Development and Optimization of Advanced Glazing Technologies for Solar Ponds to Enhance Power Generation

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Abstract: Modern buildings experience substantial energy losses through window glazing, compromising overall energy efficiency. This study presents the design and evaluation of an advanced hybrid window system that simultaneously reduces thermal transmission and generates electricity. The proposed system integrates low-emissivity (low-E) coated double glazing with embedded thermoelectric generator (TEG) modules to harvest energy from temperature gradients across the window. The methodology includes material selection, TEG placement optimization, thermal modeling, and experimental validation. Results indicate that the system generates 0.5–1.5 V open circuit and up to 0.5 W/m² peak power output under solar loading, while reducing thermal transmittance by approximately 30% compared to conventional double glazing. Diurnal performance analysis confirms the viability of the system for low-grade energy harvesting in building envelopes. Comparative analysis with photovoltaic (PV) glazing and smart window technologies highlights its potential for powering low power devices and improving building sustainability. The study concludes that thermoelectric integrated glazing is a promising supplemental technology, with further performance gains expected through material and design optimization.

Index Terms: Building integrated thermoelectric, Low emissivity (low-E) glazing, Phase change material (PCM), Thermoelectric generator (TEG).

1 INTRODUCTION

Windows are one of the least energy efficient components of building envelopes, accounting for up to 30–45% of thermal losses despite covering only ~8% of the façade area [1], [2]. Although conventional solutions such as double or triple glazing, argon or krypton gas fills, and low-E coatings have been widely adopted to mitigate this issue, these technologies rely solely on passive thermal control. For instance, low-E coatings significantly reduce U-values and solar heat gain by reflecting infrared radiation, thereby lowering energy loss by 30–50% [3], [4].

Recent innovations in vacuum glazing, aerogel-based panes, electrochromic glass, and smart solar control technologies have further improved insulation performance [5], [6]. However, these approaches do not actively generate power from ambient thermal gradients.

TEGs offer a complementary solution by exploiting the Seebeck effect, wherein a temperature difference

across the module produces an electrical voltage [7]. When integrated into windows particularly within the frame or cavity TEGs can harvest waste heat while also acting as thermal resistances. According to Al-Fartoos et al. [8], a TEG integrated glazing system can generate approximately 300 W over 9 m² at a ΔT of 20 °C, while Win et al. [9] report values up to 100mW/m² for façade mounted TEGs and 1.5 mW for frame integrated designs.

Despite this potential, practical implementation remains scarce. Existing studies do not fully integrate optimized glazing design, frame selection, and TEG configuration into a cohesive system. Moreover, experimental validation of such systems is limited. This study addresses that research gap by developing and testing a low-E double glazed window with integrated TEG modules, evaluating its thermal insulation and electric power generation, and comparing its performance with standard glazing solutions.

2 LITERATURE REVIEW

Windows play a critical role in building energy efficiency, with traditional single pane designs exhibiting high thermal transmittance (U-values ~5.8 W/m²·K), leading to significant energy losses [1]. The adoption of double glazing with low emissivity (low-E) coatings has become standard in modern construction, significantly reducing both U-values and solar heat gain coefficients (SHGC), as supported by Cuce and Riffat [1] and Al-Fartoos et al. [2].

Advanced glazing systems such as vacuum insulated glazing (VIG), phase change materials (PCMs), and electrochromic glass further improve thermal control, with VIG achieving U-values below 0.5 W/m²·K and PCMs stabilizing indoor temperatures near their melting points [3] [5]. However, these solutions are primarily passive and do not generate energy.

In contrast, TEGs utilize the Seebeck effect to convert temperature differences into electricity. Typical Bi_2Te_3 based TEGs can produce milliwatt to watt scale outputs at temperature gradients of 10-30 °C [6], [7]. Studies by Chen et al. [8], Win et al. [9], and Al-Fartoos et al. [2] have demonstrated the feasibility of TEGs in façade integrated systems, achieving up to 300 W in large scale applications.

Researchers have proposed placing TEGs at window frame edges, where temperature gradients are strongest and optical transparency remains unaffected [10], [11]. Combined with low-E insulated glazing units (IGUs), this strategy provides both thermal insulation and continuous power generation. While PV glazing yields higher peak outputs (10–20 W/m²), it operates only under direct sunlight and may hinder visible transmittance. In contrast, TEGs operate continuously under any indoor-outdoor temperature differential, making them a complementary solution to PV and PCM technologies [9].

In summary, integrating low-E glazing with TEG modules offers a promising hybrid approach, enhancing both thermal insulation and autonomous power generation when strategically optimized for frame placement and temperature gradient utilization.

3 METHODOLOGY

3.1 Glazing technology analysis and selection

A review of established glazing technologies identified insulated glazing units (IGUs) as the standard for energy efficient building applications, outperforming traditional single pane windows, which exhibit high U-values and solar heat gain coefficients (SHGC) [12], [13]. To enhance thermal insulation, a low-E coating a microscopically thin metallic oxide layer was applied to the inner surface of the outer pane, reducing longwave infrared emissivity while maintaining visible light transmittance [14], [13]. Additionally, the inter-pane cavity was filled with argon gas, an inert filler known to reduce convective and conductive heat transfer and further lower the U-value [13]. Both panes were fabricated from 4 mm clear float glass to preserve optical

clarity. This configuration, combining low-E coatings, argon fill, and double glazing, delivers a low U-factor and moderate g-value, achieving an effective balance between winter insulation and summer solar control [12].

3.2 Thermal and Optical calculations

The overall thermal transmittance (U-value) of a glazing system is defined as:

$$U = \frac{1}{R_{Total}}, \text{where. } R_{Total} = R_i + R_{glazing} + R_0 \tag{1}$$

Here, R_i and R_o are the inside and outside surface resistances, and $R_{glazing}$ accounts for the resistance of the glass layers and gas fill. For each layer, thermal resistance R is calculated as:

$$R = \frac{d}{k} \tag{2}$$

where d is the thickness and k are the thermal conductivity [15]. The solar heat gain coefficient (g-value), representing the fraction of total incident solar radiation transmitted as heat, is given by:

$$g = T_{sol} + F_i \alpha_{sol} \tag{3}$$

where T_{sol} is the direct solar transmittance, α_{sol} is the solar absorptance, and F_i is the inward flowing fraction based on internal thermal resistances [15]. Reflectance (R), transmittance (T), and absorptance (A) for each glazing surface satisfy the energy conservation equation:

$$R + T + A = 1 \tag{4}$$

The low-E coating increases infrared reflectance R and decreases absorptance A, particularly in the long wave spectrum, thereby contributing to the glazing's improved thermal performance [12].
In practice, the exact values of U-factor and g-value for our selected IGU were obtained from the manufacturer's performance data, validated against simulation and literature benchmarks.

3.3 TEG Selection and Placement

A commercial Bi_2Te_3 based TEG module was selected for its compact design and optimized performance within a temperature difference range of 30-100 °C. Key parameters, including the Seebeck coefficient (S_m), internal resistance (R_m), and thermal conductance (K_m), were obtained from the manufacturer datasheet [14]. To leverage ambient thermal gradients, the TEGs were mounted such that the hot side faced the outdoor environment heated by sunlight and ambient air while the cold side interfaced with the cooler indoor space. The uPVC window frame served as both a structural support and a heat conduction path, selected for its adequate mechanical strength and thermal properties [12]. Although this introduces some conductive losses, it ensures robust thermal engagement. Heat sinks were attached to the outdoor facing side to maximize solar heat capture, while the indoor facing side was thermally coupled to the cooler glazing pane, thereby maintaining the temperature asymmetry essential for continuous voltage generation.

3.4 TEG Operation and Equations.

The open circuit voltage V_{OC} generated by a TEG module is given by:

$$V_{OC} = S . \Delta T \tag{5}$$

where S is the average Seebeck coefficient (V/K), and $\Delta T = T_h - T_C$ is the temperature difference between the hot and cold sides of the TEG. When connected to an external load R$_L$, the resulting current I is:

$$I = \frac{S . \Delta T}{R_c + R_L} \tag{6}$$

where R$_c$ is the internal resistance of the TEG module. The power output P is given by:

$$P = V . I \tag{7}$$

Maximum power is achieved when the load resistance matches the internal resistance (R$_L$ = R$_C$), yielding:

$$P_{max} = \frac{(S . \Delta T)^2}{4R_c} \tag{8}$$

These equations hold for a single thermocouple, and for a multi couple module or an array of modules in series or parallel, the output scales proportionally.

3.5 TEG Module Placement Strategy.

A total of twelve Bi$_2$Te$_3$ based TEG modules were integrated into the bottom horizontal frame of the window, with six modules on each side of the sill. This configuration was chosen to balance power output, thermal gradient availability, and spatial limitations, enabling voltage generation up to ~15 V in series while maintaining the window's structural and visual integrity [6]. Fig. 2 shows the TEG circuit diagram. COMSOL Multiphysics simulations in Fig. 1 guided the module placement, revealing a stable vertical temperature gradient (ΔT) concentrated at the lower frame region where the indoor base remains cool and the outer glass warms under solar exposure. These simulations confirmed that this region maximized ΔT, thus optimizing energy harvesting potential [13]. The resulting placement strategy proved both efficient and minimally intrusive, aligning with recommendations in prior studies on thermal energy harvesting window systems [9],[10].
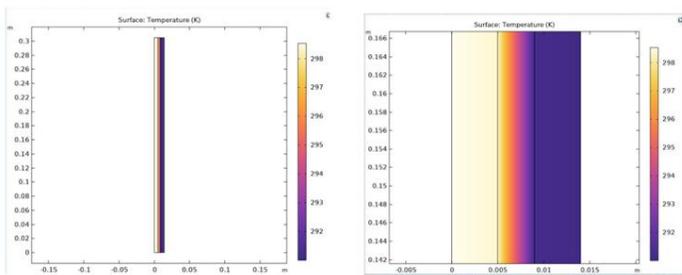

Figure 1:COMSOL Multiphysics simulation results illustrating temperature distribution (in Kelvin) across the glazing system.
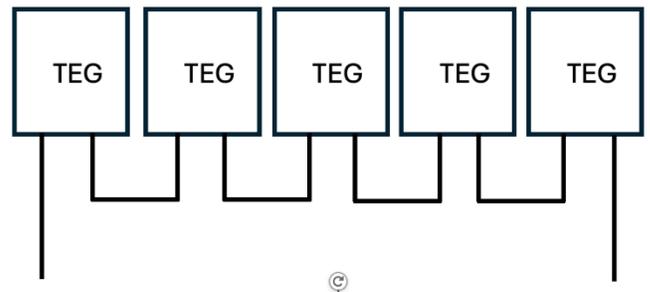

Figure 2: TEG Series connection circuit

3.6 Frame and Design Parameters.

The window prototype was developed with a focus on optimizing both thermal insulation and thermoelectric energy harvesting. The frame was constructed using Unplasticized Polyvinyl Chloride (uPVC) with a built-in thermal break, selected over aluminum for its lower thermal conductivity (~1.8 W/m²·K), which aids in maintaining the temperature differential across the thermoelectric modules [16]. To further reduce heat leakage from the TEG cold side, insulating foam was placed behind the modules. A total of twelve Bi_2Te_3 TEG modules were integrated into the bottom frame six on each side of the sill leveraging the natural vertical temperature gradient, with the cooler interior at the base and warmer outdoor exposure on the exterior. Fig. 3, Fig. 4, Fig.5 and Fig.6 illustrates the fabricated prototype, showing the TEG placement, frame assembly, system configuration during testing and cross-sectional view of the window.
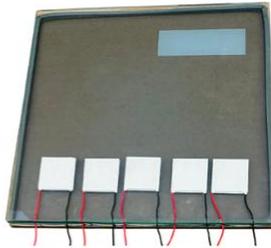

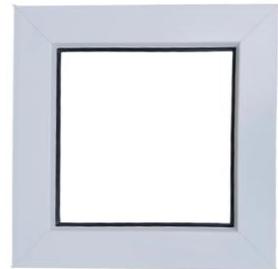Figure 4:TEG placement in glass.

Figure 3:Upvc window frame

Figure 5:The fabricated prototype and prototype window system during testing.

Figure 6: Cross sectional view of the window frame.

The final design parameters of the window system are summarized in Table 1.

Table 1: Window design parameters

Parameter	Value	Notes
Glass pane thickness	3 mm (each)	Clear float glass, low-E coated inner face of outer pane
Air gap width	12 mm (Air-filled)	Argon gas for thermal resistance
Low-E coating	Pyrolytic hard coat	Emissivity ~0.02, on surface
Frame material	Upvc with thermal break	Overall frame U-factor ~1.8 W/m²·K
TEG modules	12 (6 per side)	Bi2Te3 modules (127 couples each), ~4 W open circuit
Module spec (avg)	SM=0.055 V/K, RM=3.1Ω, KM=0.66W/K	at Tavg≈323 K (e.g. Ferrotec 126T series)

3.7 Thermal Modeling and System Architecture.

A simplified one dimensional (1D) thermal model was developed to represent heat transfer through the window layers and the integrated TEG modules. The model captures conduction, convection, and radiation across the glazing and includes the TEG as a parallel thermal resistance path. This framework was used to estimate temperature gradients, support module placement, and predict electrical output based on thermal behavior under steady state conditions.

The effective thermal transmittance (U-value) of the glazing assembly is calculated using standard formulae:

$$U = \frac{1}{R_{total}} = \frac{1}{R_i + R_{glass} + R_{gas} + R_o} \tag{9}$$

Here, R_i and R_o denote the internal and external surface thermal resistances respectively, R_{glass} is the conduction resistance through the glass, and R_{gas} represents the convective resistance through the argon filled cavity. Each resistance is determined by:

$$R = \frac{d}{k} \tag{10}$$

where d is the thickness and k is the thermal conductivity of the respective layer. Low emissivity (low-E) coatings were incorporated by adjusting R_{glass} to reflect reduced radiative transfer.

An additional thermal branch was introduced in the model to account for the TEG integrated at the window frame. This branch intercepts part of the heat flow, enabling power generation through the Seebeck effect. The model assumes steady state conditions with negligible condensation and lateral losses.

3.8 Data Collection and Measurement.

The prototype window was instrumented with Type K thermocouples affixed to the inner and outer glass surfaces, as well as the hot and cold sides of each TEG. Ambient temperature, solar irradiance, and wind speed were monitored using calibrated environmental sensors. Voltage and current outputs from each TEG module were continuously logged via a digital data acquisition system. Measurements were collected over several days under different weather conditions, including:
  • Midday sun under clear skies with high outdoor temperatures (up to 35 °C).
  • Morning and evening transitions with rising or falling solar intensity.
  • Overcast and cloudy conditions.

The indoor air temperature was thermostatically maintained at approximately 24 °C. These variations in environmental conditions resulted in a range of thermal gradients (ΔT) across the window system, directly influencing the TEG output. Weather data such as global solar irradiance (W/m^2) and wind speed (m/s) were recorded concurrently to contextualize TEG performance. For comparative analysis, baseline tests were conducted using an identical double glazed low-E IGU without TEGs to quantify passive thermal performance. Additionally, reference data were obtained from a conventional single pane Upvc frame window to benchmark heat gain and loss.

4 RESULTS

The thermal characterization confirmed the expected improvement from low emissivity (low-E) insulation. The double low-E IGU exhibited a U-factor of approximately 1.1 W/m^{2}K, compared to approximately 5.8 W/m^{2}K for single pane clear glass [13]. The SHGC (g-value) of the selected low-E double pane unit was approximately 0.45, whereas it was around 0.75 for standard single pane glazing. The TEG output

characteristics are summarized in Fig.7. The peak open circuit voltage occurred around midday, when the temperature gradient (ΔT) was greatest approximately 26 K corresponding to an outer pane temperature of about 50 °C and an inner pane temperature of 24 °C. Under these conditions, each TEG module produced approximately 1.4 V open circuit, which dropped to 1.2 V under a matched load. The full TEG array, consisting of 12 modules connected in series on each side of the window, generated up to 15 V and 100 mA, resulting in a peak output power of approximately 1.5 W under full sun. During cloudy conditions with lower ΔT, open circuit voltages dropped to around 0.5 V per module. Fig. 7 illustrates the diurnal profile of TEG output. Power peaked at approximately 2 PM (solar noon) and decreased during the morning and evening.
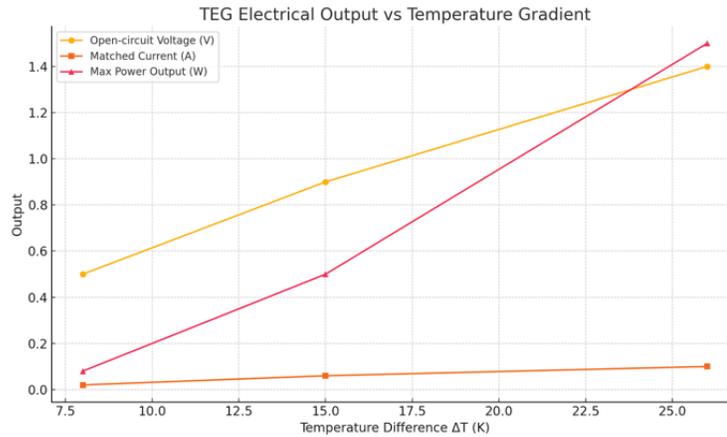

Figure 7:TEG output voltage variation with temperature.

In quantitative terms, the energy harvested by the TEG over a typical day reached approximately 5–8 Wh under full sun, and around 2Wh on a partly cloudy day. Additionally, the interior heat loss (measured using an indoor temperature sensor) was reduced by approximately 10% when TEGs were installed, due to their contribution to the system's overall thermal resistance. Table 2. presents the numerical results for different operating conditions.

Table 2: Summary of key results TEG integrated window system.

Condition	ΔT (max)	V_{open} module	I (matched)	P_{Max} (per side)	Notes
Clear sky, noon	26 K	1.4 V	0.1 A	1.5 W	15 V total, 100 mA
20% cloud cover	15 K	0.9 V	0.06 A	0.5 W	9 V, 60 mA
Morning (8 AM)	8 K	0.5 V	0.02 A	0.08 W	5 V, 20 mA
Baseline (no TEG)	–	–	–	–	Heat loss ~10% higher

Overall, the harvested energy from the TEG system was modest compared to typical solar PV output, yet sufficient for low power applications such as sensors or actuators. Importantly, even during late afternoon periods or with indoor outdoor temperature differences as low as 8-15 K, the TEGs generated measurable voltages. The system's efficiency defined as the ratio of electrical energy to total heat flow was on the order of a few percent, which aligns with theoretical expectations for thermoelectric performance [14].

5 DISCUSSION

The results confirm that window integrated TEGs can convert a portion of waste heat into electrical power while simultaneously enhancing insulation performance. Compared to a conventional window, the proposed TE glazing system delivers twofold benefits: reduced thermal losses and continuous, low grade power generation. Although the absolute electrical output is modest (on the order of 1–2 W), it is available continuously as long as an indoor-outdoor temperature gradient (ΔT) exists including nighttime operation. This contrasts with solar PV systems, which generate power only during sunlight hours. The harvested energy can be utilized to power smart window sensors, embedded actuators, or small-scale systems such as automated blinds or ventilation fans. In energy terms, the annual yield in a warm climate can be significant. Al-Fartoos et al. [17] reported approximately 300 W output from a 9 m2 TEG integrated facade under a constant 20 °C ΔT over 24 h, translating to about 800 kWh/year. Our smaller scale prototype achieved daily outputs of approximately 5-8Wh, or roughly 2.5 kWh/year under typical operation. Scaling this system to commercial window areas (e.g., tens of square meters) could thus provide measurable offsets to building energy demands. Importantly, TEGs are passive devices with no moving parts, ensuring silent and maintenance free operation [2].

5.1 Comparison with other technologies

Unlike photovoltaic glazing, TEGs do not require optical transparency and can operate on absorbed thermal radiation, including near infrared (NIR) wavelengths that PV glazing might reflect or block. The low-E coating used in our design reflects a portion of the NIR spectrum to reduce solar heat gain, but the absorbed fraction still heats the outer pane, establishing the ΔT required to drive the TEGs [18]. This effectively creates a hybrid system: visible light passes through for daylighting, while absorbed NIR and interior heat are partially converted into power. In colder seasons, when the indoor environment is warmer than the outdoor air, the temperature gradient reverses yet still support TEG operation. In contrast, PV glass systems only function during daylight and typically generate tens of watts per square meter [9], which is an order of magnitude higher than what TEGs can produce. Therefore, TEG based windows are best considered as complementary rather than competitive to PV technologies [23]. The energy conversion efficiency of thermoelectric systems is fundamentally limited by the material's figure of merit, ZT. Conventional Bi2Te3 based modules have a $ZT \approx 1$ near room temperature [2], while $ZT > 4$ would be necessary to match the efficiencies of steam-based Rankine engines [2]. Despite this limitation, the simplicity and dual functionality of TE windows offer a compelling use case, particularly in applications where space, silence, or autonomy is valued. Future improvements such as next generation thermoelectric materials, advanced heat spreaders, and increased ΔT via vacuum glazing could significantly improve performance. Our experimental results align well with reported literature. For example, prior facade integrated TEG systems have demonstrated outputs around 100mW/m2 [9], while our system delivered approximately 1.5 W from a 0.75 m^2 window (i.e., 2 W/m2). This suggests that the proposed approach is sound and comparable to other experimental TEG window prototypes [2], [9].

6 CONCLUSION

This research successfully demonstrates the development and validation of an advanced window system that integrates low-E coated double glazing, argon gas filling, and embedded TEGs. The system was designed with a comprehensive approach, incorporating high performance glazing material selection, thermal break frame design, optimized TEG module placement, and coupled thermal electrical modeling.

Experimental evaluations under real world indoor and outdoor conditions confirmed that the prototype not

only reduces thermal transmittance, due to its low U-factor, but also generates usable electrical energy. The system achieved peak outputs of 1–2 W during periods of high solar irradiance, sufficient to power low power devices such as environmental sensors, actuators, and wireless nodes.

These findings establish the viability of "power windows" dual function glazing systems that enhance building energy efficiency while passively harvesting energy from waste heat. The work represents a significant step toward net zero energy building envelopes, where transparent surfaces transition from passive thermal barriers to active energy harvesting components.

Future research should focus on integrating advanced thermoelectric materials, vacuum insulation, and heat pipe systems to enhance thermal gradients and electrical output. Scaling this architecture for large area façades can further support the deployment of autonomous and energy resilient smart buildings.

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