Abstract

Photovoltaic (PV) technology plays a critical role in the renewable energy transition by directly converting sunlight into electricity. However, traditional single-junction PV cells convert only a portion of the solar spectrum to electricity, with high-energy photons (UV and visible) generating both electrical power and excess heat, while low-energy infrared (IR) photons provide only heat; this heating is undesirable as it raises PV cell temperature and reduces efficiency. Various strategies, such as passive and active cooling have been explored to mitigate these losses. These strategies have led to the development of photovoltaic thermal (PVT) systems, which maximizes solar energy utilization by simultaneously generating electricity and usable heat from the same collector area.

Despite their potential, conventional PVT systems face performance constraints due to spectral mismatch between photovoltaic cells and the solar spectrum. This limitation restricts the electrical and thermal output of PVT systems, necessitating innovative strategies to improve solar spectrum management and overall performance. This thesis leverages spectral beam splitting (SBS) via nanofluid optical filters for this purpose.

The study begins with the design and analysis of an actively cooled PVT system to quantify annual electrical, thermal, and exergy outputs under location-specific climatic conditions. To assess the broader applicability, a detailed techno economic study is conducted for a system integrated with an absorption chiller to meet residential heating, cooling, and hot water demands. The results show that, when properly sized, the PVT system can satisfy diverse energy needs. However, widespread adoption of these hybrid systems necessitate both technological advancements and policy interventions. One such technological intervention is in improving system effectiveness by decoupling the photovoltaic and photothermal conversion processes, which is the central idea behind spectral beam splitting (SBS) approach.

To address this intrinsic thermal-electrical coupling that limits traditional PVT systems, a novel design based on SBS using nanofluid optical filtering is proposed. A coupled optical-thermal-electrical framework is developed to assess the performance of this hybrid design. This hybrid collector overcomes the inherent limitation of low-quality thermal output from traditional PVT systems, as the operational PV cell temperature no longer restricts the maximum attainable thermal output. The thesis then explores the screening, synthesis, and characterization of oxide-based nanofluids suitable for SBS in these collectors. A theoretical optical model is developed to evaluate the spectral transmittance and absorbance of these fluids, which are crucial for solar splitting practices.

Finally, a scaled photovoltaic–photothermal (PV-PT) conversion module is fabricated as a hybrid unit to test the effectiveness of the SBS. The hybrid unit combines a silicon PV module with a custom-synthesized nanofluid encasement. The encasement is fabricated using either stereolithographic (SLA) 3D-printed resin or laser-cut acrylic to house the nanofluid filter, which is tailored to match the PV module's spectral response. The unit is evaluated for its ability to generate useful heat by redirecting low-energy photons away from the PV module and utilizing their heating energy elsewhere. The experimental findings confirm the SBS effect: the PV module operates at lower temperatures, enhancing its

electrical efficiency, while the nanofluid effectively captures IR radiation for thermal energy recovery.

By actively filtering the non-electrical portion of the solar spectrum, the optimized acrylic encased PV-PT module achieved a gain of 5.65% points in total energy utilization (electrical plus thermal) compared to the electrical-only output of a standard silicon PV cell. This performance gain is achieved by incurring a manageable net electrical penalty of only 0.75% (from 6.65% bare PV to 5.9% integrated PV-PT), successfully converting otherwise wasted infrared and visible heat into useful thermal output.

Overall, this work demonstrates that SBS-enabled PVT systems, achieved through advanced optical modeling, nanofluid engineering, and system integration, can overcome the inherent spectral and thermal limitations of traditional PVT collectors. By managing the solar spectrum more effectively and decoupling the photovoltaic and photothermal conversions, the hybrid system enables higher energy yields and wider applicability. The findings pave the way for scalable, high-efficiency solar cogeneration technologies suitable for integration into distributed energy networks and hybrid renewable systems.

Keywords: Photovoltaic, Photovoltaic Thermal, Solar Spectrum, Spectral Beam Splitting, Waste Heat Recovery

*****