		N		D		SD		Mean	Std. Deviation
		fi	%	fi	%	fi	%	fi	%	fi	%		
Releasing waste heat into the environment (air, water, biodiversity etc.) raises environmental concerns	48	27	56.2	14	29.2	1	2.1	2	4.2	4	8.4	4.2083	1.21967
I believe that heat from thermal power plants would be a reliable source of heat for industrial processes	48	20	41.7	11	22.9	14	29.2	3	6.2	0	0	4.0000	.98930
I would consider heat from power plants as a source of heating if it was commercially available and economically viable	48	33	68.8	6	12.5	6	12.5	2	4.2	1	2.1	4.4167	1.00707
Supportive policies and incentives are important in promoting waste heat utilization initiatives	48	34	70.8	8	16.7	3	6.2	1	2.1	2	4.2	4.4792	1.01036
Social and cultural factors may	48	9	18.8	5	10.4	6	12.5	16	33.3	12	25.0	2.6458	1.45119

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affect the acceptance of waste heat utilization in Rwanda and Africa.													
Overall mean												3.95	

Scale: Strongly disagree-SD(1), disagree-D(2), neither disagree nor agree-N (3), agree-A (4) and strongly agree-SA(5).Source: Primary Data (2023)

The majority of respondents strongly agreed or agreed with opinion statement related to waste heat utilization. The overall mean of 3.95, categorized as high, signifies a consensus on the following points: the environmental concerns associated with releasing waste heat into the environment (air, water, biodiversity, etc.), the perception of heat from thermal power plants as a reliable source for industrial processes, the consideration of power plant heat as a heating source if commercially available and economically viable, the importance of supportive policies and incentives in promoting waste heat utilization initiatives. However, the results indicate that only 18.8% and 5% of respondents strongly agree or agree, respectively, that social and cultural factors may influence the acceptance of waste heat utilization in Rwanda and Africa. This suggests that waste heat utilization could be socially and culturally acceptable in Rwanda.

4.2.5. HQ Power plant experts' opinions regarding waste heat utilization

Interviewees at HQ Power plant expressed their perceptions regarding waste heat recovery and all agreed on the following points:

- They perceive waste heat recovery as a feasible and efficient means of energy utilization.
- Waste heat recovery and utilization could be cost-effective and financially viable in both Rwanda and Africa.
- They envision waste heat utilization playing a prominent role in future energy management in Rwanda and Africa.
- The establishment of government or industry initiatives could further encourage waste heat recovery projects.

These findings highlight a strong consensus among interviewees regarding the feasibility, economic viability, and future potential of waste heat recovery initiatives both in Rwanda and broader contexts.

Overall, the results show correlation between the perception of waste heat producer (HQ Power plant) and waste heat users regarding the challenges and opportunities in waste heat recovery and utilization. Additionally, the findings from the HQ Power plant and from potential waste heat users are consistent with the perspectives of Ambriz-Díaz, Rosas, Chávez & Rubio-Maya (2022), Wheatcroft et al. (2020), and Zhang et al. (2022). These studies collectively suggest that crucial economic factors influencing decision-making in waste heat recovery projects include elements such as cost-benefit analysis, energy savings, Return on Investment (ROI), incentives and subsidies, and technology costs, among other considerations. The findings are also in harmony with Oghenejoboh & Akpabio's (2001) study, which suggests that better management of current and potential sources of energy, better planning of future industrial projects, promoting and enforcing energy conservation policies can realize better use of local energy resources.

4.2.6. Perceived top industries for utilization of waste heat from power plants

Interviewees at HQ Power plant also presented their perspectives on industries that stand to benefit the most from utilizing waste heat generated by the HQ Power Plant. Participants were given the flexibility to select multiple industries from the provided list. Results showed that, tea processing, coffee drying, and other food and beverage industries emerged as the sectors perceived to benefit the most from harnessing waste heat from the thermal power plant such as HQ power plant. These findings align with the research conducted by Tuncer et al. (2019), where they introduced a waste heat management model as one of the ways to improve sustainable energy systems for food processing. In their model, the authors presented how waste heat would be utilized in the food industry for heating and cooling load and thermal energy storage.

V. CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

This study investigated the potential uses of exhaust waste heat from thermal power plants in Africa, focusing on the HQ Power Plant in Rwanda. The specific objectives were to examine heat loss from HQ Power plant and to identify opportunities and challenges in waste heat utilization systems in the country's thermal power plants.

Based on data collected from HQ Power Plant and from the sixteen (16) selected companies with waste heat utilization potential, the study revealed that the most significant obstacles are limited technological infrastructure, financial constraints, and a lack of awareness. The data showed homogeneity between HQ Power Plant as a producer of waste heat and the selected industries that have the potential to use waste heat, indicating consistent findings. Respondents expressed that heat from thermal power plants such as HQ Power plant could serve as a reliable source for industrial processes, and they would consider it for heating if commercially available and economically viable. Additionally, supportive policies were recognized as crucial for implementing successfully waste heat utilization.

The findings of this research highlight the considerable heat potential within thermal power plants like HQ Power plant. If properly utilized by industries requiring heat for their operations, this could enhance sustainable energy practices, resource efficiency, and decrease environmental pollution in Rwanda and Africa.

5.2. Recommendations

This study offers several recommendations for enhancing waste heat utilization from thermal power plants in Rwanda, targeting various stakeholders including HQ Power plantmanagement, potential waste heat users, investors, and government authorities. The management of HQ Power plant is recommended to invest in technological upgrades and collaborate with government bodies to advocate for supportive policies regarding waste heat recovery and utilization. Potential users of exhaust waste heat are encouraged to conduct feasibility studies, explore collaborations with thermal power plants to leverage waste heat, fostering mutually beneficial relationships for sustainable energy use. They should also stay informed about technological advancements. Investors are urged to invest in research and development and prioritize sustainability goals. They are encouraged to explore investment opportunities in financing waste heat recovery and utilization projects in Rwanda and Africa, collaborating with power plants and industries to bridge financial gaps. Rwandan authorities are recommended to formulate supportive policies, provide financial incentives, and facilitate collaboration and capacity building initiatives.

5.3. Suggestions for further research

In order to deepen the understanding of waste heat utilization and contribute valuable insights to enhance the sustainability and effectiveness of such initiatives across various domains, the research suggests further studies as follows:

- Conduct in-depth economic viability studies to evaluate the cost-effectiveness and return on investment of waste heat utilization projects in different industrial sectors.
- Investigate the effectiveness of existing policies related to waste heat utilization and propose policy recommendations to further incentivize and support such initiatives.
- Conduct a comparative analysis of waste heat recovery practices across different thermal power plants in various regions to identify best practices and variations in approaches.
- Explore emerging technologies and innovations in waste heat recovery and utilization, assessing their feasibility and potential implementation in different industrial contexts.
- Expand the scope of case studies to include a broader range of industries beyond the power sector, examining the applicability and challenges of waste heat utilization in diverse industrial settings.
- Investigate public perceptions and awareness regarding waste heat utilization, exploring factors that influence acceptance and potential strategies for increasing awareness.
- Conduct a cross-country comparison to understand how waste heat utilization initiatives vary in different socio-economic and regulatory contexts, providing insights into factors that contribute to success or challenges.

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