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Optimizing renewable energy systems: A comprehensive review of entropy generation minimization

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ABSTRACT

This comprehensive literature review examines the key concepts of entropy generation minimization and its significant impact on the advancement of renewable energy systems. The study begins by introducing the fundamental principles of entropy generation and their relevance to thermodynamic processes. It emphasizes the critical role of reducing entropy production in enhancing the overall efficiency of energy conversion technologies. This review evaluates various approaches to identifying and mitigating irreversibility in renewable energy applications, including analytical methods, numerical simulations, and optimization strategies. It also explores how the principles of entropy generation minimization can be integrated into system design and operation to improve the performance of a wide range of renewable energy technologies, such as biomass conversion, wind turbines, solar photovoltaic systems, and geothermal energy. Furthermore, this review provides a thorough examination of the literature, spanning from classical theories to the latest innovations in thermodynamics and heat transfer. The novelty of this review lies in addressing the gap between entropy generation minimization and its application to renewable energy systems, thereby paving the way for future research and technological advancements in the field.

INTRODUCTION

This study employs entropy generation minimization as a method to improve the performance of energy systems, with a particular focus on renewable energy sources. The concept of minimizing entropy production is crucial as it aims to control the rate of irreversibility in a system, thereby optimizing its overall efficiency. Entropy generation minimization can be applied to various renewable energy sources, ranging from solar and wind energy to hydroelectric and geothermal power plants. The benefits of minimizing entropy generation in renewable energy systems include reduced energy losses, enhanced system performance, increased reliability, and cost saving. Low entropy generation is among the most effective strategies for improving the efficiency of alternative energy producing systems. By reducing energy losses, minimizing entropy production enhances the viability of renewable energy systems while also contributing to cost reduction—an especially pertinent benefit as global energy consumption steadily shifts toward renewable resources. The usefulness of entropy generation minimization in renewable energy systems has been demonstrated in numerous studies. Figure 1 shows the flow chart of entropy generation with minimization methods, its relation with sustainable energy, and its application. Finite-size thermodynamics and finite-time thermodynamics represent a paradigm shift in thermodynamics, focusing on energy management by avoiding excessive losses while achieving high energy-use efficiency.[1] One method for improving energy systems involves minimizing losses by linking traditional thermal practices with advanced thermodynamic principles, as discussed in

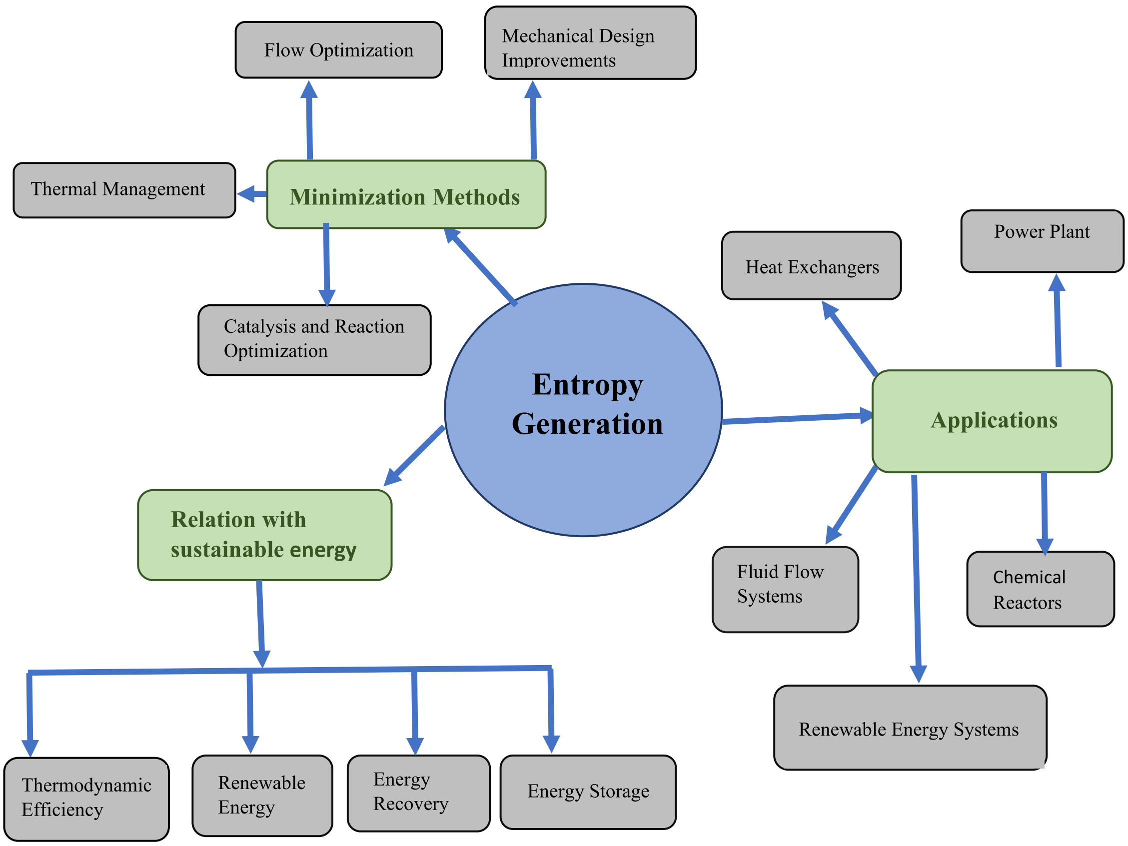

FIG. 1. Flow chart of entropy generation minimization.

Ref. 2. Adopting a rigorous approach to maintain entropy generation low significantly enhances the operational efficiency of energy systems by reducing entropy production.[3]

The goal of entropy generation minimization is to reduce energy wastage and losses. Paramount emphasis is placed on improving power systems, as discussed in Ref. 4, which includes combining entropy generation minimization with efficiency enhancement strategies. Recent work in Ref. 5 introduces a novel approach to reducing entropy production in energy systems. This study elaborates on the underlying principles, the implementation process, and various applications of the concept in promoting sustainability, with the aim of improving energy performance and quality. The paper also examines ways to reduce energy losses in industrial settings, particularly in parallel heat exchangers within heat pipelines, aiming to optimize processes and eliminate unnecessary losses.[6] In addition, it discusses the application of entropy generation minimization to improve the design of finned heat sinks, which facilitates better thermal control and significantly reduces energy wastage.[7] A detailed investigation into exergy analysis, entropy generation minimization, and flow architecture is presented in Ref. 8, offering a comprehensive perspective on these principles and their interrelation for effective thermal system design. The study further explores methods to achieve minimal entropy generation for internal flows under constant heat flux conditions, establishing the current velocity and hydraulic profile of river channels to minimize energy wastage and maximize heat transfer.[9] Research on counterflow heat exchanger geometry employs entropy generation minimization techniques to enhance thermal performance, improve energy efficiency, and reduce thermal irreversibility in the heat exchange process.[10] This approach, which contributes to sustainability, minimizes energy and waste, thereby reducing environmental impact.[11] For shell-and-tube heat exchangers, entropy generation minimization is identified as an effective design strategy. The use of genetic algorithms is highlighted as a means to further enhance thermal performance and minimize energy losses.[12] Multi-objective optimization of heat exchangers, focusing on thermal performance, cost reduction, and energy efficiency, integrates entropy generation minimization to enhance overall system sustainability.[13] Second-law analyses of absorption chillers demonstrate the importance of entropy generation in assessing system thermodynamics, identifying areas for improvement to boost productivity while minimizing environmental degradation.[14] In the thermal decomposition of methane into hydrogen, genetic algorithms are employed to optimize reaction conditions, increasing conversion, selectivity, and yield while reducing energy waste.[15] The enhancement of peripheral finned-tube evaporators using entropy generation minimization forms the basis for research in Ref. 16, focusing on reducing irreversibility in heat transfer processes. This leads to improved thermal performance and efficiency and lower energy consumption by the evaporator system. For solar heat exchangers, pseudo-optimization designs utilizing entropy generation maps provide specific improvements in thermal performance and system efficiency.[17] Entropy generation minimization is shown to be an effective method for enhancing thermodynamic processes. This method minimizes irreversibility, increases system coefficients, and improves system performance, offering a framework for evaluating thermodynamic cycles and processes.[18] Finally, the diagnosis of entropy generation in latent heat storage systems offers insights into minimizing global thermal losses and irreversibility, enabling configuration adjustments to improve thermal and overall system efficiency.[19]

This study applies entropy generation minimization to optimize the thermodynamic performance of ground heat exchangers with a single U-tube design. The primary goal is to reduce energy losses, particularly due to irreversibility, and maximize heat transfer rates, thereby enhancing efficiency and performance in geothermal applications.[20] The design and efficiency of vertical ground heat exchangers and small-scale geothermal systems require optimization to maximize energy output. This is achieved by fine-tuning heat exchanger parameters and employing effective operational control strategies to improve energy efficacy and system performance.[21,22] Sustainability assessments of biomass resource utilization, such as a case study on bioethanol production, rely on entropy production metrics. These assessments evaluate environmental and economic impacts while identifying strategies to enhance resource efficiency and minimize entropy generation.[23] A review on entropy generation analysis highlights its utility as a design tool in engineering. By evaluating entropy generation, designers can optimize systems, resulting in improved energy efficiency, reduced waste, and enhanced overall performance across diverse engineering applications.[24] The entropy generation minimization analysis of oscillating-flow regenerators examines thermodynamic performance by identifying and reducing irreversibility. This improves energy recovery and efficiency in systems such as heat exchangers and thermal energy storage.[25] A study on entropy generation minimization and its integration with multi-objective optimization for air distribution in grate coolers employs genetic algorithms. This approach enhances thermal efficiency and airflow distribution, achieving optimal performance while adhering to sustainable design principles.[26,27] In the context of conjugate heat transfer and entropy generation minimization in electroosmotic flows of non-Newtonian fluids, the study focuses on improving thermodynamic performance. It investigates methods to enhance flow dynamics and heat transfer in complex fluid systems, contributing to greater energy efficiency.[28]

An experimental investigation was conducted on the thermal characteristics of a highly concentrated parabolic trough solar collector using Cu-Therminol nanofluid.[29] The importance of entropy generation minimization in thermal optimization is notable, as it reduces irreversibility in thermal processes, thereby improving overall efficiency, enhancing energy savings, and lowering operating expenses across various applications, including power plants, refrigeration systems, and heat exchangers.[30] This study also examines the thermodynamic performance and entropy generation of a miniature loop heat pipe utilizing graphene–water nanofluid, combining theoretical modeling with experimental validation.[31] The relationship between entropy generation and energy efficiency in natural convection processes within enclosures is explored, with emphasis on practical applications.[32] Optimal sizing of renewable energy sources for community microgrids is determined using a Markov model to analyze diverse operational scenarios.[33] Strategies for minimizing entropy generation in the CO_2 hydrogenation process for light olefin production, aiming to enhance overall thermodynamic efficiency, are documented in Ref. 34. Research in Ref. 35 investigates methods to reduce entropy generation in isothermal crystallization processes by applying a generalized mass diffusion law, improving process efficiency. Advances in renewable energy and thermodynamic systems for efficiency improvements through entropy analysis and optimization are discussed in Refs. 36–40. It is predicted in Ref. 41 that non-uniform heat-generating systems can be thermodynamically optimized using entropy minimization and structural design principles. Studies in Refs. 42–45 explore entropy generation minimization and thermodynamic optimization in complex thermal systems, employing nanofluids and innovative design techniques. Entropy generation analysis and thermodynamic efficiency in fluid dynamics and renewable energy systems are highlighted in Refs. 46–48. Integrated energy and exergy analyses for sustainable polygeneration systems, as well as entropy generation minimization in immiscible fluid dynamics, have been extensively researched in Refs. 49 and 50. Studies in Refs. 51 and 52 present entropy-based decision models for sustainable clean energy selection and energy evaluation in pump turbines. Environmental regulations and solar thermal systems are explored through energy and entropy analysis, with a focus on residential buildings and technological progress.[52–54] Research in Refs. 55–57 investigates entropy-driven methods for sustainable energy systems, focusing on decision models, energy assessment, and optimization techniques. The reduction of entropy production in energy systems, including the study of MHD flow dynamics, environmental impacts, and heat and fluid flow mechanisms, is detailed in Refs. 58 and 59. Battery thermal management optimization using phase change materials and finned heat sinks, analyzed through a machine learning approach, is described in Ref. 60. Finally, solar-powered combined energy systems for sustainable electricity and freshwater production have been economically and thermodynamically optimized in Ref. 61.

An integrated analysis of energy efficiency in buildings and heat transfer systems investigates solar radiation, entropy dynamics, and optimization techniques, as described in Refs. 62–64. Understanding efficiency in thermal systems necessitates a comprehension of entropy generation, which is underscored in Ref. 65. The broad scope of entropy studies is highlighted in Ref. 66, focusing on the dual aspects of entropy generation and thermal performance. According to Refs. 67–69, the analysis incorporates diverse approaches, including numerical simulations and heat transfer studies. The study in Ref. 70 emphasizes the use of hybrid nanofluids to enhance thermal properties, specifying the type of fluid analyzed. For effective liquid hydrogen storage systems, Ref. 71 presents a theoretical analysis of entropy generation in variable-density multilayer insulations, aiming to enhance overall system efficiency and minimize energy losses. Studies in Refs. 72–74 advance the design and operation of sustainable renewable energy systems by exploring artificial neural networks to predict entropy generation in hybrid nanofluid microchannel heat sinks, energy dissipation

TABLE I. Future perspectives.

Perspectives	Actions to be taken
1. Development of an advanced model in entropy generation minimization	• Develop increasingly intricate mathematical models that take into account real-world circumstances and intricate thermodynamic cycles • Investigate machine learning methods for entropy generation prediction and optimization in diverse renewable systems
2. Including technology for entropy generation minimization	• Examine how EGM principles can be applied to innovative renewable technologies such as smart grids, energy storage systems, and hydrogen production • Examine the possibility of EGM in renewable energy hybrid systems that combine several sources (such as solar and wind)
3. Validation of entropy generation minimization techniques through experimentation	• Verify theoretical EGM models and optimization techniques in actual renewable energy installations through experimental research • Create pilot projects that apply EGM techniques and assess how they affect productivity and performance
4. Economic and policy analysis	• Examine cost–benefit analyses and the financial effects of integrating EGM techniques into renewable energy systems • Examine the legislative frameworks that support the use of EGM techniques in renewable energy initiatives
5. Evaluation of the entropy generation minimization applications' lifecycle	• To assess the environmental effects of EGM strategies in renewable energy systems and conduct thorough lifecycle assessments • Determine any possible trade-offs between material/resource consumption and energy efficiency improvements
6. Industrial collaboration	• To make it easier to implement EGM in commercial renewable energy projects and cultivate alliances with industry players • Provide training courses on EGM techniques and their advantages for engineers and practitioners
7. Education and public awareness	• Raise public awareness of EGM's significance in renewable energy through seminars, workshops, and instructional resources • Encourage multidisciplinary studies that integrate engineering, environmental science, and thermodynamics

mechanisms in two-stage vertical pumps functioning as turbines, and single-thermodynamic optimization models for central concentrating solar plants. For optimizing energy storage solutions in renewable energy applications, Ref. 75 assesses hydraulic dissipation in a reversible mixed-flow pump for micro-pumped hydro storage. The study employs entropy production theory to evaluate the pump system's performance and efficiency. Entropy analysis of unsteady magnetohydrodynamics (MHD) nanofluid flow over a stretching surface is comprehensively undertaken in Ref. 76. Studies in Refs. 77–79 delve into fossil fuel thermophoretic convective heat transfer, examining its impact on climate change and sustainability. These studies also analyze convective heat transfer and entropy generation in twisted elliptical tubes using the response surface method and conduct comprehensive sustainability assessments. In Ref. 80, researchers investigate the effects of internal heat generation, magnetism, and Joule heating on entropy generation and mixed convective flow in a square domain. This review emphasizes the concept of entropy generation minimization (EGM), highlighting its importance in developing sustainable energy systems. It discusses EGM's applications in renewable energy technologies, including solar, wind, and biomass systems. Various methodologies for EGM, such as thermodynamic analysis and optimization techniques, are outlined. The potential of EGM to enhance energy efficiency and reduce environmental impacts is explored through recent developments and case studies. Based on the literature review, the future perspectives and gaps identified in this study are summarized Table I.

CONCLUSIONS

The study emphasizes the critical role of Entropy Generation Minimization (EGM) in enhancing the sustainability and efficiency of renewable energy systems. By reviewing various EGM methods and techniques, the literature establishes that EGM is indispensable for optimizing energy systems. Renewable energy technologies can achieve improved performance, reduced energy losses, and minimized environmental impact through entropy reduction. The key takeaways from the literature review are as follows:

- **Efficiency Enhancement Through Entropy Reduction:** The efficiency of renewable energy systems is inherently constrained by entropy production. Reducing entropy is essential for maximizing system performance.
- **EGM's Environmental and Energy Benefits:** One of EGM's primary advantages is its ability to enable a shift toward significantly higher energy efficiency levels while reducing environmental impact and energy losses.
- **Diverse EGM Strategies:** The literature highlights various EGM strategies, including advanced system design methodologies, innovative materials, and optimization techniques. These approaches are pivotal in achieving energy system improvements.
- **Future Research Directions:** Future work should prioritize the development of advanced EGM models, the integration of EGM into emerging technologies, and the experimental evaluation of EGM strategies to validate their effectiveness.

By addressing these aspects, EGM can play a transformative role in advancing renewable energy systems and achieving long-term sustainability goals.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

All authors have equal work. All authors have read and agreed to the published version of the manuscript.

Hossam A. Nabwey: Conceptualization (equal); Investigation (equal); Resources (equal); Writing – original draft (equal); Writing – review & editing (equal). **Muhammad Ashraf**: Conceptualization (equal); Resources (equal); Writing – original draft (equal); Writing – review & editing (equal). **Hajra Nadeem**: Formal analysis (equal); Resources (equal); Writing – original draft (equal). **A. M. Rashad**: Conceptualization (equal); Writing – review & editing (equal). **Ali J. Chamkha**: Conceptualization (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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