Extended Abstract

An overall thermal and exergy analysis of photovoltaic thermal collectors integrated biogas plant: A modeling and experimental studies

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The excessive dependence on fossil fuels for global energy demands has led to serious environmental problems such as global warming, air pollution, and ozone depletion. Therefore, adopting standalone decentralized hybrid renewable energy systems offers a promising solution to address these energy needs while mitigating the adverse effects of fossil fuels. Integrating solar energy with biogas for slurry heating in cold climates provides an innovative approach to efficient energy use and meeting rising energy demands. This thesis involves an experimental study and modeling analysis of a hybrid system under cold climatic conditions, focusing on optimizing slurry temperature for optimal performance. The study evaluates the performance of photovoltaic thermal (PVT) and flat plate collectors (FPC) integrated with storage tanks and biogas plants using water as the removal fluid, considering both opaque (glass-to-aluminum) and semitransparent (glass-to-glass) PV modules. The research examines the performance of aluminum-based (flexible) N-PVT-TEC collectors in series and parallel configurations. An improved expression for the heat removal factor and instantaneous thermal efficiency of the n^{th} Al-based N-PVT-TEC collector in series has been derived, resembling the Hottle-Willer-Bliss equation for conventional FPC when n=1 and m=1, and $\beta=\beta tec=0$. A detailed comparative analysis of N-PVT-FPC combinations integrated with biogas plants has been conducted, considering factors like mass flow rate in the collector and digester loops, number of PVT and FPC, hot charging, and packing factor (PF) on overall thermal and exergy performance.

A thermal model has been developed to assess the performance of the n^{th} Al-based N-PVT collector integrated with a storage tank. An improved instantaneous thermal (Hottle-Williams-Bliss equation) and electrical efficiency of the solar cell for n^{th} Al/Cu PVT-M water collectors, based on energy balance and including a previously unconsidered correction factor, has also been derived. The study explores the effects of the number of PVT-M water collectors, mass flow rate, and packing factors (β) on thermal and electrical power performance. Numerical calculations reveal that the electrical efficiency of solar cells decreases and overall exergy increases with more n^{th} Al/Cu PVT-M water collectors due to the rise in solar cell/water temperature.

A concept for optimizing flexible PVT-TEC collectors in series and parallel combinations (n in series and m in parallel) for a total of N (=n×m) collectors aims to maximize overall exergy based on thermal and electrical energies. A new expression for the heat removal factor and instantaneous thermal efficiency of the n^{th} flexible PVT-TEC collector has been developed to assess its impact on performance. Numerical computations for the coldest climatic conditions in Srinagar, India, using design parameters of Al-based PVT-TEC collectors and MATLAB R2021b have been performed.

To boost biogas production in winter or cold climates, a self-sustained N-photovoltaic thermal and flat plate collector (PVT-FPC) hybrid active heating biogas plant has been analyzed for thermal and electrical energy. A general analytical expression for the thermal and electrical energy of the biogas plant, considering climatic and design parameters, has been derived from first-order coupled differential equations. Various N-PVT-FPC configurations have been optimized for maximum electrical and thermal energy gain. Mathematical computations for cold climatic conditions in India indicate that N-PVT-FPC combinations consistently outperform N-FPCPVT collectors in maximizing electrical and thermal energy.

A mathematical model for the N-PVT-FPC integrated biogas plant has been developed for thermal modeling analysis using MATLAB2021b, with experimental validation showing fair agreement between theoretical and experimental values. The correlation coefficient and root mean square percentage deviation between the experimental data were between 0.911-0.998 and 0.610-5.7%, respectively.

An economic analysis of the newly developed hybrid energy system has been conducted to assess its financial viability, cost-effectiveness, investment potential, market competitiveness, and support for sustainable development. Energy metrics such as Energy Payback Time (EPBT), Energy Production Factor (EPF), and Life Cycle Conversion Efficiency (LCCE) for the hybrid N-semi-transparent photovoltaic thermal and flat plate collector (N-sPVT-FPC) integrated biogas plant were evaluated, with the EPBT calculated at 2.74 years and the EPF at 0.3647 on an energy basis.

In conclusion, this thesis explores the innovative integration of hybrid N-semi-transparent photovoltaic thermal and flat plate collector systems with biogas plants, highlighting their potential to enhance energy efficiency and sustainability. The thorough examination of thermal and electrical performance, along with economic evaluation, confirms the viability of this approach for meeting energy needs in cold climates. The positive outcomes and significant carbon credit benefits underscore the potential of this system as a sustainable energy solution, providing a solid foundation for further research and application in renewable energy.