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A Review on Energy Harvesting Transparent Windows using Thermoelectric Generators

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ABSTRACT

The increasing demand for electrical energy and the need for sustainable building technologies have encouraged research into transparent energy-harvesting windows. Conventional solar photovoltaic panels generally require separate installation areas and may not be suitable for applications where natural daylight and visibility are important. This review examines energy-harvesting transparent windows with particular emphasis on solar-thermal energy conversion using thermoelectric generators. It discusses the operating principle of thermoelectric generators based on the Seebeck effect, solar heat collection, copper heat-transfer components, and heat-dissipation arrangements. Alternative technologies, including transparent photovoltaic systems, luminescent solar concentrators, and thermocell-based windows, are also considered for comparison. A proposed LUMINA GLASS concept is discussed, in which a transparent glass panel is integrated with copper heat-transfer pipes and thermoelectric modules positioned near the window edges to reduce obstruction of the viewing area. A microcontroller-based monitoring arrangement using voltage, current, and temperature sensors is proposed for observing the electrical and thermal parameters. The major challenges include maintaining a sufficient temperature difference, minimizing thermal losses, preserving transparency, and obtaining useful electrical output. This review identifies the potential and limitations of integrating energy-harvesting technologies into transparent building components and outlines possible directions for further development.

Keywords— Energy Harvesting, Transparent Windows, Thermoelectric Generator, Seebeck Effect, Solar Thermal Energy, Smart Buildings.

INTRODUCTION

The increasing demand for electrical energy and growing environmental concerns have encouraged the development of renewable energy technologies. Solar energy is one of the most widely available renewable energy sources and can be utilized for electricity generation in residential, commercial, and industrial applications. Conventional solar photovoltaic panels are generally installed on rooftops or open areas. However, the use of dedicated installation space and the requirement for maintaining natural daylight inside buildings create opportunities for integrating energy-harvesting technologies into transparent building components.

Transparent energy-harvesting windows are an emerging approach that combines the primary function of glass with renewable energy generation. These windows are designed to utilize incident solar radiation while maintaining sufficient visible-light transmission. Different technologies have been investigated for this purpose, including transparent photovoltaic cells, luminescent solar concentrators, and solar-thermal-electric conversion systems. Each technology has different operating principles, advantages, and limitations.

One promising approach is solar-thermal-electric conversion, in which a portion of the absorbed solar radiation is converted into heat. This thermal energy produces a temperature difference across a thermoelectric generator (TEG). Based on the Seebeck effect, the TEG converts the temperature difference directly into electrical energy. Zhang et al. demonstrated a transparent power-generating window by combining wavelength-selective solar absorption with thermoelectric conversion, showing the potential of this approach for building applications [1].

The performance of a thermoelectric energy-harvesting system depends on several factors, including the temperature difference between the hot and cold sides, thermal contact, heat-transfer efficiency, and cooling arrangements. Heat-transfer components can be used to transfer thermal energy towards the thermoelectric modules, while heat sinks help dissipate heat from the cold side. Maintaining an effective temperature difference is essential for obtaining electrical output from the system [2], [3].

LUMINA GLASS is a proposed energy-harvesting transparent window that aims to integrate transparent glass, copper heat-transfer pipes, and thermoelectric generator modules. The thermal components and TEG modules are intended to be arranged near the window edges to minimize obstruction of the central viewing area. The system also considers an electronic monitoring arrangement using a microcontroller such as ESP32 or Arduino, together with voltage, current, and temperature sensors, to measure and display the electrical and thermal parameters.

This review discusses existing research and technologies related to transparent energy-harvesting windows, thermoelectric conversion, solar-thermal energy collection, and electronic monitoring. It further examines the proposed LUMINA GLASS concept, its potential applications, technical challenges, and possible future improvements. The objective is to understand the feasibility of integrating renewable energy-harvesting technology into transparent window structures while maintaining their basic daylighting function.

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LITERATURE REVIEW

A. A. Solar-Thermal-Electric Transparent Windows

Zhang et al. [1] proposed a transparent power-generating window based on solar-thermal-electric conversion. Their system uses a wavelength-selective film that allows a significant portion of visible light to pass through while absorbing selected parts of solar radiation. The absorbed energy is converted into heat, producing a temperature difference across thermoelectric generator modules positioned along the edges of the glass. Their study demonstrated the possibility of generating electricity through a transparent window while maintaining daylight transmission. It also highlighted the importance of heat transfer, thermal insulation, and cold-side heat dissipation. This work is directly relevant to LUMINA GLASS because it demonstrates the feasibility of integrating thermoelectric modules with a window structure.

B. B. Solar Heat Pipe and Thermoelectric Hybrid Systems

Ong [2] reviewed solar, heat-pipe, and thermoelectric hybrid systems for power generation and heating applications. The study discussed solar heat collection and the transfer of thermal energy to thermoelectric modules. Heat-transfer components can move thermal energy from a collection region towards a TEG, while the TEG converts the maintained temperature difference into electrical energy. This work is relevant to the proposed design because it emphasizes the role of thermal collection and transfer. In LUMINA GLASS, copper heat-transfer pipes are proposed to transfer collected heat towards the hot side of the TEG modules. The proposed copper pipes should not be described as sealed heat pipes unless they contain a sealed working fluid.

C. C. Review of Thermoelectric Generator Technologies

Jaziri et al. [3] presented a comprehensive review of thermoelectric generator technologies, materials, and common applications. The review discussed the conversion of thermal energy into electrical energy and the factors affecting thermoelectric performance. The material properties and temperature conditions influence the performance of a TEG. The study provides background for selecting thermoelectric modules and understanding the limitations of low-temperature-difference energy harvesting. It also supports the need to consider the complete thermal system rather than selecting a TEG module in isolation.

D. D. Thermoelectric Generator Applications and Thermal Management

Ridwan et al. [4] reviewed the operating principles and applications of thermoelectric generators. TEGs generate electrical energy through the Seebeck effect when a temperature difference is maintained between their hot and cold sides. The study discusses practical applications and design considerations associated with thermoelectric generation. Thermal contact, heat transfer, heat dissipation, electrical loading, and power-management circuits influence the output. Heat sinks are important because they help remove heat from the cold side and support the temperature difference required for generation. These considerations are useful for the proposed LUMINA GLASS thermal arrangement and monitoring system.

E. E. Transparent Thermocell-Based Energy-Harvesting Windows

Lee et al. [5] developed an electricity-generating window using transparent thermocells. Their system converts a temperature difference into electrical energy using thermocell technology. The study demonstrates that thermal energy harvesting can be integrated into a window structure while retaining a degree of transparency. However, thermocells use an electrochemical conversion mechanism and are different from conventional solid-state thermoelectric generator modules. Therefore, this work is included as a related transparent-window technology for comparison rather than as a direct example of the TEG arrangement proposed in LUMINA GLASS.

F. F. Research Gap and Relevance to LUMINA GLASS

The reviewed studies demonstrate the potential of transparent windows for harvesting solar and thermal energy. Previous research has established the feasibility of solar-thermal-electric window systems, the use of thermal-transfer arrangements, and the importance of maintaining a suitable temperature difference across thermoelectric modules. However, the practical design of a compact window system requires further consideration of thermal transfer, cold-side cooling, component placement, transparency, and electrical monitoring. The proposed LUMINA GLASS concept considers a transparent glass panel integrated with copper heat-transfer pipes, TEG modules, and heat sinks. The copper components are intended to transfer collected heat towards the hot side of the TEG modules, while the heat sinks dissipate heat from the cold side. A microcontroller-based monitoring arrangement is proposed to measure temperature, voltage, and current. The project will investigate the feasibility of combining transparent window construction with solar-thermal energy harvesting for low-power applications.

WORKING PRINCIPLE AND TECHNOLOGIES

G. A. Solar Heat Collection

Solar radiation incident on the window may be partly absorbed by a suitable thermal-absorbing region or component. The absorbed radiation is converted into thermal energy. The design must balance heat absorption with the requirement to maintain daylight transmission through the transparent area. The actual absorber arrangement and its optical properties must be finalized during prototype development.

H. B. Heat Transfer Through Copper Components

Copper heat-transfer pipes are proposed to transfer thermal energy from the collection region towards the hot side of the TEG modules. Copper is commonly used in thermal applications because of its high thermal conductivity. The thermal contact between the copper components and the TEG hot side should be designed carefully to reduce contact resistance and unwanted heat loss. The term heat pipe should be used only if the component is a sealed, fluid-filled heat-transfer device.

I. C. Thermoelectric Energy Conversion

A thermoelectric generator converts a temperature difference directly into electrical energy through the Seebeck

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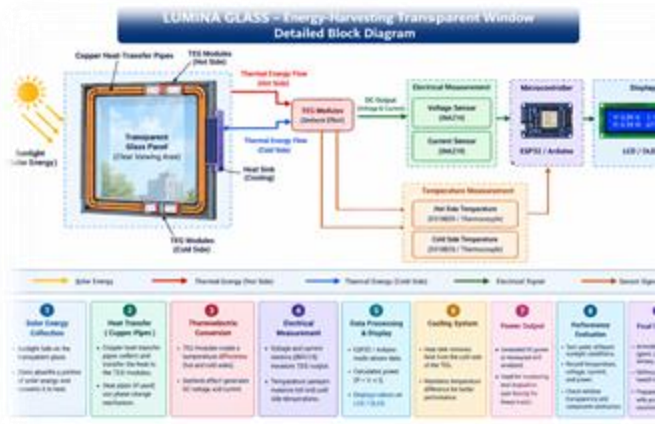
effect. When the hot side of the module is maintained at a higher temperature than the cold side, a voltage is developed across its terminals. The generated voltage depends on the temperature difference and the characteristics of the selected module. The electrical output is generally low and may require suitable power-conditioning circuitry before it can be used by an electronic load.

J. D. Cold-Side Cooling Using Heat Sinks

Heat sinks are proposed on the cold side of the TEG modules to dissipate heat to the surrounding air. Their purpose is to prevent the cold side from becoming too hot and to help maintain a temperature difference across the module. The heat-sink size, fin arrangement, airflow, ambient temperature, and mounting method can influence the thermal performance. Any fan-assisted cooling should be evaluated against its own power consumption.

K. E. Electrical Monitoring and Output Measurement

An ESP32 or Arduino-based controller may be used to monitor the system. Voltage and current measurement circuitry, such as an INA219 module where suitable for the expected electrical range, can be used to observe electrical output. Temperature sensors can measure the hot-side, cold-side, and ambient temperatures. The measured voltage and current can be used to calculate electrical power using the relation $P = V \times I$. A 16 × 2 LCD may be used to display the measured parameters. Sensor range, wiring, calibration, and electrical isolation must be checked during implementation.



PROPOSED LUMINA GLASS SYSTEM

The proposed LUMINA GLASS system is intended to integrate a transparent window panel with a solar-thermal energy-harvesting arrangement. The main elements considered in the proposed design are a transparent glass panel, copper heat-transfer pipes, thermoelectric generator modules, heat sinks, temperature sensors, voltage and current measurement circuitry, a microcontroller, and a display unit.

During operation, solar radiation falls on the window assembly and a portion of the energy is converted into heat by the selected thermal collection arrangement. The copper heat-transfer components are intended to carry this heat towards the hot side of the TEG modules. Heat sinks are placed at the cold side to dissipate heat to the surroundings. When a temperature difference is established across a TEG module, it produces an electrical voltage through the Seebeck effect. The electrical output is measured by the sensing circuit and the microcontroller displays the voltage, current, and temperature values.

The proposed arrangement aims to position the thermal components and TEG modules near the edges of the window so that the central viewing region remains as unobstructed as practicable. The design is at the proposal stage; its actual transparency, temperature difference, voltage, current, and power output must be established through prototype testing. No measured performance is claimed in this review paper.

COMPARATIVE ANALYSIS AND RESEARCH GAP

Existing transparent energy-harvesting approaches use different physical mechanisms. Transparent photovoltaic systems convert light directly into electricity, luminescent solar concentrators absorb selected wavelengths and guide emitted light towards photovoltaic cells at the edges, thermocells use temperature-dependent electrochemical processes, and solid-state TEGs convert a temperature difference into electricity through the Seebeck effect. These technologies should be distinguished because their materials, construction, output characteristics, and design requirements are different.

Technology / Study	Conversion approach	Key consideration	Relation to LUMINA GLASS
Transparent solar-thermal window [1]	Solar heat converted by edge-mounted TEGs	Visible transmission and thermal management	Directly relevant
Solar heat-pipe/TEG hybrid [2]	Thermal collection and TEG conversion	Heat transfer and temperature difference	Supports thermal design
TEG technology review [3], [4]	Seebeck-effect conversion	Module selection, thermal contact and cooling	Supports TEG implementation
Transparent thermocell window [5]	Electrochemical thermocell conversion	Transparency and temperature difference	Related technology; different from solid-state TEG
Proposed LUMINA GLASS	Copper heat transfer + solid-state TEG modules	Compact construction, cold-side cooling and monitoring	Proposed system to be evaluated experimentally

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POTENTIAL APPLICATIONS

Energy-harvesting transparent windows may be useful in buildings where window surfaces receive sunlight for a significant part of the day. Potential applications include low-power environmental sensors, building-monitoring systems, wireless sensor nodes, and selected building-automation functions. The generated energy may also be considered for charging a small storage element or supplying intermittent low-power electronics, subject to the measured output and the requirements of the load.

The proposed LUMINA GLASS concept is intended primarily for low-power applications. Its suitability for any specific application will depend on experimental measurements of voltage, current, power, operating duration, transparency, and the energy consumed by monitoring or cooling components.

CHALLENGES AND FUTURE SCOPE

L. A. Maintaining Temperature Difference

The electrical output of a TEG depends on the temperature difference between its hot and cold sides. In outdoor conditions, solar intensity, wind, ambient temperature, and shading may vary. Future work should investigate suitable heat collection and cold-side cooling arrangements under different environmental conditions.

M. B. Transparency and Window Appearance

Thermal components, pipes, modules, wiring, and heat sinks may affect the visible area, appearance, weight, and installation of the window. Their placement should minimize obstruction while maintaining adequate thermal contact and mechanical strength.

N. C. Thermal Losses and Contact Resistance

Unwanted heat loss and poor thermal contact can reduce the temperature difference across the TEG. Thermal interface materials, insulation, mechanical clamping, and careful component placement may be evaluated to improve heat transfer.

O. D. Low Electrical Output and Power Conditioning

The voltage and power produced by a small TEG arrangement may be insufficient for directly operating some electronic loads. A suitable DC-DC converter, energy-storage element, and power-management circuit may be required. Their efficiency should be included when evaluating the usable output.

P. E. Experimental Validation

Future work should fabricate a prototype and measure hot-side temperature, cold-side temperature, ambient temperature, open-circuit voltage, loaded voltage, current, and output power under controlled and outdoor conditions. Tests should be repeated at different solar intensities and operating times. The results should be compared with the energy consumed by sensors, controller, display, and any fan used for cooling.

CONCLUSION

This review has examined the potential of transparent windows as platforms for renewable energy harvesting, with particular emphasis on solar-thermal conversion using thermoelectric generators. Previous studies indicate that transparent window structures can be combined with thermal energy collection and thermoelectric modules, but the system performance depends strongly on heat transfer and the maintenance of a temperature difference. The proposed LUMINA GLASS concept considers transparent glass integrated with copper heat-transfer pipes, TEG modules, heat sinks, and a microcontroller-based monitoring arrangement. The design aims to preserve the central viewing area while investigating the possibility of generating electrical energy for low-power applications. Important challenges include maintaining the temperature difference, reducing thermal losses, preserving transparency, and managing the relatively low electrical output. Prototype fabrication and systematic testing are required to evaluate the practical feasibility and performance of the proposed system.

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