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Hybrid Solar Thermal Water Purification System with Metaheuristic Optimization for Improved Efficiency

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Abstract – *The present study focuses on the hybrid solar thermal water purification system with metaheuristic optimization for improved efficiency aimed at addressing the growing demand for safe drinking water using renewable energy sources. The proposed system utilizes solar energy as the primary power input, which is stored in a battery and subsequently used to operate a heating unit. Water is heated to a controlled temperature below its boiling point to initiate the purification process. The generated vapor is then condensed to obtain distilled water, which undergoes an additional filtration stage using a suitable filtering medium to enhance water quality. A secondary condensation stage ensures that the purified water is delivered at ambient temperature for direct consumption. The development process followed a systematic product design approach, beginning with the identification of user requirements and proceeding through design, prototyping, and evaluation stages. Furthermore, an economic assessment was carried out to evaluate the feasibility of large-scale production. To improve system performance, metaheuristic optimization techniques were applied to key processes, including heating, cooling, and purification. The results indicate that the proposed system is an energy-efficient and cost-effective solution for decentralized water purification, particularly suitable for rural and remote areas. If implemented effectively, the system has significant potential to alleviate the scarcity of potable water.*

Keywords- *Solar Energy, Water Purification, Metaheuristic Optimization, Thermal Distillation, Hybrid System, Renewable Energy, Sustainable Water Treatment*

INTRODUCTION

Water is an essential resource for sustaining human life, and the demand for safe and potable water is continuously increasing due to population growth and industrialization. In modern society, water purification systems have become indispensable for ensuring water quality. Conventional purification methods typically rely on external energy sources such as electricity, thermal energy, or chemical treatments, which may not be readily available or cost-effective in remote and rural regions. To address these challenges, the present work focuses on the utilization of solar energy as a sustainable and economical driving source for water purification. Solar energy is abundant, renewable, and widely accessible, making it an ideal alternative for decentralized applications. In the proposed system, solar panels are used to convert solar radiation into electrical energy, which is stored in a battery to ensure continuous operation during periods of low sunlight. This stored energy is supplied to a heating element that raises the temperature of impure water to a level sufficient for effective disinfection and evaporation. The generated vapor is subsequently condensed to produce distilled water. To further enhance water quality, the condensed water is passed through a filtration medium before being collected as potable water at near-ambient temperature. The development of the system followed a structured product design methodology. Initially, customer requirements were identified through surveys and analyzed using Quality Function Deployment (QFD) to translate them into engineering specifications. Functional decomposition was performed using a black-box modeling approach to define system operations. The design was developed using computer-aided design (CAD) tools, followed by stress analysis to ensure structural integrity. Material selection, manufacturing processes, and cost evaluation were also systematically carried out. Finally, a prototype was fabricated, tested, and evaluated to assess its performance in producing safe drinking water.

LITERATURE REVIEW

Recent advancements in water purification technologies have focused on improving efficiency, reducing cost, and integrating renewable energy sources. Solar-based purification systems have gained significant attention due to their sustainability and suitability for decentralized applications. Modern research emphasizes hybrid systems, advanced materials, and optimization techniques to enhance overall system performance. For instance, solar nanophotocatalytic pretreatment combined with optimization techniques such as genetic algorithms has demonstrated improved efficiency in reducing membrane fouling and enhancing water treatment processes [1]. Similarly, hydrogel-based solar purification systems have shown high solar–thermal conversion efficiency along with improved water transport mechanisms, making them promising candidates for next-generation purification technologies [2]. Recent studies have also reported significant improvements in solar still performance through the use of advanced materials and structural modifications, leading to higher evaporation rates and increased water productivity [3]. In addition, eco-friendly desalination approaches utilizing agricultural waste materials have been explored to enhance evaporation efficiency while maintaining low system cost [4]. The integration of artificial intelligence and metaheuristic optimization techniques has further contributed to performance enhancement in water purification systems. Machine learning and nature-inspired algorithms have been applied to optimize solar-driven and photocatalytic purification processes, resulting in better energy utilization and improved system efficiency [5]. Furthermore, optimization of solar stills using algorithms such as artificial bee colony and hybrid machine learning models has demonstrated considerable improvements in water yield and thermal efficiency [6]. Comprehensive review studies have summarized recent developments in solar desalination, including hybrid systems, phase change materials, and advanced membrane technologies, highlighting their potential for scalable and cost-effective solutions [7], [8]. Overall, the literature indicates significant progress in solar-based and hybrid water purification technologies; however, challenges related to cost, scalability, and system optimization still persist. The integration of renewable energy with advanced optimization techniques presents a promising pathway for developing efficient and sustainable water purification systems.

METHOLOGY

Quality Function Deployment (QFD) is a systematic approach used to translate customer requirements into engineering characteristics for a product or service. The first step in QFD involves identifying the target customers and understanding their specific needs. For this study, the target market for the solar water purifier was categorized into three segments: urban residential, industrial, and rural residential sectors. A survey was conducted with 88 participants across these sectors using a combination of direct questionnaires, online surveys, and telephone interviews. The collected customer requirements were then categorized based on their priority, as summarized in Table 1.

Table 1: Customer Requirements and Preferences

Preference	Requirements
High	Low cost, Easy to clean, Low maintenance cost, Effective mechanism
Medium	Easy to use, Iron control mechanism, Chemical-free water, Multiple output lines, Alarm system, Compact design
Low	Backup power system, Temperature control system, Odorless water, Switching system instead of rotating tap

The QFD process was then applied to convert these customer requirements into technical specifications, resulting in a House of Quality diagram (Figure 1).

Figure 1: Product Planning Diagram (House of Quality) for Solar Water Purifier

From this analysis, key technical requirements such as battery life, storage capacity, movement mechanism, and solar panel efficiency were identified as critical for product performance. Functional decomposition was performed to break the product into smaller components for easier analysis and design. A black-box model was developed to outline the system's input-output relationships and overall functionality (Figure 2).

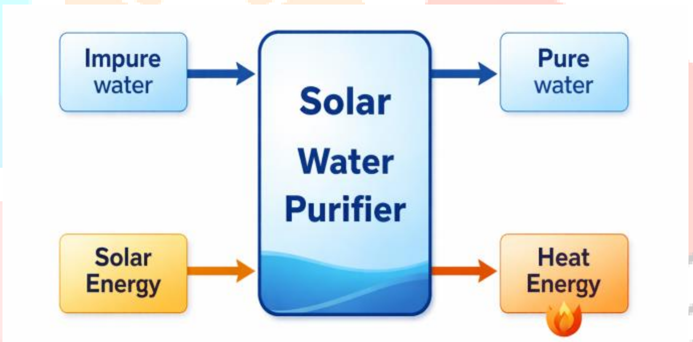


Figure 2: Black Box Model of the Solar Water Purifier

The component hierarchy and cluster functions of the solar water purifier are illustrated in Figures 3 and 4, respectively. The product development process followed a structured sequence: planning, concept development, and system-level design. Initial rough sketches were refined into detailed CAD models using SolidWorks software, incorporating critical design features for functionality and manufacturability. Stress analysis was conducted on essential components to ensure structural integrity.

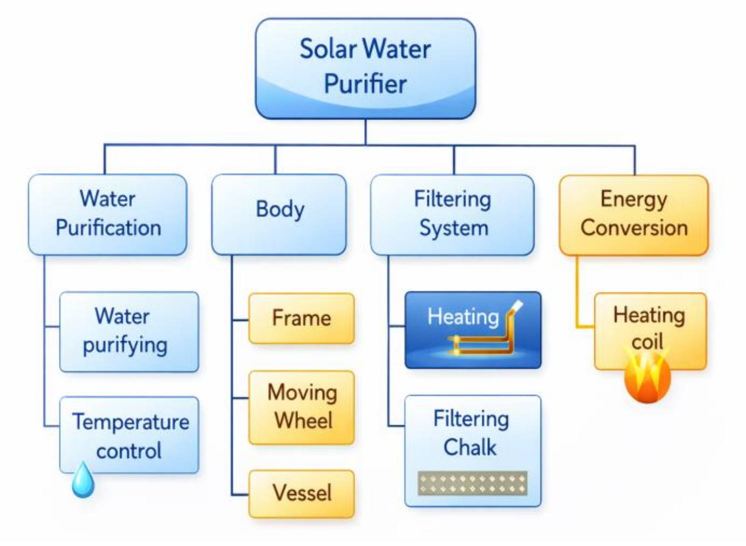


Figure 3: Component hierarchy of Solar Water Purifier

Following design and analysis, the prototype was fabricated, assembled, and tested. The final model and functional prototype are shown in Figures 5 and 9, respectively. Performance testing confirmed that the system effectively purified water, with the results summarized in Table 3.

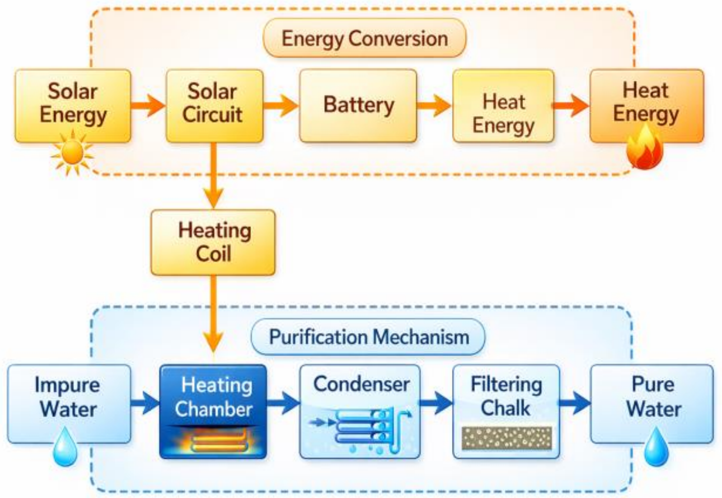
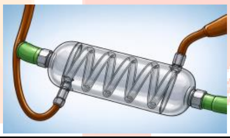
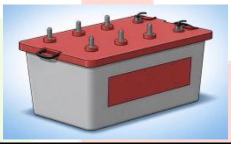
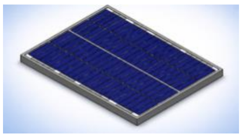


Figure 4: Cluster Function of Solar Water Purifier

Table 2: Parts of solar water purifier

Part Name	CAD Design
Condenser	
Battery	
Heating Coil & holder	
Chalk Filter	
Solar Panel	
Body	

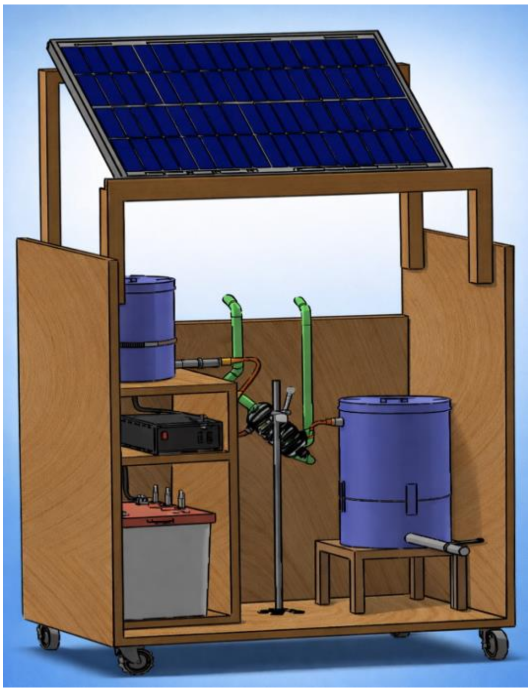


Figure 5: CAD model for Solar Water Purifier

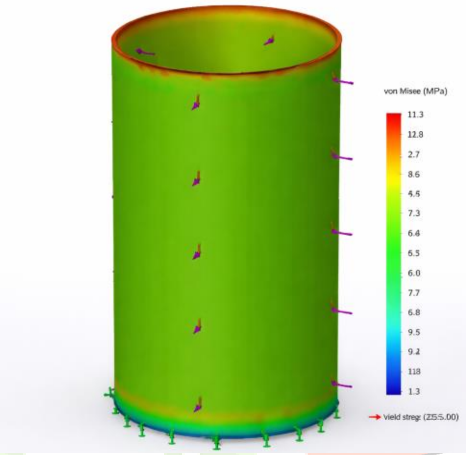
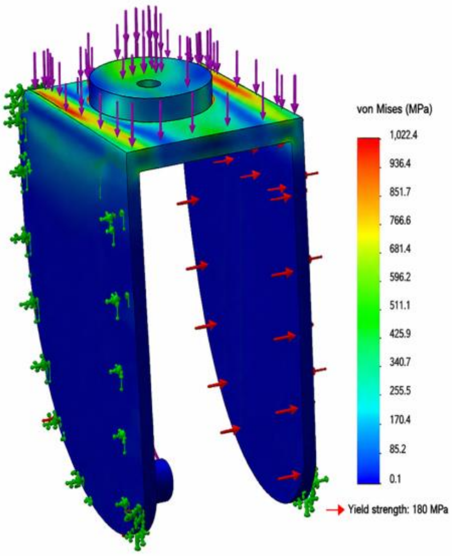


Figure 6: Stress analysis of heating vessel



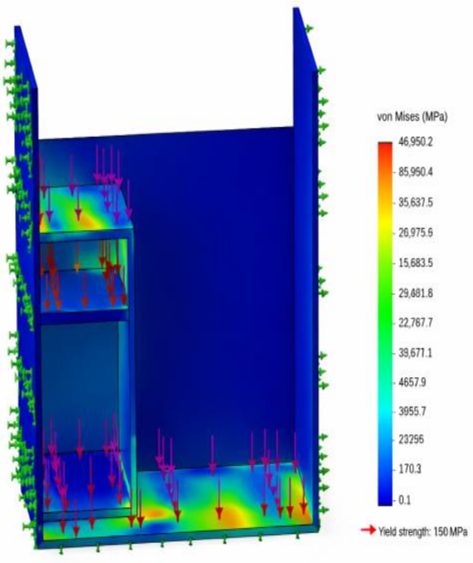


Figure 8: Stress analysis of body

Table 2: Results of the water test

Water Quality Parameter	Values Before Treatment	Values After Treatment
pH Level	7.1	7.1
Biochemical Oxygen Demand (BOD, mg/L)	5.3	4.9
Chemical Oxygen Demand (COD, mg/L)	8.5	8.3
Iron Concentration (mg/L)	0.02	0.0195
Dissolved Oxygen (mg/L)	5.8	5.4
Nitrate Content (mg/L)	0.05	0.047

Figure 9: Manufactured Solar Water Purifier

CONCLUSION

Bangladesh faces significant challenges in accessing safe drinking water and sustainable energy. The developed solar water purifier provides a potential solution to address both issues simultaneously. The product design followed a systematic approach, from gathering customer requirements to the manufacturing stage. Water quality tests demonstrated that while the system does not substantially affect pH levels, it effectively reduces BOD, COD, and other contaminants. Currently, the system is most suitable for domestic use. To make it viable for industrial applications, further optimization and scaling are necessary. Additionally, future research could focus on removing arsenic, a serious health hazard in Bangladesh, from drinking water. Arsenic contamination affects numerous water sources and causes widespread health problems, and an effective purification solution could have a significant social impact. As of now, such solar-based water purifiers are not widely available in the Bangladeshi market. With improved performance and broader implementation, this technology has the potential to benefit both urban and rural communities across the country.

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