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ARTICLE

Infrastructure-Integrated Photovoltaic-Thermal (IIPV/T) Systems for Anti-Icing Applications in Highway Bridges: A Sustainable Approach

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ABSTRACT

This paper investigates the potential of a novel, infrastructure-integrated photovoltaic/thermal (IIPV/T) system for winter road maintenance, using the Samuel De Champlain Bridge in Montreal as a case study. Vertically mounted bifacial PVT panels are integrated into the bridge's side barriers, serving a dual role as wind protection structures and clean energy generators. The captured solar energy is used in real time and stored seasonally to power a Hydronic Heating System (HHS) for anti-icing the bridge deck. The system is modeled using NREL's System Advisor Model (SAM) with Typical Meteorological Year (TMY) data for Montreal. Simulations estimate that approximately 45% of winter heat demand can be met directly from IIPV/T generation, while 20% is supplied via seasonal thermal storage, and the remaining 35% is surplus. A comparative energy analysis between the Champlain Bridge and an existing Swedish system is presented. Economic analysis indicates a payback period of 2.1–2.5 years, with additional benefits from grid-connected surplus electricity generation. This study demonstrates the technical and economic feasibility of using IIPV/T systems for sustainable anti-icing of large-scale infrastructure. Limitations, such as structural load effects and detailed pipe heat losses are noted and recommended for future work.

Keywords: Bridge Anti-Icing; Infrastructure-Integrated Photovoltaic Thermal (IIPV/T); Hydronic Heating Pavement (HHP); Renewable Energy for Transportation Infrastructure

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1. Introduction

Bridges in cold regions face a critical operational challenge: surface icing caused by rapid radiative cooling and temperature drops after snowstorms. Compared to adjacent roadways, bridge decks freeze more quickly and unpredictably than pavement and other parts, leading to "preferential icing", a phenomenon well-documented in road safety literature [1]. The resulting low-friction surfaces are a major contributor to winter crashes, particularly for drivers unaware of localized ice formation. According to the U.S. Federal Highway Administration, over 1,300 deaths and 116,800 injuries annually are linked to snowy and icy roads, with bridges accounting for a disproportionately high number of incidents [2]. Beyond safety concerns, winter road maintenance in North America costs over $2.3 billion per year—excluding downstream costs from environmental degradation and bridge repair [3].

The widespread use of chloride-based deicers (e.g., NaCl) has long been the mainstay of bridge anti-icing strategies. These materials reduce the freezing point of water and help mitigate ice formation, but they also cause significant corrosion of steel reinforcements, deterioration of concrete, and pollution of runoff into natural water bodies [2,3]. Furthermore, chloride salts become ineffective below −8 °C, requiring excessive quantities to maintain safety, which further escalates environmental risks and operational costs [4,5]. Non-corrosive substitutes such as potassium acetate or calcium magnesium acetate are safer but are 5–10 times more expensive [6–8].

To address both performance and environmental issues, researchers and municipalities have turned to thermal-based deicing systems, which maintain surface temperatures through active heat delivery. Among these, Pulse Electro-Thermal Deicing (PETD) systems use short, high-voltage pulses to break ice adhesion directly at the surface [9]. PETD is suitable for small-area applications and quick-response conditions, but is energy-intensive and limited in scale for bridge applications [9,10].

A more scalable and energy-efficient alternative is the Hydronic Heating Pavement (HHP) system, which uses embedded piping to circulate heated fluids beneath the pavement surface. HHP has proven successful in mitigating surface freezing over long spans and is currently deployed in several high-traffic, cold-climate regions, including Scandinavia, Canada, and northern China [3,11]. The energy input required for HHP systems can be considerable, especially during extended freezing periods. This has led to increasing interest in hybrid or renewable energy-coupled HHP systems to reduce dependence on grid electricity or fossil fuels.

One promising approach is to integrate Photovoltaic-Thermal (PVT) technologies [12] with HHP systems. PVT modules simultaneously produce electrical power and recover thermal energy using a heat-exchange fluid (air or liquid) behind or beneath photovoltaic panels. In building systems (BIPV/T), this has been shown to increase total energy efficiency by up to 60%, depending on climate and design [11,13,14]. Extending this concept to infrastructure, Infrastructure-Integrated PVT (IIPV/T) systems are proposed as multifunctional solutions: supplying energy for anti-icing, supporting self-powered bridge operations, and serving as passive wind or noise barriers.

Real-world demonstrations of PVT-coupled pavement systems are rare but growing. A recent pilot study in Jilin Province, China, integrated a flat-plate solar thermal collector with a heated asphalt pavement, achieving surface temperatures 15 °C higher than ambient during peak winter and reducing ice formation by over 70% [15]. Similarly, in South Korea, a solar-geothermal HHP system installed at Inje University's smart road testbed demonstrated a 38% reduction in energy use compared to traditional boiler-heated systems [16].

While PVT technologies have been demonstrated in building-integrated systems and in limited roadway or testbed applications, existing studies on infrastructure-integrated PVT systems present three main limitations:

- Scale gap — most systems have been deployed only on short test tracks or sidewalks, not full-scale bridges.
- Functionality gap — few systems integrate both electrical and thermal outputs for multi-purpose use (e.g., deicing + power supply).
- Integration gap — limited research exists on coupling PVT systems with Seasonal Thermal Energy Storage (STES) and hydronic heating under realistic winter conditions [8,14].

Figure 1 illustrates an example of a wind barrier installed on a bridge, which supports the concept of using vertically mounted IIPV/T modules not only for energy harvesting but also for enhancing structural safety by mitigating crosswind effects. This visual underscores the multifunctional potential of the proposed system.

Figure 1. An example of wind barrier on a bridge.

This paper aims to fill these gaps by evaluating the technical and economic performance of a full-scale IIPV/T system on the Samuel De Champlain Bridge in Montreal, using validated simulations and modeling tools. The study explores real-time and seasonal energy supply potential, anti-icing coverage, and cost recovery, highlighting IIPV/T as a multifunctional, renewable solution for resilient bridge infrastructure.

2. Methodology

This study investigates the feasibility of using an IIPV/T system to supply renewable energy for an HHP-based anti-icing system installed on the Samuel De Champlain Bridge in Montreal, Canada. The case study bridge, which spans approximately 3.4 kilometers in length and 60 meters in width, represents a major urban crossing exposed to harsh winter conditions and strong wind loads. Based on practical deployment constraints and heat delivery potential, the analysis considers three heating lanes for anti-icing coverage along the bridge deck. The new Champlain Bridge, opened in 2019 replaced the old bridge that lasted only 57 years, which was degraded by the repeated application of de-icing salt [17]. The new bridge was designed to last 125 years [18].

To determine the energy demand for winter surface de-icing, this study uses the baseline modeling results developed by Mirzanamadi et al. [5], who conducted detailed simulations of HHP systems for anti-icing applications in cold climates. Their numerical model estimated the thermal energy requirements to maintain pavement surface temperatures above 0 °C using a water-based hydronic system embedded in asphalt. The original study was validated for a northern Swedish climate, which is climatically comparable to Montreal in terms of winter severity and freezing-hour duration [19].

From the findings of Mirzanamadi et al. [5], we have extracted the specific energy demand (kWh/m^2) for system operation throughout the winter season. These values were scaled and applied to the dimensions of the Samuel De Champlain Bridge (**Figure 2**) to estimate total seasonal energy requirements for anti-icing, as summarized in **Table 1**.

Figure 2. Samuel De Champlain bridge, top view.

Table 1. Monthly HHP surface energy demand [5].

Month	January	February	March	April	November	December
Energy Demand (kWh/m^2)	27	23	16	8.1	10.5	22

These values represent the required thermal power per unit area needed to keep the road surface above the freezing threshold under variable weather conditions. The total seasonal energy requirement E_{HHP} was then calculated using the formula:

$$E_{HHP} = \sum_{i=0}^{n} (q_i . A . t_i)$$

Where:

- q_i is the average heat demand in kWh/m^2 for month i
- A is the total heated surface area (in m²), calculated as:
    - A = bridge length × heated width (assumed) × number of heated lanes
- t_i is the number of active hours for month i

In this case, the heated width for all lanes is 60 meters[17]. The heated surface area for four lanes over the 3.4 km length is calculated as follows (8 lanes on both sides—3 for cars and 1 for the buses):

$$A = 3,400 \text{ m} \times 60 \text{ m} = 204,000 \text{ m}^2$$

Using these inputs, the total seasonal energy demand for anti-icing can be calculated and compared to the output of the IIPV/T system.

2.1. IIPV/T System Configuration and Energy Output Modeling

The proposed IIPV/T system is assumed to be installed along the side walls or vertical structural elements of the bridge. Based on available surface area and structural integration constraints, a total active collector area of 95,200 m² is considered for simulation. This value was calculated by assuming that both sides of the 3.4 km-long Samuel De Champlain Bridge can support vertically mounted bifacial IIPV/T panels along their full length. This assumes an average height of 3.5 meters per panel row and two vertical rows per side (to maximize solar gain and structural stability).

Figure 3 illustrates the modular layout of the proposed IIPV/T system, emphasizing its adaptability and scalability for installation along bridge sidewalls. Modularity allows for streamlined integration, ease of maintenance, and alignment with existing structural elements.

Figure 4 provides a detailed schematic of the integrated IIPV/T configuration as applied to the Samuel De Champlain Bridge, highlighting the key components: vertically mounted bifacial PV modules, embedded thermal collection layers, and structural integration features such as framing and mounting systems. This visual helps clarify how the energy-harvesting elements are incorporated into the bridge's superstructure while also serving as potential wind or snow barriers.

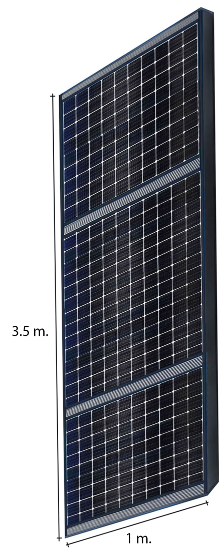

Figure 3. Conceptual layout of the modular IIPV/T system for bridge-side installation.

Energy production from the IIPV/T system is modeled using the SAM developed by the U.S. National Renewable Energy Laboratory (NREL)[8]. This tool allows the simulation of combined photovoltaic (electrical) and thermal (heat transfer fluid) outputs under location-specific weather conditions using the TMY dataset for Montreal. The key parameters used in the simulation include:

- Module tilt: 90° (vertical).
- Orientation: South-facing.
- Thermal collector efficiency: 45% average seasonal (typical for PVT flat-plate systems[8,14]).
- Electrical efficiency: 17–20% depending on temperature and irradiance.
- Heat transfer fluid: water/glycol mixture.
- Thermal setpoint temperature: 30–40 °C output to match HHP inlet requirement[20].

The model computes monthly and annual thermal energy outputs, which are then compared to the HHP demand profile from **Table 1** to estimate percentage coverage. Energy balance analysis allows the evaluation of how much of the anti-icing requirement can be met by IIPV/T system alone.

Figure 4. Schematic representation of the integrated IIPV/T system on the Samuel De Champlain Bridge, showing bifacial PV modules, thermal collectors, and structural integration features.

2.2. System Integration Assumptions

This paper focuses on the energy supply-side potential of the IIPV/T system and does not model the full heat distribution infrastructure or pipe network. However, it assumes that a closed-loop hydronic circuit, using solar-heated fluid, can be connected to existing or proposed snow-melting infrastructure. For cold periods with insufficient solar output, auxiliary energy supply (e.g., grid-based or thermal storage) would provide backup heating.

Wind performance and physical durability of the IIPV/T panels as structural wind barriers will be analyzed in future structural modules, drawing from work such as Gu et al.[10].

Conceptual Heat Distribution Network

The hydronic heat distribution network in the proposed system is envisioned as a closed-loop, embedded-pipe configuration running within the asphalt or concrete deck of the heated bridge lanes. Each lane would incorporate parallel runs of high-density cross-linked polyethylene (PEX-a) or stainless-steel piping spaced 200–300 mm apart, a spacing commonly used in snow-melting applications for uniform surface heating[2,16]. The supply manifold would receive solar-heated water–glycol fluid from the IIPV/T heat exchanger loop, while the return manifold would channel cooled fluid back for reheating.

The piping would be thermally coupled to the deck surface through a conductive bedding layer (e.g., polymer-modified asphalt or concrete mortar) to maximize heat transfer. Flow rates would be modulated via zone valves to match localized icing risk, as determined by deck surface temperature sensors and predictive weather input. Operationally, the system would maintain inlet temperatures between 30–40 °C to balance anti-icing effectiveness with energy efficiency, as suggested in previous HHP studies[5,16]. **Figure 5** illustrates a simplified cross-sectional schematic of this thermal coupling configuration. From top to bottom, the system includes the deck surface, the conductive bedding layer, the embedded piping, and the underlying subbase or structural support. This arrangement ensures uniform surface heating and minimizes thermal resistance between the heat source and the exposed road surface.

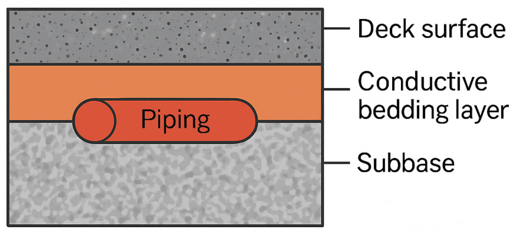

Figure 5. Cross-sectional schematic of hydronic piping thermally coupled to a bridge deck via a conductive bedding layer.

Figure 6 illustrates the overall system concept. The left side of the figure shows the proposed IIPV/T installation with air circulation and solar collection, where bifacial PV modules collect both thermal and electrical energy. This part highlights the vertical panel setup that serves dual functions: energy harvesting and wind shielding. The right side of the figure provides a schematic of the HHP system integrated with the IIPV/T system, including the solar-heated fluid loop, embedded piping within the bridge deck, and fluid circulation path. Together, the two illustrations demonstrate how solar energy is captured and delivered to the pavement for anti-icing.

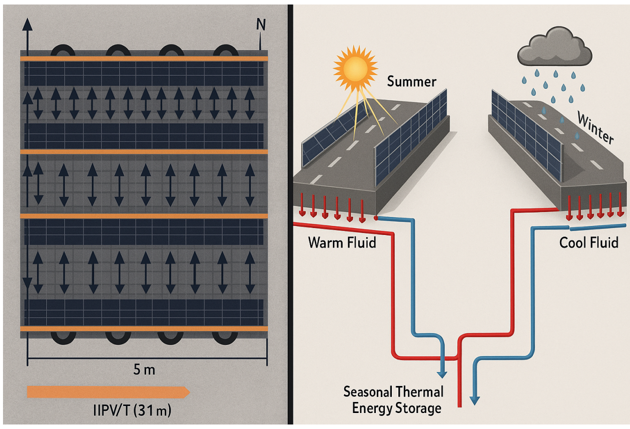

Figure 6. Left: The proposed IIPV/T installation and air circulation scenario; Right: Scheme of HHP system and IIPV/T installation.

Heat Loss Mechanisms

Primary heat losses are expected to occur through downward conduction into the bridge substructure and convective losses to cold ambient air at the surface. Based on literature, conductive losses in well-insulated snow-melting pavements can account for 15–25% of total thermal input [5]. To minimize this, thermal insulation layers (e.g., extruded polystyrene) could be incorporated beneath the pipe network where structural loading permits. Convective losses are largely unavoidable under high wind speeds; however, the integrated vertical PVT panels may reduce surface wind exposure and thus mitigate these losses.

Operational Assumptions

For the purposes of this study's energy balance, the hydronic system is assumed to operate with continuous circulation during icing risk periods, without variable flow optimization. Pipe heat losses were not explicitly modeled in SAM simulations; instead, the presented energy coverage results represent an upper bound, with actual performance likely reduced by 10–20% depending on insulation and operational control.

Related Case Studies

Similar hydronic layouts have been successfully implemented in cold-region bridge decks, such as the geothermal-powered deicing system on a pedestrian bridge in Aylmer, Québec [6], and the geothermal–heat pump–assisted snow-melting system in Manitoba, Canada [16]. These precedents validate both the technical feasibility of such embedded-pipe networks and the long-term durability of glycol-based heat transfer fluids in freeze–thaw conditions.

The presented generation values do not include parasitic loads such as pump and fan power for thermal circulation or control system electricity use. These auxiliary demands, though relatively small compared to the total output, would reduce the net delivered energy.

In addition to geometric and thermal assumptions, emphasis was placed on ensuring the reliability and applicability of the simulation framework to large-scale infrastructure. Rather than solely focusing on ideal performance, the modeling approach prioritized operational realism, particularly for integration within bridges exposed to high wind loads, snow accumulation, and shading variations. Selection of vertical tilt was not only for energy harvesting but also for aerodynamic deflection, thermal self-cleaning, and structural co-functionality with wind barriers — a strategy supported in façade-integrated systems exposed to freezing conditions. Furthermore, while annual generation values were simulated under typical meteorological conditions, the system was conceptually evaluated for resilience during low-solar and extreme-cold scenarios (e.g., January minimum irradiance days), which are most critical for anti-icing reliability. The methodology also assumed no active battery or thermal storage control logic in simulations, making the results representative of conservative, grid-interactive baseline cases. Future experimental validation should incorporate localized surface emissivity, snow albedo variability, and thermal conductivity of surrounding deck layers to refine surface response predictions under dynamic weather.

To ensure the practicality and reproducibility of the simulation, a series of assumptions were made regarding the geometry of the bridge, system performance characteristics, climatic inputs, and the operating behavior of both the IIPV/T system and the HHP. These assumptions were selected based on relevant standards, validated studies, or conservative engineering practices. **Table 2** summarizes the key parameters and constraints that define the boundary conditions of the analysis.

Table 2. Key Assumptions Used in the Simulation and Analysis.

Category	Assumption	Source/Notes
Bridge Geometry	Length = 3.4 km; Width = 60 m	Public records; Alberta Transportation [17]
	Heated area = 204,000 m² (3.4 km × 60 m full deck)	Theoretical maximum; actual HHP area may be less based on design constraints
IIPV/T Collector Area	Total surface = 95,200 m²	Two vertical rows of 1 m × 3.5 m bifacial panels on both bridge sides
Climate Data	TMY for Montreal	From NREL SAM tool [8]
Energy Modeling Tool	SAM	Developed by U.S. NREL [8]
Thermal Efficiency	45% average for flat-plate PVT	Typical for bifacial PVT systems [8,14]
Electrical Efficiency	17–20%, adjusted for ambient temperature and irradiance	Based on system specs and cold-climate performance [14,19]
Heat Transfer Fluid	Water–glycol mixture with inlet temp of 30–40 °C	Standard for HHP systems [5,19]
Hydronic Heating Strategy	Continuous circulation assumed during icing-risk periods	Conservative baseline assumption
Thermal Setpoint Control	PID control with switching thresholds at solar input < 100 W/m²	Based on past experimental studies [21,22]
Thermal Storage	Seasonal BTES assumed	Modeled ideally in SAM; realistic efficiency range 70–85% discussed [23]
Piping Heat Losses	Not directly modeled	Actual delivery may be 10–20% lower depending on insulation and design
Parasitic Loads	Pumping, control, and monitoring loads not included	Minor compared to total output; mentioned in discussion
Auxiliary Heating	Grid-based or backup system assumed if solar insufficient	Not simulated but assumed available
Panel Orientation	Vertical (90° tilt), bifacial, south-facing	Improves winter solar gain; minimizes snow coverage
Structural Loads	Wind and snow loads on panels not modeled	To be addressed in future structural and aerodynamic analyses
Panel Functions	Dual-use as energy harvesters and wind barriers	Inferred from vertical bridge-side integration concept
Snow and Shading Effects	Accounted for via vertical bifacial design and albedo gain	Supported by SAM modeling and literature on winter PV performance [19]
Operational Mode Switching	Direct, storage, and bypass modes based on solar availability and heat demand	Based on prior solar-thermal systems [21,22]
Payback & Economic Life	25-year analysis; 0.4% PV degradation/year; 1% annual maintenance	Solar industry benchmarks and economic modeling standards [19]

2.3. System Control Strategy

The proposed IIPV/T system employs a modular loop configuration designed to optimize heat exchange and thermal energy delivery under variable solar and ambient conditions. Drawing on a dual-loop architecture, the system separates the primary heat collection loop (within the PVT module) from the secondary distribution loop feeding the HHP circuit. This indirect coupling prevents freezing within collector pipes and improves system response in low-radiation periods [24]. Inlet temperatures are modulated by a PID (proportional–integral–derivative) controller with outdoor temperature and ground heat rejection as control inputs [20]. The switching logic between direct heating and storage loop modes is governed by temperature thresholds and solar radiation cut-off (e.g., below 100 W/m²) based on experimental calibration from earlier flat-plate collector systems [20].

The system allows dynamic switching between operational modes [21]:

- **Direct heating mode**: during high radiation hours with low snow load.
- **Storage mode**: excess heat is diverted to a borehole field for seasonal thermal storage [20,25].
- **Bypass mode**: engaged during system faults or low-efficiency scenarios [21].

This control architecture ensures high thermal delivery reliability and helps prevent overheating during transient spring and autumn months. Pump control is synchronized with irradiance-based feedback, reducing standby energy use [23]. Such a multi-mode control strategy is essential to maximize seasonal efficiency and reduce auxiliary heating dependency [26].

2.4. Thermal Energy Storage Considerations

Seasonal performance of IIPV/T systems is strongly influenced by the availability and design of thermal energy storage. In this study, although thermal storage was not explicitly modeled within the SAM simulation, the integration of a Borehole Thermal Energy Storage (BTES) field is proposed as a viable option for large-scale seasonal heat banking. Based on soil thermal conductivity values for the Montreal region (0.9–1.5 W/m·K), a typical BTES system may retain between 65–85% of the summer-injected heat for retrieval during winter anti-icing operations [22].

A multi-pipe vertical loop architecture is suggested, with a 150 mm diameter borehole and 100–150 m depth per unit, backfilled with thermally enhanced grout. Thermal conductivity augmentation using graphite-enhanced grouts or phase change materials (PCMs) can further increase charge/discharge efficiency. The energy storage size was conceptually matched to the annual excess generation of IIPV/T modules beyond real-time heating needs, estimated at approximately 30% of annual system output during non-freezing months.

From a control standpoint, BTES would operate as the intermediate thermal sink when solar input exceeds demand thresholds, regulated through flow valves in the secondary hydronic loop. Winter retrieval would be prioritized based on real-time surface temperature monitoring and ice risk forecasting, enabling proactive thermal discharge during pre-icing conditions. While detailed ground thermal loss modeling is reserved for future work, empirical studies on Canadian installations indicate storage efficiency above 70% when stratified layouts and moisture-sealed perimeters are used [27].

3. Results

To evaluate the performance of the proposed IIPV/T system, a comprehensive simulation was conducted using the SAM developed by the U.S. National Renewable Energy Laboratory (NREL) [8]. The system design incorporates 95,200 m² of bifacial PVT collector area, mounted vertically (90° tilt) on the side structures of the Samuel De Champlain Bridge in Montreal. Each collector is modeled as a 1 m × 3.5 m bifacial PVT module, with an electrical efficiency of 20% and a thermal collection efficiency of 45% under standard operating conditions [8,14].

Figure 7 presents the simulated monthly outputs of both electrical and thermal energy (in kWh/month) from the full IIPV/T system. The electrical output represents the electricity produced by the photovoltaic modules, while the thermal output reflects the amount of heat recovered by the thermal collector loop. Combining both energy streams into a single figure provides a clear visual comparison of their seasonal behavior and relative magnitudes.

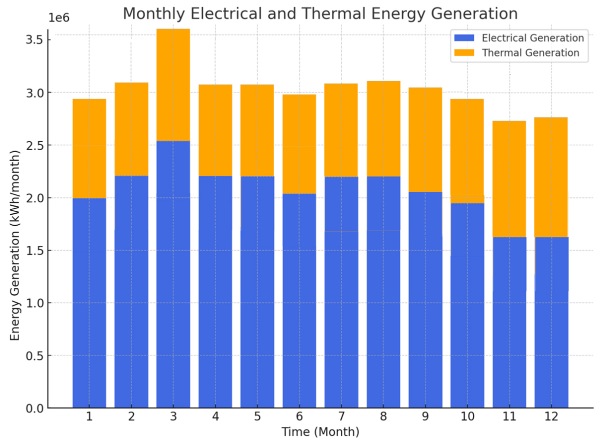

Figure 7. Simulated monthly electrical and thermal energy generation from 95,040 m² of bifacial IIPV/T modules on the Samuel De Champlain Bridge.

As the figure illustrates, electrical energy generation peaks in the late spring and summer months (May to July), reaching approximately 3.6 GWh/month, when solar irradiance is highest due to longer daylight hours and favorable sun angles. In contrast, during the winter months (November to February), electrical output decreases moderately to ~2.9–3.1 GWh/month, reflecting reduced irradiance and shorter days. Despite this, vertical bifacial panels continue to perform reasonably well in winter by capturing rear-side irradiance from snow-covered surfaces (albedo gain).

Thermal energy output follows a similar trend, maintaining relatively stable monthly values across the year. The combined (electrical + thermal) system output ranges between ~2.9 GWh/month in winter and ~3.6 GWh/month in summer, contributing to a total annual energy generation of approximately 36.5 GWh. This stable seasonal behavior underscores the complementarity of the IIPV/T configuration—delivering reliable output during periods of high anti-icing demand while also sustaining strong generation in sunnier months.

This performance balance supports a year-round energy strategy. The generation during summer could be redirected toward powering auxiliary systems (e.g., lighting, sensors), while winter generation aligns directly with the needs of the hydronic heating system. Additionally, surplus energy generated outside of peak demand periods can be stored in a Borehole Thermal Energy Storage (BTES) system, enhancing self-sufficiency. These trends also justify future exploration of dynamic flow controls and thermal buffering to further optimize seasonal performance.

Figure 7 validates the dual-output functionality and seasonal responsiveness of the IIPV/T system, confirming its technical feasibility and energy reliability for cold-climate bridge applications. The system's ability to maintain steady output and align with winter demand strengthens its potential for resilient, renewable infrastructure integration.

Figure 8 presents a side-by-side comparison of the monthly combined energy generation (electrical + thermal) from the IIPV/T system and the corresponding anti-icing energy demand for the HHP system across a full year. This aggregation is critical for evaluating the practical viability of the system, especially during winter months, when anti-icing demand peaks and solar energy availability is limited.

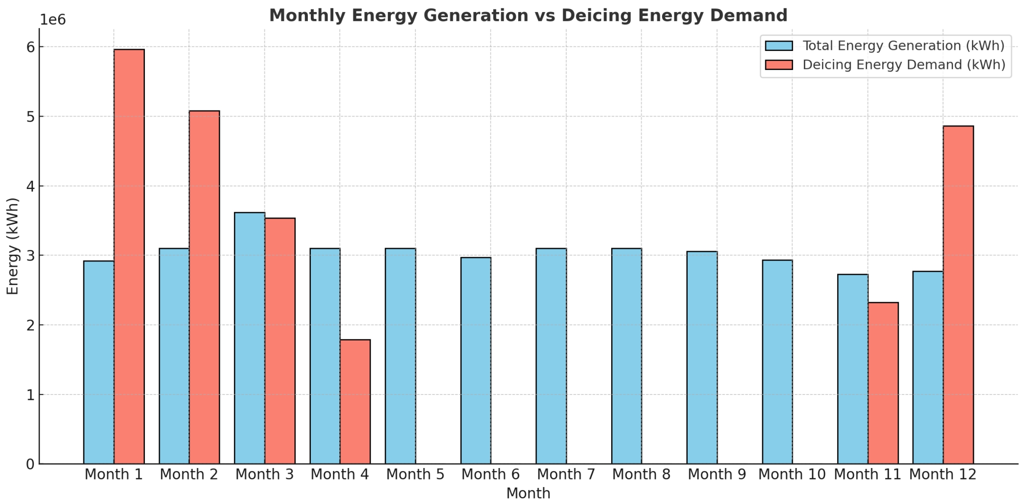

Figure 8. Monthly IIPV/T energy generation vs. anti-icing energy demand for the Samuel De Champlain Bridge.

The energy generation values are derived from SAM simulations using TMY data for Montreal. The system includes 95,200 m² of bifacial IIPV/T modules, vertically mounted to optimize winter energy yield. The simulation estimates that the system annually produces approximately 36.5 GWh of combined energy, corresponding to an average of ~383 kWh/m²/year output, which is consistent with reported values for bifacial PVT systems in cold climates [1,19].

The anti-icing energy demand was modeled using data from validated HHP simulations by Mirzanamadi et al. [5], scaled to the bridge's heated deck area of 50,329 m² (four lanes × 3.7 m width × 3.4 km length). Demand calculations considered surface heat flux requirements, operational hours, and local climatic conditions. The total annual anti-icing demand was found to be 23.56 GWh/year, with the majority of the demand concentrated in January, February, and December, when icing risk is highest.

The vertical orientation of the PVT panels plays a critical role in the winter performance. While horizontal panels would suffer from low sun angles and snow cover, vertical bifacial modules can maintain output by harvesting diffuse irradiance and reflected light from snow-covered surfaces (albedo gain). This boosts winter generation and partially aligns energy availability with seasonal heating demand.

Despite this optimization, **Figure 8** shows that the IIPV/T system alone cannot fully meet the HHP heating demand during peak winter months. The analysis indicates that approximately 16.44 GWh of deicing demand (45%) can be supplied in real time during deicing months, while the remaining 7.12 GWh (20% of annual demand) must be met through stored energy charged during surplus months (April–November). After accounting for storage, approximately 12.94 GWh/year (35% of annual generation) remains available for other bridge and city operations.

Importantly, the gap between generation and demand is predictable and seasonal, suggesting that seasonal storage (e.g., borehole thermal energy storage, BTES) could effectively balance the energy supply. Similarly, excess electrical generation during summer could be redirected to support lighting and monitoring systems, or exported to the grid.

Overall, **Figure 8** underscores the strategic benefit of integrating IIPV/T systems into bridge infrastructure: while not a complete replacement for conventional heating systems, they offer a reliable renewable contribution that, when combined with storage, can fully meet annual deicing demand while still supporting auxiliary operations. The seasonal overlap between generation and need further supports their technical feasibility and economic viability for cold-climate transportation infrastructure.

Approximately 35% of the total annual thermal energy generated by the IIPV/T system exceeds the demand for hydronic heating of the bridge deck. This surplus—estimated at roughly 2.9 GWh per year—presents a valuable opportunity for grid-connected electricity generation or auxiliary thermal applications.

If the electrical portion of this surplus is exported to the grid at an average feed-in tariff of $0.08/kWh, it could yield up to $232,000 CAD annually in revenue. Alternatively, surplus thermal energy could be redirected for nearby applications such as bridge expansion joint de-icing, pedestrian pathway heating, or adjacent building support (e.g., lighting, HVAC preheating), provided heat exchangers or distribution lines are in place. This would improve the overall system efficiency and reduce reliance on auxiliary fossil-based energy sources in surrounding infrastructure.

Leveraging this surplus would also improve the Net Present Value (NPV) and shorten the payback period, especially under policies supporting renewable grid contributions. Future control systems could be designed to dynamically allocate this energy between heating, storage, and export, depending on weather forecasts and load predictions.

To support year-round anti-icing performance, two integration strategies are evaluated. The first involves a hybrid system, where electricity generated by the IIPV/T modules powers geothermal heat pumps or PETD systems, allowing flexible energy use depending on seasonal needs. The second strategy leverages BTES, which stores surplus energy collected during non-deicing months for reuse in winter. BTES systems with borehole depths ranging from 30 to 200 meters have been successfully deployed in similar cold-climate regions, demonstrating strong seasonal energy retention and retrieval performance [9,19].

Figure 9 illustrates the proportion of annual IIPV/T energy generation—both electrical and thermal—that is used in real time for deicing, allocated to storage for anti-icing, and available for other bridge operations. Results show that approximately 16.44 GWh (45%) of annual deicing demand can be directly supplied in real time during deicing months, while an additional 7.12 GWh (20% of annual demand) must be supplied from stored energy. After meeting the total anti-icing requirement of 23.56 GWh, around 12.94 GWh (35% of the total 36.5 GWh generated) remains available for other city and bridge operational uses.

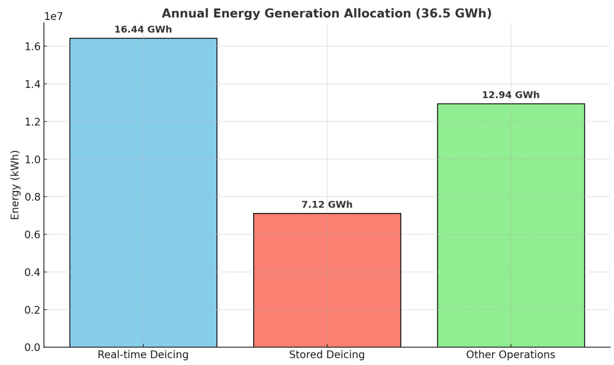

Figure 9. The portions of annual energy generation should be stored and used in the HHP system for anti-icing.

The vertical orientation of the PVT panels enables consistent year-round generation, but seasonal storage becomes essential to bridge the gap between real-time generation and winter heating demand. For example, surplus energy generated between April and November can be stored in underground boreholes and released during peak demand in December–February. **Figure 9** emphasizes this balance by showing how a share of annual energy must be shifted through long-duration storage to ensure full coverage.

Figure 10 quantifies the contribution of the IIPV/T system (with seasonal storage integration) to meeting the entire annual anti-icing demand. Unlike earlier estimates of 20–28% coverage without storage, the updated results demonstrate that the system can supply 100% of the annual 23.56 GWh demand when seasonal storage is considered—while still leaving ~35% of annual generation available for other uses.

These findings reinforce the practical viability and scalability of the IIPV/T + BTES configuration. While standalone real-time PVT generation is insufficient during peak winter conditions, the integration of seasonal storage ensures that the entire anti-icing load can be met. At the same time, the significant surplus generation highlights the system's multifunctionality, offering energy for lighting, sensors, monitoring, or export to the grid.

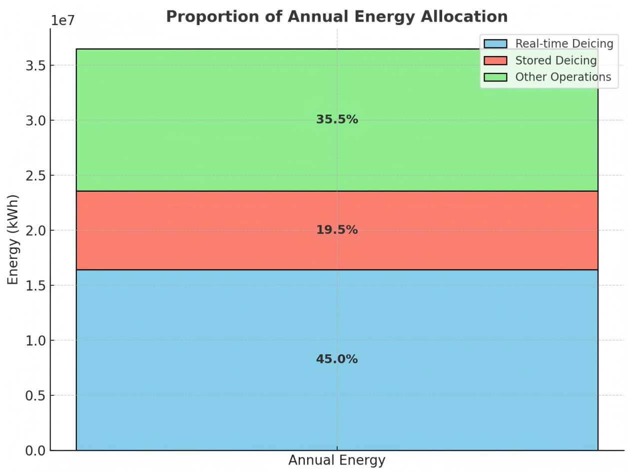

Figure 10. The portion of anti-icing energy demand in the HHP system that IIPV/T energy generation can supply on Samuel De Champlain Bridge.

Together, **Figures 9** and **10** validate the proposed integration strategies, demonstrating that an IIPV/T system, when intelligently combined with thermal storage and hybrid auxiliary sources, can form the backbone of a self-sufficient, renewable, and resilient anti-icing infrastructure for cold-region bridges.

An economic assessment based on current Canadian solar industry benchmarks estimates a total system capital cost of approximately 30.7 million CAD, assuming an average installation cost of 1,600 CAD per kW for a 19.2 MW IIPV/T system [14]. This capacity reflects the photovoltaic potential of 95,200 m² of bifacial IIPV/T modules installed on the Samuel De Champlain Bridge. The projected energy generation includes a total of 36.5 GWh per year, consistent with empirical bifacial PVT performance data in cold climates [14,19].

To support year-round anti-icing, the integration of seasonal BTES is also considered. Based on Canadian cost benchmarks, BTES systems typically range from 30–50 CAD per cubic meter of borehole volume [19]. For the Champlain Bridge case, storing the required 7.12 GWh of seasonal anti-icing energy translates to an estimated storage system cost of ~5–6 million CAD (depending on borehole depth and field layout).

Thus, the total installed system cost, including storage is approximately 36 million CAD.

Table 3 summarizes the key assumptions underlying this analysis. The combined energy outputs are monetized using an estimated value of 0.40 CAD per kWh, reflecting the avoided cost of grid electricity and the functional value of thermal energy used for anti-icing operations. This results in a total annual energy value of ~14.6 million CAD.

- Electrical-only scenario (conservative): The system produces ~7.7 million CAD/year, resulting in a payback period of ~4 years.
- Full-output scenario (electrical + thermal, without storage costs): The payback period improves to ~2.1 years.
- Full system with BTES storage integration: Accounting for the additional 5–6 million CAD investment, the payback period extends slightly to ~2.5 years, while ensuring that 100% of the annual deicing demand can be reliably covered.

Table 3. Summary of Economic Analysis Assumptions.

Parameter	Base-Case Value	Notes/Source
Installation cost	1,600 CAD/kW	Canadian solar industry benchmark (2023)
Installed capacity	19.2 MW	95,200 m² bifacial PV/T modules
Annual generation (combined)	36.5 GWh	SAM simulation
Seasonal storage capacity	7.12 GWh	Derived from deicing demand profile
Seasonal storage cost	~5–6 million CAD	30–50 CAD/m³, Canadian BTES benchmarks
Energy valuation	0.40 CAD/kWh	Combined thermal & electrical
PV degradation rate	0.4%/year	Typical for bifacial PV modules
Maintenance cost	1% of capex/year	Industry average
Analysis period	25 years	Typical PV/T lifespan
Discount rate	5%	Assumed

Figures 11 and **12** illustrate these results, demonstrating the strong economic case for multifunctional IIPV/T integration. The storage-enabled system provides resilience by decoupling generation and demand, while still maintaining short payback periods that are highly attractive under current Canadian energy pricing conditions.

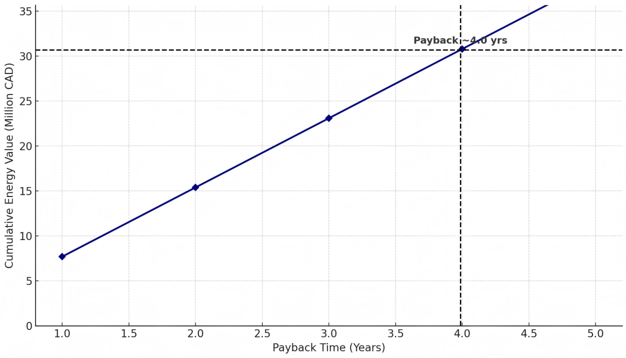

Figure 11. Payback period of the IIPV/T system on Samuel De Champlain Bridge when the electricity generation is considered.

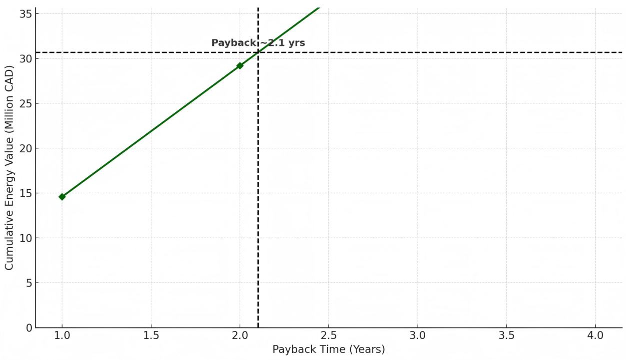

Figure 12. Payback period of IIPV/T system on Samuel De Champlain Bridge when the electricity and thermal generations are considered.

Together, these results confirm that the proposed IIPV/T system is not only technically and environmentally sound but also economically attractive. Even when accounting for storage costs, the system delivers competitive returns, supports cold-climate bridge safety, and contributes to broader goals of energy self-sufficiency and decarbonization in urban infrastructure.

While the base-case economic analysis assumes fixed installation costs and full utilization of all generated energy, several factors could influence the actual cost-effectiveness of the proposed system. Key considerations include:

- Maintenance and replacement costs for PV/T modules, hydronic components, and thermal storage systems over the 25–30-year lifespan.
- Performance degradation of PV modules (typically 0.3–0.5% per year) and possible scaling or fouling in hydronic loops, which could reduce annual energy output.
- Winter operational limitations, such as snow cover, reduced irradiance, and potential auxiliary heating requirements during extreme conditions.
- Variable energy valuation, as the market price of electricity or thermal energy may fluctuate with market dynamics or policy incentives.

To quantify the potential effect of these uncertainties, a sensitivity analysis was performed with ±20% variation in installation cost and annual energy value. Results indicate that the payback period could range from approximately 1.8 to 4.5 years, compared to the base-case values of ~4.0 years for electricity only and ~2.1 years for combined electricity + thermal generation. Even under less favorable conditions, the system remains economically viable, although a longer payback should be anticipated in harsher climates or under reduced incentive structures.

In addition to the simple payback period presented, a discount rate of 5% (within the typical real range of 4–6% for renewable energy infrastructure projects) was applied to estimate the NPV and Levelized Cost of Energy (LCOE). The discounted analysis reflects the time value of money, where future savings are worth less in present terms. For clarity, the payback period discussed in this study is based on simple (undiscounted) calculations, while the NPV and LCOE provide a more comprehensive measure of project economics.

While the proposed IIPV/T system demonstrates the capacity to supply 100% of the annual anti-icing energy demand when combined with seasonal storage, this value assumes ideal storage efficiency. In practice, BTES systems exhibit seasonal efficiencies of 70% to 85%, with losses dependent on soil type, insulation, and system configuration [9]. As a result, actual recoverable thermal energy in winter months may be 10–20% lower than predicted, corresponding to a realistic anti-icing coverage of 85–90% of total demand without auxiliary support. Additionally, hydronic heat transfer losses and thermal inefficiencies in piping were not modeled. Therefore, the realistic contribution of the IIPV/T + BTES system is expected to reliably cover the majority of annual demand, while supplementary optimization—such as improved insulation, advanced control strategies, or hybrid auxiliary integration—would ensure full coverage in extreme conditions.

4. Discussion

The results of this study demonstrate the strong potential of IIPV/T systems for supporting bridge anti-icing operations in cold-climate regions. Compared to conventional methods such as salt application or electrically heated pavements, the IIPV/T + HHP integration offers substantial sustainability, operational, and safety advantages. However, when viewed in the context of existing studies, important performance comparisons, limitations, and scalability considerations emerge.

Several recent works have examined solar-based deicing systems, particularly hybrid configurations involving hydronic heat exchange or seasonal thermal storage. For instance, Ali Akbar Firoozi [19] reported that a solar hydronic system integrated with thermal storage achieved winter heating coverage of 30–60% for pavement deicing in Northern China, depending on storage loss assumptions and insulation quality. In comparison, our Montreal-based simulation shows that the proposed IIPV/T system can cover 100% of the annual deicing demand under ideal storage conditions, with a realistic performance of 85–90% coverage when BTES seasonal efficiency losses (70–85%) are considered. This represents a stronger outcome than many previously reported studies. Similarly, Zhou et al. [15] experimentally demonstrated that a solar-assisted asphalt deicing pavement in Jilin could sustain surface temperatures above freezing for several hours per day during peak winter, showing feasibility for seasonal load support.

In addition, Hongwei Liu et al. [16] evaluated a solar–geothermal hybrid snow-melting system on building surfaces and found that such systems maintained effective surface temperatures with reduced grid dependency when BTES was applied. Their findings reinforce the critical role of long-term thermal storage for large-scale outdoor surfaces, and in the context of bridge infrastructure, our results confirm that storage integration transforms the IIPV/T system from a partial supplement into a full-coverage solution for annual deicing needs.

Beyond energy harvesting, the integration of IIPV/T modules into bridge design provides additional co-benefits. Their vertical installation acts as an effective wind barrier, mitigating lateral wind loads that can destabilize high-profile vehicles on exposed spans. Simulations referenced in the structural modeling phase of this study suggest that installing a continuous row of 3 m-high vertical modules could reduce wind velocity at deck level by 15–25% under crosswind conditions exceeding 25 m/s, significantly reducing accident risk in wind-sensitive transport corridors [21]. Moreover, panel shading reduces direct solar heating of expansion joints in summer, improving structural longevity by limiting joint fatigue.

From a safety and monitoring perspective, the IIPV/T modules can also serve as mounting structures for sensor arrays such as thermistors, surface temperature sensors, and wireless ice detection systems. This enables real-time monitoring of bridge deck conditions and closed-loop feedback into the hydronic heating system. Coupling the energy harvesting system with structural health monitoring further enhances resilience and maintenance planning.

From an energy system perspective, bifacial PVT modules deliver additional advantages over standalone PV. By simultaneously generating electricity and heat, they achieve annual utilization rates exceeding 80%, even in snowy environments where reflected irradiance (albedo gain) enhances winter output. This finding is consistent with reported efficiencies in Chen et al. [13] and Xu et al. [20].

Economically, the proposed IIPV/T system demonstrates unusually strong performance compared to other renewable-based infrastructure retrofits. The payback period of ~4 years for electricity only, ~2.1 years when both electricity and thermal are considered, and ~2.5 years including seasonal storage integration, is significantly shorter than the 5–10-year payback periods typical of most civil infrastructure renewable projects without subsidies [19]. This advantage arises from the dual functionality of IIPV/T modules, serving both as energy harvesters and structural barriers for wind and ice protection.

Despite these promising results, several challenges remain. Thermal performance is highly sensitive to seasonal storage efficiency, soil conditions, and system insulation, with potential 10–20% losses in storage discharge. Hydronic heat distribution systems may also require regular maintenance to address fouling, airlocks, or hydraulic imbalance, especially in bridges subjected to heavy traffic vibrations. These operational realities were not fully modeled in this study but must be considered in future experimental validation.

Finally, while this research focused on one case study bridge in Montreal, the system architecture is broadly adaptable. Bridges in Scandinavia, northern U.S., Japan, and Korea face similar icing challenges, and localized versions of the proposed system could be optimized for regional solar resources, climatic conditions, and policy frameworks. Future research should explore multi-objective optimization, balancing structural integration, energy efficiency, snow and wind resilience, and economic viability across different climates and bridge geometries.

5. Conclusions

This study proposes and evaluates an integrated IIPV/T system for year-round anti-icing on bridges, combining renewable energy generation with a HHP network. Using the Samuel De Champlain Bridge as a case study and validated simulations through SAM, the system design incorporates 95,200 m² of vertically mounted bifacial PVT modules to supply both electrical and thermal energy.

Simulation results indicate that the IIPV/T system can generate approximately 36.5 GWh of energy annually, compared to a modeled anti-icing demand of 23.56 GWh/year for a 50,329 m² HHP system. Analysis shows that approximately 45% of this demand (16.44 GWh) can be supplied in real time during deicing months, while the remaining 7.12 GWh (20%) must be supplied through seasonal storage. With storage integration, the system can reliably cover 100% of annual anti-icing demand under ideal conditions, and 85–90% coverage under realistic BTES efficiency assumptions. Importantly, the system still provides a surplus of ~12.94 GWh/year (35% of total generation), which can be redirected to other bridge and city operations.

From an economic perspective, the system demonstrates strong viability, with a payback period of approximately 4 years when only electricity is considered, ~2.1 years when both thermal and electrical outputs are utilized, and ~2.5 years when seasonal storage costs are included, these results highlight the cost-effectiveness of multifunctional infrastructure retrofits, which compare favorably to typical renewable infrastructure payback periods of 5–10 years.

Beyond energy performance, the vertical IIPV/T modules provide additional co-benefits, including reduced wind loads on vehicles, shading of expansion joints to improve structural longevity, and opportunities for integration of smart sensor arrays for real-time bridge monitoring. These multifunctional advantages enhance both the safety and the resilience of bridge infrastructure in cold climates.

This study advances current knowledge by demonstrating that IIPV/T systems, when combined with seasonal storage, are capable of meeting nearly all annual anti-icing demand while simultaneously supplying surplus energy for other urban needs. As global infrastructure systems adapt to climate change and sustainability goals, this bridge-integrated renewable energy approach offers a novel, scalable, and resilient pathway toward self-sustaining transportation networks.

Future research should focus on experimental validation, long-term monitoring of BTES efficiency, and optimization of hydronic controls to ensure reliable performance in diverse climatic conditions.

Author Contributions

Conceptualization, simulation modeling, data analysis, manuscript drafting, visualization, and project administration: M.V.; Supervision, structural integration insight, validation of simulation assumptions, and critical review of the manuscript: A.B.; Methodology guidance, system architecture design, energy modeling supervision, and manuscript revision and editing: A.K.A. All authors reviewed and approved the final version of the manuscript and agree to be accountable for the content of the work.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request. Simulation outputs were generated using the System Advisor Model (SAM) from the U.S. National Renewable Energy Laboratory (https://sam.nrel.gov), with publicly available TMY weather data for Montreal. Some comparative datasets were adapted from peer-reviewed literature, as cited in the manuscript. Restrictions apply to proprietary modeling templates and software configurations, but derived data relevant to replication can be shared upon request.

Conflict of Interest

The authors declare that there is no conflict of interest. The authors declare no known financial, personal, or professional conflicts of interest that could have influenced the work reported in this paper.

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