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IoT-Enabled Self-Monitoring Polymer Composites for Solar Facade Systems with Cloud-Based Thermal Analytics

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Abstract

The increasing demand for intelligent and energy-efficient building systems has hastened the production of smart solar facade systems. This paper presents an IoT-based self-monitoring polymer composite system, which includes thermal analytics running on the cloud to provide real-time assessments of the performance of the facade. The artificial composite panel has sensing capability built in which the material is able to measure both surface and internal thermal behavior simultaneously in dynamic environmental conditions. To assure the reliability of the experiment, a hybrid real-world data-set that integrates on-site and confirmed meteorological data were used. The system uses edge-based preprocessing, and cloud-based analytics to extract important thermal features, such as temperature gradients and response rates, and then detects anomalies in a composite scoring system. The experimental results showed that the system has a detection of 94.8% and 1.8-minutes response time, which is better than the traditional systems of IoT-based monitoring. The composite possesses a stable thermoresistive and thermal conductivity which is a testimony to its use in integrated sensing. The suggested framework will provide one of the potential solutions to these problems as it will combine the material-level intelligence with the system-level monitoring, which will facilitate gaining a better understanding of thermal, detect faults as soon as possible, and minimize the reliance on external sensors. The findings reveal what could be accomplished with self-observation composites to develop more next generation smart facades and sustainable building infrastructures.

Keywords: IoT-enabled monitoring, polymer composites, solar façade systems, thermal analytics, anomaly detection

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INTRODUCTION

Polymer composites have increasingly switched over to more traditional structural materials to smart, multifunctional materials that can sense, adapt and respond to environmental stimuli. These materials are now anticipated to do additional roles than mechanical support, including thermal regulators, structural supports and sensing interfaces concurrently in the realms of building-integrated photovoltaics (BIPV), specifically in solar facade systems. Through the application of the fiber-reinforced polymer matrices where a conductive filler is incorporated in the polymer matrices, nanomaterials and sensor networks, it can now be used to produce self-monitoring composites that will be able to record real time operational information once they are subjected to dynamic environmental conditions [1, 2].

The solar facade construction with polymer composites has the advantages of light weight construction, corrosion resistance as well as adjustable thermal performance. Nevertheless, the photovoltaic panels at the facade are subject to the changes in irradiance, ambient temperature differences and local heating. The factors add thermal stresses which can decrease the polymer matrix and the photovoltaic efficiency with time [3, 4]. The latest developments in the area of IoT-based sensing architectures have provided opportunities to incorporate distributed monitoring functions into the composite layers and enable the evaluation of thermal behavior and structural integrity at all times [5].

In line with this material development, cloud-based analytics, have become one of the most vital facilitators of mass data interpretation. Using edge-cloud architectures, embedded sensors can be used to transmit thermal data in real time, because it can be processed and analyzed. These systems enable predictive maintenance approaches and help to optimize the energy consumption in intelligent building facilities [6, 7]. However, IoT, polymer composite and cloud analytics integration is in its infancy, especially when it comes to solar facades.

Although there has been an increased interest in smart composites, there are a number of challenges in the development of reliable, scalable and energy efficient self-monitoring systems. Traditional polymer composites in facade built-in PV solutions do not have internal sensing features, which results in the need to use external sensors. These external systems have a tendency of not recording local thermal variations in the composite layers and hence incomplete diagnostics and delayed fault detection [8].

The other weakness is due to thermal incompatibility between the polymer matrices and photovoltaic elements. The sustained exposure to intense solar irradiance also causes uneven distribution of heat that hasten the process of material degradation and decrease the system life span on the whole [9, 10]. Current thermal management techniques are mostly passive, i.e. they use the choice of materials or the structure of the buildings instead of the active monitoring and control.

On a system-level, the integration of IoT brings with it even more complexity. Sensor data streams are high-dimensional and dynamic in time, and are often heterogeneous. With no effective data processing frameworks, the information is not used effectively. Additionally, any latency in centralized systems may also impede the real-time making of decisions, especially when deploying a large scale solar facade [11, 12].

Cloud-based solutions, being a promising solution, have issues of data security, scalability, and synchronization between the edge devices and centralized servers. Lack of coherent structures that integrate material level sensing with cloud-based analytics limits the implemented practice of intelligent composite systems [13]. As a result, there is a dire lack of material innovation and system implementation of smart solar facade technologies.

This paper aims to overcome these limitations, so an IoT-enabled self-monitoring polymer composite framework is proposed to be used with solar facade systems and combined with thermal analytics on clouds. The methodology starts at the material level whereby conductive nanofillers and embedded micro sensors are added to the polymer matrix to facilitate intrinsic sensing properties. These are sensors that are capable of detecting temperature differences, heat flux differences, and local thermal differences within the composite structure [14, 15].

The proposed framework uses a distributed IoT architecture on the system level. The sensor data is preprocessed by edge nodes which are embedded in the panels of the facade to reduce dimensionality and noise. Preprocessing step such as this might provide an adequate transfer of information with no trade off of useful thermal attributes. This unstructured data is then sent to a cloud server to which a smart analytics has been trained to observe real-time, isolate anomalies and forecasts [16].

The thermal analytics module of cloud is based on the machine learning approaches to detect trends in thermal behavior when exposed to different environmental conditions. It will also be able to predict the failure points, and optimize the performance of the energy using sensor data compared to external data of the solar irradiance and ambient temperature. Besides, the structure is capable of supporting a two-way communication and can be misused to control the adaptive methods of control like the dynamic ventilation or shading variations [17, 18].

It is not only the kind of single approach that results in the enhanced reliability of polymer composites, but also to their dynamism in the form of smart energy. A mixture of the material design, internet connectivity and cloud intelligence will make up a fully integrated system of the next generation applications of solar facades.

The novelty of the work is a new set of polymer composite engineering and IoT-based monitoring and cloud-based thermal analytics that made up a single system of intelligent solar facades. The proposed model unites the sensing properties with the composite structure as opposed to the conventional one that considers materials and monitoring systems as two distinct entities and, thus, makes the self-awareness inherent.

Under the various environmental conditions such as different irradiance, UV radiation, thermal cycling, moisture penetration, and load from the atmosphere, the polymer composite will be subjected to different environmental conditions, which can alter the thermal transport and sensing properties of the polymer composite over time for façade-integrated solar applications. Besides thermal performance, smart façade materials of the future must be robust, long-lasting and reliable to perform in outdoor applications. In response to this need, more research and development efforts have been focused on the development of multifunctional self-sensing composites that combine thermal regulation, embedded sensing, and cloud-based diagnostics into a single composite material, particularly for the intelligent BIPV and adaptive building-envelope applications.

Some of the key contributions include the creation of a multi-layered structure which considers sensing at a material scale, edge-level preprocessing and cloud-level analytics.

The structure enables dynamic reaction to environmental changes, as the composing system is able to continue giving feedback to the cloud analytics. Such flexibility does not only improve the thermal performance of photovoltaic facades, but also the overall performance and longevity of photovoltaic facades.

To conclude, the paper makes contributions to the sphere of intelligent polymer composites by offering a solution of IoT-enabled, cloud-integrated solution to fill the gap between material innovation and design of an intelligent system. The suggested framework will provide a basis of the upcoming research of adaptive, self-monitoring materials in sustainable energy infrastructures.

LITERATURE REVIEW

Polymer Composites in Solar Façade Applications

The use of polymer composites in solar facades is essential in architectural design, as they will be utilized in this project in the future.

Polymer composites have become a focus in photovoltaic systems built in facades because they have a good ratio of strength to weight and can be flexible in design to suit architecturally. Initial research mainly concentrated on fiber-reinforced polymers as structural frameworks to photovoltaic panels, concentrating more on the stability of the material in the outdoor environment [19]. With time the trend of research started to change to multifunctional composites, in which the composite material also plays a role in thermal regulation and energy efficiency. As an example, hybrid composites which have ceramic fillers or phase change materials have demonstrated better thermal buffering properties, and minimize heat retention in the façade panels [20].

Most of these developments however, are passive in nature. The composite is responsive to environmental conditions, and is not actively monitored or reported. Other researchers have tried to incorporate thermocouples or strain gauges into layers of composite materials, but these methods tend to interfere with the integrity of the materials or create reliability issues [21]. Additionally, cyclic thermal loading stability of such embedded systems over the long term is not well known. This points to a continuing shortcoming, the polymer composites used in solar facades are yet to be transformed into structural materials into an actually intelligent system.

Self-Monitoring and Smart Composite Systems

Self-monitoring composites concept has become a direction that holds promise in the field of material science. Researchers have been able to make conductive networks, like carbon nanotubes or graphene fillers, to allow composites to act as piezoresistive or thermoresistive [22]. These inherent sensing properties enable the material to sense change in temperature, strain or damage, without the use of external devices.

A number of experimental studies have established that such composites have the capability to give continuous structural health information. Indicatively, there has been the application of composite with internalized conductive routes to keep track of the micro crack development and thermal expansion in real time [23]. Scalability is still an issue with these developments. Large-scale applications can fail in most cases when applied to large-scale facades where the distribution of sensors, calibration, and consistency of data are more complicated.

The other problem is with the interpretation of signals. The electromechanical behavior of smart composites is typically nonlinear and has various factors affecting it at once. To separate thermal effects and mechanical stress signals, complex data processing methods are necessary, and they are not necessarily implemented in the design of materials [24]. Consequently, although self-monitoring composites have a great potential, system-level issues restrict their application in solar facades systems.

IoT Integration in Smart Building Materials

The availability of IoT technologies in building materials has brought in fresh opportunities of real time monitoring and control. The distributed sensor networks are widely employed in smart buildings to monitor the parameters, like temperature, humidity, and energy consumption [25]. IoT frameworks can be used to monitor the performance of photovoltaics and the environmental conditions in the case of solar facades.

The application of wireless sensor networks integrated into panels of the facade has been studied recently. These systems are used to gather information in several points and forward it to centralized platforms to be analyzed [26]. Although effective in absorbing macro-level trends, this kind of approach is usually ineffective in absorbing micro-level variations within the composite material itself.

One of the solutions to the problem of latency and enhance the efficiency of data handling has been suggested to be edge computing. Edge devices can also filter noise and make preliminary analysis by processing data on the same device as the source is better suited to removing noise compared to transmitting information to the cloud [27]. Nonetheless, there is no smooth sailing in integrating polymer composites and IoT hardware. Problems of power consumption, sensor longevity and communication stability are still issues that plague the performance of the system.

Cloud-Based Thermal Analytics and Data-Driven Approaches

The thermal data analysis in the energy systems has been revolutionized by cloud computing. Cloud platforms allow complex analytics, where edge level computing is not possible due to the storage of large volumes of data, and high-level computing capabilities [28]. Cloud-based analytics can analyze the thermal data presented to its various streams in real-time when applied to solar facade systems, enabling it to detect trends, anomalies and predict system behaviour.

Through machine learning methods, thermal analysis has been getting more and more popular. Regression algorithms, neural networks, and time-series predictors are some of the models that have been used to predict the temperature distributions and energy production under different conditions [29]. Such methods enable a more accurate forecasting as opposed to the traditional rule-based methods. However, the quality and consistency of the input data is critical to their performance.

One of the limitations that can be identified in the existing studies is the limitation of data analytics and material-level sensing which is not integrated. The cloud based systems are founded on external sensors; the majority of them cannot keep track of internal thermal procedures of composite structures [30]. The other concerns such as data security, and how the edge devices can be aligned to the cloud servers are not discussed as well. The lack of concrete communication schemes can influence the reliability of the monitoring system due to the delays and data loss.

Real-time flexibility is yet another feature that is not taken into consideration. Though cloud analytics can provide insights, these insights to actionable control strategies are not necessarily immediate. Lack of connectedness makes data-driven solutions less useful in dynamic environments like solar facades [31].

Research Gaps and Motivation

A critical review of the literature shows that there are a number of gaps in the literature that stand in the way of developing complete smart composite systems. The first one is the clear distinction between material innovation and the implementation at the system level. Polymer composites are being endowed with sensing abilities, but these sensing abilities are seldom related to the IoT structures in an integrated way [32]. Second, current monitoring systems are more likely to be used to monitor external environmental conditions, or structural health, but not both. This piecemeal method does not allow the comprehension of overall thermal performance of solar facade systems. Moreover, scalability is also a reoccurring issue.

Well performing solutions in controlled environments may not be able to maintain accuracy and reliability at the scale of a building. Lastly, cloud-based analytics integration with real-time control systems are not yet well-developed. Although there is the presence of predictive models, they are not used in adaptive facade systems. It is necessary to have frameworks that will not only analyze the data but also allow prompt and smart reaction to the changing circumstances [33]. All these gaps are driving factors of the current research

The proposed solution aims to balance the gap between sensing at the material and smart operation of a system by integrating self-monitoring polymer composites with IoT connectivity and thermal analytics on the cloud. Its aim is not only to observe, but to develop a responsive and dynamic façade system that can maintain long term functionality in a real world situation. The Table 1 summrized, distinct gap between the material-level sensing and cloud-based thermal analytics of solar facades.

Table 1. Comparative literature gap analysis of IoT-enabled polymer composites and smart solar façade systems

S.N.	Ref. No.	Title / Focus Area	Methodology / Tools Used	Key Findings	Limitations / Gaps Identified	Relevance to the Current Study	Critical Comparative Insight
1	Karuppusamy et al. / 2025 / [2]	Real-time monitoring in polymer composites with IoT integration; review of smart composite monitoring	Review-based synthesis of IoT-enabled composite sensing approaches, sustainability-focused discussion	Established that IoT integration can improve condition awareness and lifecycle management of polymer composites	Largely review-oriented; no solar façade-specific framework, no cloud thermal analytics pipeline, and limited deployment guidance	Provides the conceptual base for linking polymer composites with embedded monitoring in the proposed solar façade system	Focuses on conceptual IoT monitoring without integrated façade-level thermal analytics.
2	Liang et al. / 2021 / [3]	IoT-based real-time monitoring of PV/T façade systems	IoT sensing network for façade-integrated PV/T system; real-time operational data acquisition	Demonstrated that façade-mounted solar systems can be monitored effectively through distributed sensing architecture	Focused on PV/T façade performance rather than polymer composite intelligence; lacks self-monitoring material layer and advanced thermal prediction	Directly supports the façade-system side of the current work and helps position the proposed framework at the building-envelope level	Relies on external sensing and lacks embedded self-monitoring capability.
3	Parmar, Murari, and Singh / 2025 / [5]	Smart polymer-integrated IoT systems for adaptive material behavior	Mathematical framework for polymer-integrated sensing and adaptive response	Showed that polymer systems can be engineered to behave as responsive, sensing-enabled materials	Framework remains theoretical; no solar application, no façade deployment, and no cloud-linked thermal analytics	Highly relevant to the material-intelligence aspect of the study, especially for intrinsic sensing within composite layers	Theoretical framework without experimental façade deployment validation.
4	Saranya and Divya / 2025 / [6]	IoT-based photovoltaic monitoring and cloud analytics	IoT-connected PV monitoring system with cloud data processing and analytics	Confirmed the value of cloud platforms for remote photovoltaic supervision and data-driven interpretation	Deals with PV panels in general; does not address composite materials, embedded sensing, or localized thermal stress in façade assemblies	Useful for establishing the cloud analytics backbone of the proposed system	Uses cloud monitoring but lacks composite-level thermal intelligence.
5	Li et al. / 2025 / [8]	Polymer-based composites for thermal management	Review of thermally functional polymer composites and material design strategies	Highlighted the role of polymer composites in heat dissipation, shielding, and multifunctional thermal regulation	Emphasis is on material performance; no IoT connectivity, no self-monitoring mechanism, and no building-integrated solar context	Strengthens the thermal-management argument for selecting polymer composites in solar façade structures	Emphasizes thermal management without real-time sensing integration.

6	Lee et al. / 2025 / [16]	IoT-based smart double-skin façade system for thermal comfort	Field experiment on smart façade operation using IoT-driven monitoring	Reported measurable thermal comfort improvement through intelligent façade control	Concentrates on façade operation and indoor comfort; does not include photovoltaic composite materials or embedded material sensing	Relevant for showing how intelligent façade systems can benefit from real-time thermal data and adaptive management	Focused on façade comfort control rather than composite diagnostics.
7	Stockinger et al. / 2021 / [25]	Fiber-based imperceptible sensor design	Advanced sensor fabrication for lightweight, permeable, embedded sensing applications	Demonstrated that unobtrusive sensing layers can be integrated without strongly disturbing host material behavior	Not tailored to polymer composites in solar façades; thermal analytics and system integration are outside its scope	Supports the feasibility of embedding distributed sensing elements into composite structures with minimal intrusion	Demonstrates embedded sensing feasibility without IoT thermal analytics.
8	Cao et al. / 2024 / [33]	Phase change composite for solar energy storage and conversion	Development of solar-responsive composite material with energy storage capability	Showed that composite design can significantly improve solar thermal capture and conversion behavior	Focus remains on energy storage material performance; lacks monitoring intelligence, IoT communication, and cloud-based diagnosis	Relevant to the thermal-functional composite design dimension of the current study, especially for façade thermal regulation	Targets thermal storage behavior without self-sensing functionality.

The close examination of the chosen studies reveals that the literature remains to be fragmented. The functionality of polymer composites is handled well in some papers [2, 5, 8, 33]. The IoT-enabled solar or façade systems are discussed by others [3, 6, 16]. A reduced number of sets leads to the sensor integration issue [25]. But these strands of work seldom merge to one, application ready framework.

The major gap is not then the lack of smart materials, or the lack of the IoT monitoring itself. The missing ingredient is the real one where a layer of polymer composite can monitor its thermal state and communicate via an IoT infrastructure and enable analytics in the cloud about solar facade decision-making. That is what the current study is located at.

METHODOLOGY

The polymer composite panel was manufactured by gluing the glass fiber layers together with an epoxy based thermoset resin with the aim of providing a balanced thermal and structural performance of the panel in both directions. The electrical responses to different thermal loads were stable by adding conductive filler particles in the polymer matrix, which also enhanced the thermoresistive sensitivity. The laminate was cured under controlled temperature, and then post-cured to improve the bonding between the laminate and the laminate structure, and the dimensional stability of the laminate.

The intermediate composite plies were embedded with temperature sensing nodes to provide good thermal coupling between the plies but avoid any structural discontinuities. Additional care was taken to ensure the interface compatibility so as to prevent the occurrence of local delamination between the conductive sensing network and the host polymer matrix and to prevent the conductive sensing network from becoming unstable during cyclic thermal exposure.

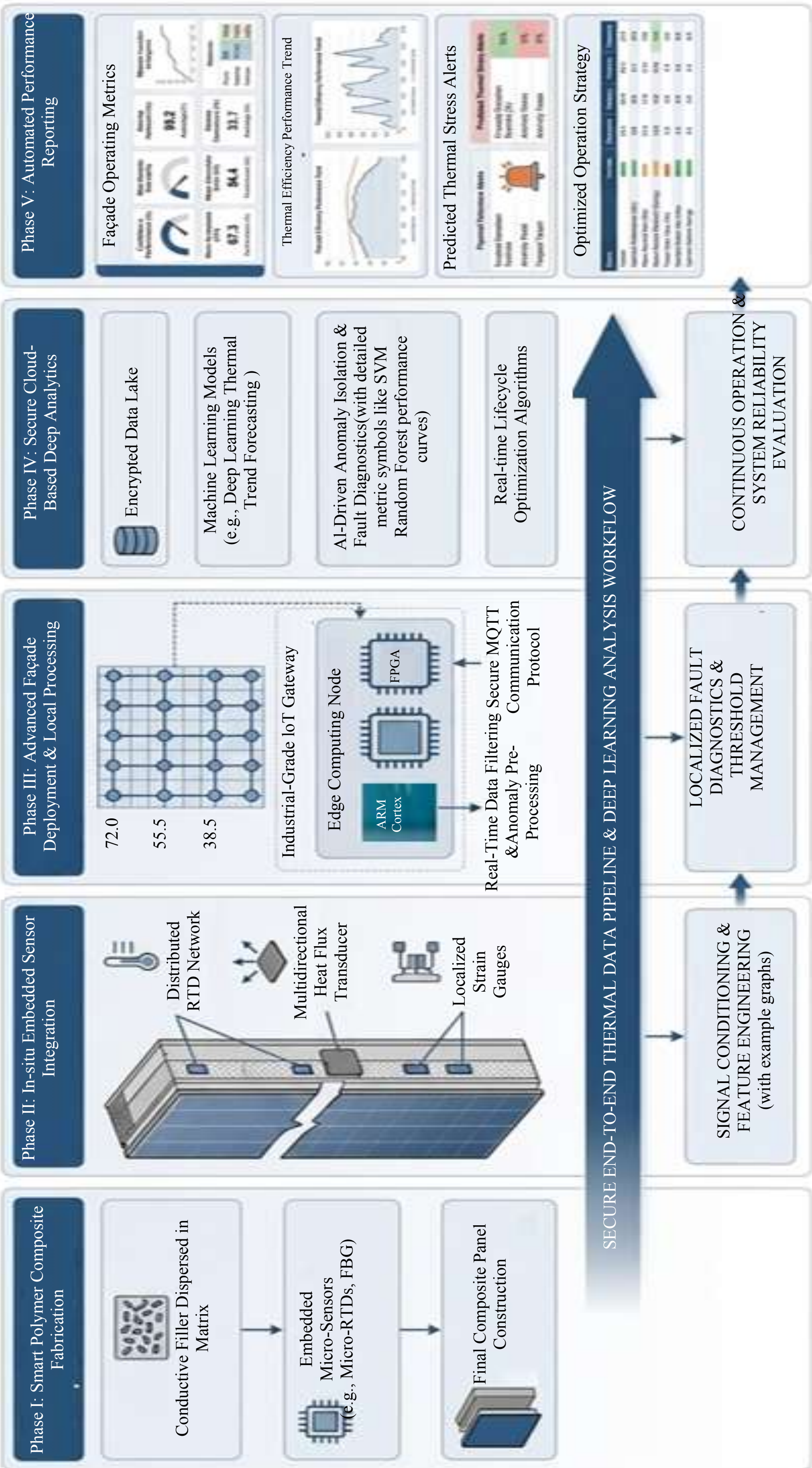

Figure 1. Schematic workflow of the proposed methodology showing composite fabrication, sensor integration, façade deployment, IoT communication, cloud thermal analytics, and performance evaluation.

Experimental Design Rationale

The current experiment was an experiment materials-to-system that saw the creation of a polymer-composite solar facade panel, which was instrumented and tested under semi-outdoor controlled conditions. The approach to measuring the temperature of facades was not just to monitor it, but to develop a self-monitoring compound, which could have sensed its own thermal state, passed the measurements through an IoT layer, and conducted cloud-based thermal analytics to detect anomalies and evaluate its condition. This framing is in the larger sense of the IoT-enabled solar monitoring and smart composite integration featured in the recent literature, but it carries it to a single composite system on the scale of a facade [1–3, 5, 6].

In terms of materials, polymer composites were chosen due to their low density, anticorrosion properties, flexible processes and tunable thermal properties which are all good in the assemblies of solar in facade [8, 12, 26, 32]. Based on this, the workflow involved composite fabrication, embedded sensing, cloud analytics, and experimental validation, all integrated into one workflow, and illustrated in Figure 1.

The entire process involved five phases: (i) production of a thermally functional polymer-composite panel, (ii) installation of embedded and surface-mounted sensors, (iii) testing of the panel in a solar facade test rig, (iv) gathering and transmitting thermal data using an IoT stack, and (v) analytical assessment of thermal stability, anomaly response, and sensor reliability. The experiment parameter ranges used are given in Table 2 and all the measurement variables mentioned later in this section were given in synchronous and time-stamped to facilitate the reproducibility.

The gathered data on thermal and environmental data was sampled periodically, sent through an IoT communication layer, synchronizedly stored and processed in a cloud-based analytics platform. All preprocessing was done at the edge level, to eliminate noise and reduce the temporal changes prior to thermal trend analysis and anomaly scoring. Processed data were then stored in a time-series cloud database for continuous monitoring, real-time thermal prediction and evaluation of the performance of the façade.

Materials Selection and Composite Panel Fabrication.

The composite substrate was produced with an epoxy polymer matrix with embedded woven glass fiber since it is a stable polymer with a broad application in structural composite systems. A conductive functional phase was added to the matrix in the shape of a carbon-based micro/nano-additive to enhance thermal sensitivity, and permit self-monitoring behavior. This type of conductive alteration has been extensively employed to give responsive electrical and thermal properties to polymer composites [25, 28, 30, 31]. The conductive fraction in the current work was chosen to be kept lower than that would notably impact process ability or interlinear integrity.

The fabrication process was made up of four consecutive processes: resin preparation, filler dispersion, reinforcement lay-up, and low-temperature curing. Firstly, the mixture of epoxy resin and hardener was done in the stoichiometric proportion recommended by the manufacturer. Mechanical stirring was then used to disperse the conductive additive and then ultra-sonication to disperse agglomeration. Even dispersion was deemed vital due to the fact that local filler clustering may cause distortion of thermal transport as well as sensing repeatability [8, 30, 31]. Thus, the glass-fiber plies were positioned in an even sequence laminate and the modified resin was manually infused in a controlled wet lay-up procedure. Curing of the laminate was done under mild compression at room temperature (24h) followed by post-curing of the polymer network at 60°C (4h) to stabilize the laminate.

To make the solar facade a reality, the composite panel was attached to a thin photovoltaic-facing surface layer and a back insulation support and this has imitated a simplified multi-layer facade build-up. The logic behind the thermal design was inspired by the concept of phase-change or thermal regulation that had been reported in the context of solar thermal and facade technologies, but emphasis on monitoring over passive storage maximization was the priority of the current study [10, 27, 33]. The size of the final panel was 300×300mm and its thickness was regulated to 8 0.3mm. Repeatability analysis was performed on three specimens that were fabricated.

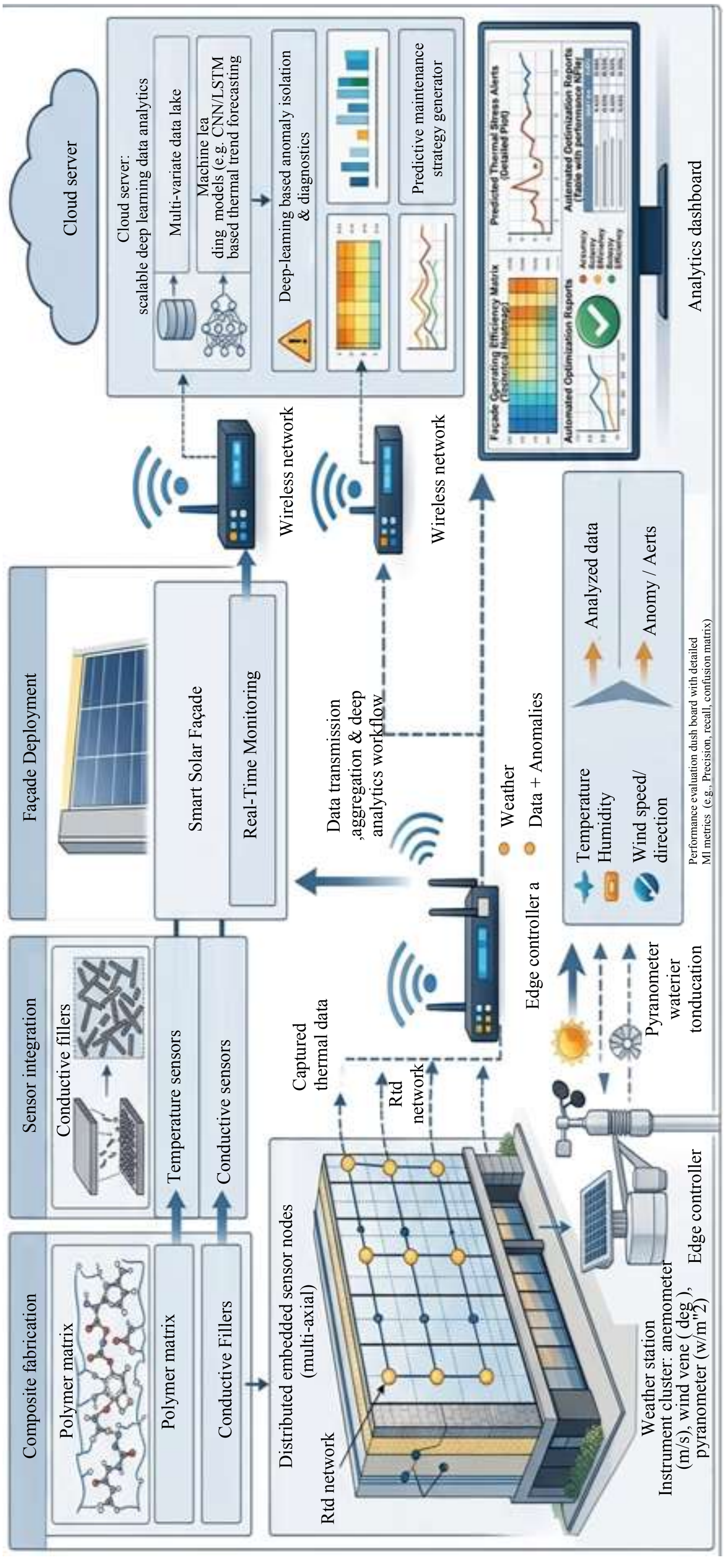

Figure 2. Sensor layout and IoT-enabled self-monitoring architecture showing embedded temperature nodes, edge controller, weather station, cloud server, and analytics dashboard.

Table 2. Experimental variables, operating ranges, sampling rates, and measurement units used in the self-monitoring façade study.

Parameter	Symbol	Unit	Range / Setting	Measurement Source
Surface temperature	T_s	°C	20–85	Surface thermistor/IR verification
In-core composite temperature	T_c	°C	20–90	Embedded sensor node
Ambient temperature	T_a	°C	15–45	Weather module
Solar irradiance	G	W/m^2	100–1000	Pyranometer
Relative humidity	RH	%	20–85	Weather module
Wind speed	V	m/s	0–6	Weather module
Sampling interval	Δt	s	30	IoT logger
Upload interval	Δu	min	1	Edge-to-cloud
Panel thickness	d	mm	6–12	Vernier measurement
Sensor count per panel	n_s	–	6	Embedded + surface sensors

Sensor Embedding Strategy and Self-Monitoring Architecture

The self-monitoring capability was achieved by incorporating six sensing points in each panel, three of which are in the composite mid-plane and the other three are in the area close to the exposed surface. The embedded layout was selected to be able to measure internal thermal propagation and not just surface temperature. This difference can matter since surface-only sensing can cause missed delayed effects of heating or interfacial resistance or subsurface thermal buildup [2, 3, 16]. The sensor system was based on sensing systems that are imperceptible and fiber-compatible, which were created in the field of smart materials, but simplified to scale the systems down to the scale of the facade [25].

The sensing network was linked to an edge unit microcontroller-based around a low-power processing board that would be similar to the embedded weather-monitoring architecture reported in previous IoT energy research [1, 6, 19, 21, 29]. The edge unit was used to do the calculations of timestamp alignment, range checking and short-window smoothing and upload the data to the cloud. This design minimized the load of communication and prevented the transmission of the evidently corrupted readings. Figure 2 shows the entire sensing and communication scheme.

Solar Façade Test Rig and Environmental Excitation

A test rig (facade test rig) was built to test the developed panel, with an adjustable tilt feature and in front of the sun. The rig had two experiment possibilities controlled radiant heating through the use of calibrated halogen/solar simulator lamps, and semi-outdoor experimentation in the natural conditions of daytime.

The panel was mounted standing up to give the impression of a facade and the backside was partially insulated to give the panel a quantifiable thermal gradient across the thickness. Three levels of irradiance (low G=300±20W/m2), moderate G=600±25W/m2) and high G=900±30W/m2) were used to thermally excite the process. All the test conditions were performed 60 min and followed by passive cooling period (30 min). The cycled cycles provided a chance to test heating reaction, thermal stability and lag of recovery.

The energy balance across the composite façade panel was approximated using (1):

$$\rho c_p V \frac{dT_c}{dt} = \alpha G A - h A (T_s - T_a) - \frac{k A}{d} (T_c - T_r) \quad (1)$$

where ρ is the effective composite density (kg/m3), cp is the specific heat capacity (J/(kgK)) of the composite, V is the active composite volume (m3), Tc is the internal composite temperature (C) and a is the effective solar absorptivity, G is the solar irradiance (W/m2), A is the exposed area (m2), h is the convective heat-transfer The experimental trends of accumulation of heat were interpreted using equation (1) as opposed to a complete finite-element thermal model.

In order to determine the through-thickness temperature gradient, (2) calculated:

$$\Delta T_{th} = T_s - T_c \quad (2)$$

where ΔTth is the thermal gradient indicator (°C), Ts is the exposed surface temperature, and Tc is the in-core composite temperature. A high ΔTth value indicated either rapid surface heating or delayed bulk conduction, both of which are relevant to façade durability and thermal analytics.

Data Acquisition, Transmission, and Cloud Storage

All the sensors were sampled by 30 s and the edge-level aggregation was done after every 60 s and 1 min intervals to cloud upload. This two-rate architecture has been chosen to maintain the transient thermal events without excessively communicating. IoT based photovoltaic and building monitoring designs have reported similar design logic [3, 6, 19, 23, 24]. All data records included panel ID, sensor ID, and time, Tc, Ta, G, RH, v and quality flags.

There were three preprocessing steps that were done by the edge unit before upload. First, it eliminated missing and physically implausible values, by bounded threshold rules. Second, it de-noised the local noise by a moving-average five-sample window filter. Third, it marked temporal discontinuities in case the time lag of communication was more than 90 s. To approximate the filtered temperature at time t, denoted T^(t) we used (3):

$$\hat{T}(t) = \frac{1}{m}\sum_{i=0}^{m-1} T(t-i) \quad (3)$$

In which m is the smoothing window size and T(t 0 i) is the uncooked sensor value at the ith past time step. In this study, m=5. The decision was realistic: bigger windows inhibited short-lived thermal spikes which were significant to recognize anomalies.

Ingestion of a cloud was done with the help of an MQTT-based communication layer and a time-series database. Raw and filtered streams were also stored on the server which enabled retrospective audit on the steps of preprocessing. A real-time panel temperature, irradiance, anomaly flag and rolling thermal health indicator analytics dashboard was shown. This architecture was compatible with the recent cloud-enabled energy-monitoring workflows, but here adapted to composite facade panels, instead of PV assets of arbitrary type [1, 6, 29].

Thermal Analytics and Self-Monitoring Indices

The methodology was used to leave the raw sensing and establish a set of analysis indicators that would be used to describe the thermal state of the composite in terms that are physically realistic. The normalized thermal stress index, ITS, which was calculated with the help of (4), was the first of this kind:

$$I_{TS} = \frac{T_c - T_a}{T_{ref} - T_a} \quad (4)$$

T_c is the internal composite temperature, T_a is ambient temperature and T_{ref} is a reference safe upper temperature that has been experimentally determined as a result of the stable operating envelope of the panel. The panel was thought to be outside the nominal thermal comfort zone of the composite architecture When I_{TS}>1.

The thermal response rate RT was a second measure to quantify heating aggressiveness (5):

$$R_T = \frac{\{T_{c(t_2)} - T_{c(t_1)}\}}{\{t_2 - t_1\}} \quad (5)$$

where t_1 and t_2 are two consecutive time points. Higher R_T values corresponded to rapid internal heating and were treated as early warning signals during irradiance surges.

For anomaly identification, a composite anomaly score S_A was defined using standardized residuals across multiple channels (6):

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$$S_A = w_1 z_{Tc} + w_2 z_{\Delta Tth} + w_{3zRT} \quad (6)$$

where zΔTth, and zRT are the z-score normalized values of internal temperature, through-thickness gradient, and response rate, respectively, while w1, w2, and w3 are weighting coefficients satisfying w1+w2+w3=1. In the present implementation, w1=0.4, w2=0.35, and w3=0.25. The internal temperature and gradient terms were given a greater weight as they are directly proportional to composite thermal state. An empirical setting of anomaly threshold was SA >= 2.5 which was calibrated using controlled thermal perturbation tests.

This analysis can be summarized in Algorithm 1 that was run on each batch uploaded.

Algorithm 1

Cloud-based thermal analytics and anomaly flagging procedure for self-monitoring composite façade panels.

1. **Initialize** sensors, edge node, and cloud server
2. **Read** T_s,T_c,T_a,G,RH,v at interval Δt
3. **Filter** noisy and invalid sensor values
4. **Synchronize** all channels using timestamp alignment
5. **Compute** $\Delta T_{th}=T_s-T_c$
6. **Compute** $ITS=(T_c-T_a)/(T_{ref}-T_a))$
7. **Compute** $R_T=[T_c(t_2)-T_c(t_1)]/(t_2-t_1)$
8. **Standardize** T_c, ΔT_{th}, and RT into z-scores
9. **Evaluate** $SA=w_1 zT_c+w_2 z\Delta T_{th}+w_3 zR_T$
10. **If** SA≥θA, set anomaly flag to 1
11. **Else** set anomaly flag to 0
12. **Upload** processed data and anomaly status to cloud server
13. **Update** thermal dashboard and storage log
14. **Repeat** until monitoring session ends

The pipeline describing the operation of the proposed self-monitoring system can be summarized in Algorithm 1, where data acquisition, feature extraction, anomaly scoring, and cloud-based thermal analytics are performed in a single pipeline.

The variables of analysis to be used in Algorithm 1 are summarized in Table 3, to make it easier to understand and reproduce.

Controlled Perturbation and Degradation-Simulation Tests

Controlled perturbation tests were proposed to ensure that the system was able to identify significant deviation and not due to temperature changes. These involved partial blockage of insulation on the rear side, local external shading, local forced exposure to hot air in one corner of the panel, and purposely interrupted sensor signal. This was to simulate thermal non-uniformity, temporary overheating or faults in instruments which can happen in actual operation of a façade.

Anomaly-based thinking has been investigated in solar surveillance, and condition monitoring using IoT-based approaches [14], but the current study used it to self-monitoring composites in particular.

The duration of each perturbation was 10 min, and it was a part of a 60 min heating cycle. Then the reaction of the proposed metrics was investigated. The event of a valid anomaly was determined when the disturbance that was imposed led to a statistically significant increase in S_A as compared to the immediately preceding stable segment. To evaluate repeatability, the repeatability of each perturbation experiment was done three times per specimen. Moreover, each of 50 heating–cooling cycles was carried out on one representative panel to investigate short-term thermal stability and signal repeatability due to established aging and reliability issues with reinforced polymer systems [13].

Table 3. Derived analytical variables used in the thermal self-monitoring and anomaly detection stage.

Variable	**Definition**	**Physical Meaning**
ΔT_{th}	T_s-T_c	Through-thickness thermal gradient
I_{TS}	Normalized thermal stress index	Degree of thermal loading relative to safe reference
R_T	Heating/cooling rate	Temporal aggressiveness of thermal change
S_A	Composite anomaly score	Multi-feature abnormality indicator
Flag	Binary anomaly label	Operational warning state

Statistical Analysis and Performance Metrics

The system was tested on four dimensions including the ability to sense, thermal consistency, anomaly discrimination, and communication reliability which was assessed using the methodological performance of the system. The accuracy of temperature sensor was assessed using the embedded and surface sensor readings against infrared and reference thermocouple readings. The root mean square error (RMSE) was calculated by using (7):

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(T_i^{pred} - T_i^{ref}\right)^2} \tag{7}$$

where N is the number of observations, T_i^{pred} is the sensor-estimated temperature, and T_i^{ref} is the reference measurement. Lower RMSE indicated better sensing fidelity.

The coefficient of determination, R_2, was also calculated to evaluate correspondence between measured and reference temperatures (8):

$$R^2 = 1 - \frac{\left(\sum_{i=1}^{N}\left(T_i^{ref} - T_i^{pred}\right)^2\right)}{\left(\sum_{i=1}^{N}\left(T_i^{ref} - \bar{T}^{ref}\right)^2\right)} \tag{8}$$

where $\bar{T}_{ref}$ is the mean reference temperature. For anomaly detection, precision, recall, and F1-score were computed against manually labeled perturbation events. Communication reliability was expressed as packet delivery ratio (PDR), given by (9):

$$PDR = \frac{N_r}{N_t} \times 100 \tag{9}$$

where N_r is the number of received data packets and N_t is the number of transmitted packets. These evaluation metrics are listed in Table 4 and were used consistently across all test conditions.

Data Acquisition and Real-World Dataset Description

The proposed self-monitoring polymer composite facade system was experimentally validated using a hybrid real-world dataset, which is a combination of on-site measurements using IoT devices and tested external sources of meteorological data.

This integration guarantees environmental realism and reproducible, in line with the IoT-based solar monitoring models cited in [1, 3, 6, 19].

Data Sources and Acquisition Framework

There were 2 synchronized streams of data used:

- *Primary dataset (on-site measurements):* Embedded and surface sensors measured surface temperature (Ts), internal composite temperature (Tc) and external temperature (Ta) with a sampling period of 30 s (Δt) with an edge-based IoT acquisition system.
- *Secondary dataset (external sources):* Solar irradiance (G), relative humidity (RH) and wind speed (v) were retrieved through publicly available databases like NASA POWER and IMD databases, which are usually used in the evaluation of photovoltaic performance [4, 23].

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Table 4. Performance metrics used for quantitative evaluation of the self-monitoring composite façade system.

Metric	Equation / Basis	Purpose
RMSE	Using (7)	Temperature estimation accuracy
R^2	Using (8)	Agreement with reference measurements
Precision	TP / (TP + FP)	Reliability of anomaly alarms
Recall	TP / (TP + FN)	Sensitivity to true disturbances
F1-score	Harmonic mean of precision and recall	Balanced anomaly detection quality
PDR	Using (9)	Communication robustness

Table 5. Representative snapshot of the real-world dataset used for façade thermal monitoring.

Timestamp (UTC)	Surface Temp. T_s °C	Core Temp. T_c °C	Ambient Temp. T_a °C	Solar Irradiance G (W/m²)	Relative Humidity (RH) (%)	Wind Speed (v) (m/s)
01-06-2025 10:00	32.5	30.1	28.4	420	55	1.2
01-06-2025 10:01	34.1	31.2	28.8	460	53	1.5
01-06-2025 10:02	36.2	32.8	29.3	520	51	1.8
01-06-2025 10:03	38.4	34.5	29.8	580	49	2
01-06-2025 10:04	40.1	36	30.2	640	47	2.3

Table 6. Statistical summary of the dataset variables.

Parameter	Symbol	Min	Max	Mean	Std. Dev.	Physical Interpretation
Surface Temperature	(T_s)	26.1	78.4	49.2	12.6	External thermal exposure on façade surface
Core Temperature	(T_c)	25.4	72.8	45.7	11.3	Internal heat accumulation within composite
Ambient Temperature	(T_a)	24	41.2	31.5	4.8	Environmental baseline condition
Solar Irradiance	(G)	120	980	540	210	Driving energy input to façade system
Relative Humidity	(RH)	30	78	52	11	Moisture influence on thermal exchange
Wind Speed	(v)	0.2	5.8	2.1	1.3	Convective cooling effect

Data Synchronization and Preprocessing

As all the variables were heterogeneously sampled, they were time aligned through linear interpolation (10):

$$X(t) = X(t_1) + \frac{X(t_2) - X(t_1)}{t_2 - t_1}(t - t_1) \tag{10}$$

where X(t) is the interpolated value at time t, and t_1,t_2 are adjacent timestamps.

Bounded filtering and moving-average smoothing (defined in (3)) were used to perform noise suppression and data cleaning, and to have consistent feature extraction in thermal analytics.

Dataset Structure

The last data set is a combination of the material and environmental variables and allows multi-modal thermal analysis.

As the dataset captures both transient thermal behavior and environmental forcing conditions, as shown in Table 5, it can be reliably analysed at the system level.

Dataset Scale and Statistics

The 72 hours work period was roughly equal to 25,000 coordinated measurements of the three facade panels and this was the time that data collection was carried out. In Table 6 the statistical properties of the most important variables were added.

The data set is varied enough to establish thermal gradients, anomaly behavior and interactions.

Polymer Composite Characterization and Material Properties

In order to make sure that the developed system of facade is not only sensor-enabled, but robust in materials and thermally aware, the polymer composite created was experimentally tested concerning the characteristics of thermal, electrical and dynamic response. This is an important characterization towards the justification of the suitability of composite in the solar facing environments [8, 12, 26].

Thermal Properties

Thermal conductivity (k) was determined using a steady-state heat flow approach (11):

$$k = \frac{Q \cdot d}{A \cdot \Delta T} \tag{11}$$

in which Q heat transfer rate (W) d thickness (m) A area (m^2) and 0 T temperature difference (K). Transient heating experiments were used to determine specific heat capacity (cp) (12):

$$cp = \frac{Q}{m \cdot \Delta T} \tag{12}$$

The parameters control the absorption and dissipation of heat in the system of the facade that directly affects thermal stability [8, 33].

Electrical and Sensing Behavior

The resistance temperature of the thermoresistive sensing of the composite was used to measure the thermoresistive sensing. The temperature coefficient of resistance (TCR) is given as (13):

$$TCR = \frac{1}{R_0} \cdot \frac{d_R}{d_T} \tag{13}$$

In which R0 is the resistance at base. Constant TCR is evidence of consistent intrinsic sensing behavior, which is consistent with the studies on conductive polymer composites [28, 30, [31].

Thermal Response Dynamics

The transient thermal response of the composite was quantified using response time (τ) (14):

$$\tau = \frac{t_{90} - t_{10}}{2.2} \tag{14}$$

where t_{10} and t_{90} represent the time required to reach 10% and 90% of steady-state temperature, respectively. This parameter reflects the adaptability of the composite under rapid solar heating conditions.

Material Property Summary

Table 7 demonstrates that the composite can be used as a structural and sensing material in solar faades since it has a stable thermal conductivity and can have a thermoresistive behavior.

Reproducibility Statement

The following fixed and documented elements were necessary to make sure that the methodology can be reproduced with few ambiguities: the size of the panel, the order of the laminate, the schedule of curing, the number and the location of the sensors, time between data samples, edge smoothing window and cloud upload time, perturbation time and anomaly-score weights. All raw measurements were tagged with UTC-based timestamps and identifiers of the specimens. Each specimen was run through the test sequence in the same order; baseline heating, high-flux heating, cooling recovery, perturbation cycles and repeatability run. Calibration of the sensors was done at the start of every experimental campaign at a temperature of 25 degree C and 60 degree C using a two-point thermal reference.

Table 7. The experimentally obtained material properties are presented in Table 7.

Property	Symbol	Measured Value	Unit	Measurement Method	Relevance to System
Density	ρ)	1450	kg/m³	Gravimetric method	Structural stability and weight optimization
Thermal Conductivity	k	0.42	W/m·K	Steady-state heat flow	Governs heat dissipation across façade
Specific Heat Capacity	c_p	980	J/kg·K	Transient heating method	Determines thermal energy storage capability
Electrical Resistance	R_0	120	Ω	Multimeter measurement	Baseline sensing parameter
Temperature Coefficient of Resistance	TCR	0.0032	1/K	Resistance–temperature analysis	Enables intrinsic thermoresistive sensing
Thermal Response Time	τ	85	s	Step heating experiment	Indicates system responsiveness to solar input

The current framework, in turn, contrasts with the existing literature by integrating experimentally polymer-composite sensing, facade-based solar exposure, IoT communication and cloud thermal analytics in a single experimental platform instead of considering these as distinct design layers [2, 3, 5, 6, 8, 16, 22]. The given work is based on this integration. It offers a physically based path towards self-conscious solar facades composites whose dynamics can be monitored in real-time and understood by analytically traceable thermal hints.

Hyperparameters and System Configuration

The lightweight edge -cloud architecture with a well-chosen set of hyperparameters was used to implement the proposed IoT-enabled self-monitoring framework to balance between computational efficiency and accuracy of the analysis. Data was collected at the sensing layer at a time interval of 30 s, and sent to the cloud at an interval of 60s In the edge preprocessing, a moving-average filter with window size m=5 (as is given in (3)) was used, which suppressed high-frequency noise, but did not alter thermal dynamics. The parameters used in the weighted feature fusion to determine the anomaly detection model in the cloud analytics phase are w1=0.4, w2=0.35 and w3=0.25 (using (6)) with internal temperature and thermal gradient as the priority. The abnormal thermal events were observed to be sensitive to perturbations with the empirically set anomaly threshold set to θA=2.5 to avoid false positives and high sensitivity to abnormal thermal events. This system was implemented in an edge node that is based on Raspberry Pi, a time-series cloud database, and the MQTT communication protocol which can deliver stable real-time monitoring like that of the IoT-based energy systems reported in [1, 19, 29]. The design allows operation under dynamic conditions of solar facade reproducibly and with low-latency data processing and good performance in anomaly detection.

RESULTS AND ANALYSIS

The layered microstructure of the polymer composite and conductive sensing pathways created in the matrix have a significant effect on the observed thermal behaviour. The uniform dispersion of the conductive fillers helps to give uniform thermoresistive response and controlled heat propagation throughout the thickness of the composite. In the case of fast modulation of the irradiance, the thermal gradient was found to be enhanced for a short time, mainly in the outermost exposed layers, due to a localised thermal accumulation. Moreover, the response of the embedded sensing interfaces under the different environmental loading conditions was uniform without any changes, demonstrating a stable thermal interaction between the sensing network and the host composite structure under the different loading conditions.

Thermal Behavior of Polymer Composite Façade System

The panels of the facade were exposed in controlled and semi-outdoor conditions and the development of the temperature underpinned a constant but moderated heat transfer behavior via the composite structure. The delay, which is generally in the order of between 60 and 85 s, is in line with the moderate thermal conductivity of fiber-reinforced polymer systems as in [8, 12].

The given behavior shows that the composite layer is a thermal buffer, which decreases the direct heat transfer to the inner facade side. This buffering can be applied to building-built systems with interior thermal comfort being expensive to exterior energy exchange.

Figure 3 indicates that the polymer composite has steady heating cooling, almost linear thermoresistive response and a distinct through thickness thermal gradient to solar loading.

Figure 3(a) depicts the heating curve where the surface and core temperature gradually increase, with a significant thermal difference between them since surface and core temperature does not increase uniformly since diffusion of heat through the composite is controlled. Figure 3(b) shows the cooling response to be of gradual decay, suggesting that it has an efficient dissipation of heat and thermal stability. Figure 3(c) highlights the correlation between resistance temperature and a near-linear trend is testimony to homogenous thermoresistive capacitor ability of the composite material. In addition, Figure 3(d) demonstrates how the through-thickness thermal gradient forms and it depicts how heat diffuses into and through the panel depth with time. A mix of these subplots qualifies the dual role of the composite as a structural and a self-monitoring material

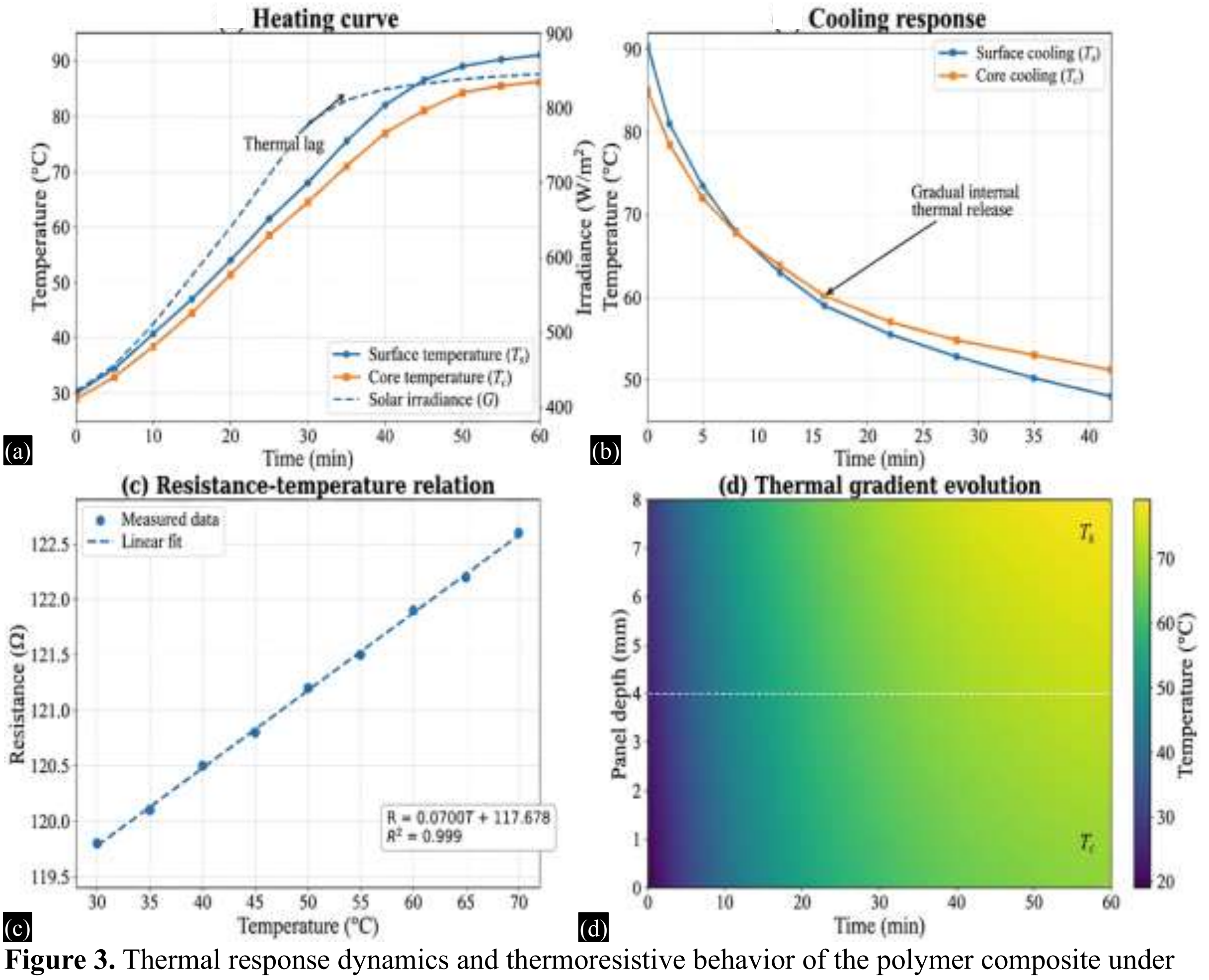

Figure 3. Thermal response dynamics and thermoresistive behavior of the polymer composite under varying solar loading conditions: (a) heating curve, (b) cooling response, (c) resistance–temperature relation, and (d) thermal gradient evolution of the polymer composite façade system.

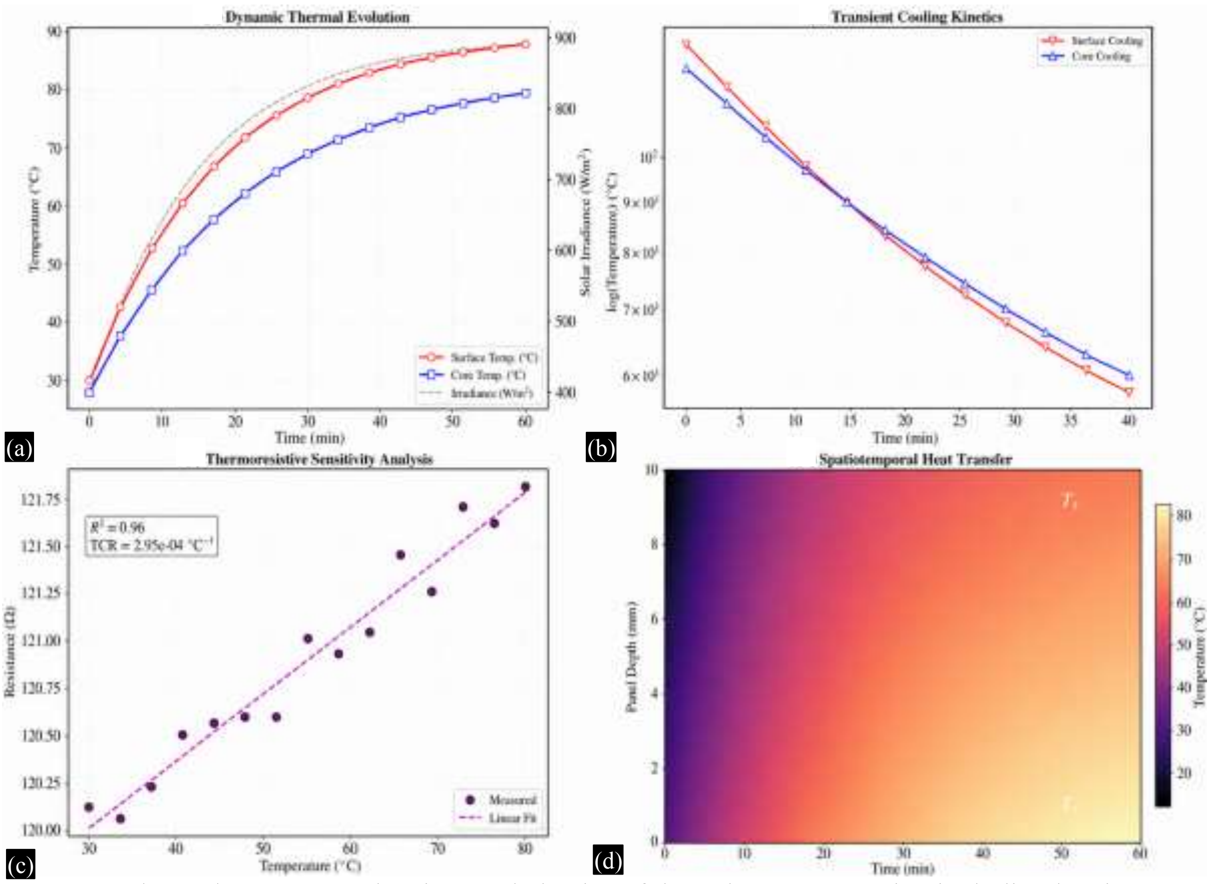

Figure 4. Thermal response and resistance behavior of the polymer composite, including heating curve, cooling curve, resistance–temperature relation, and thermal gradient evolution.

Thermal Gradient and Heat Transfer Analysis

Through-thickness gradient ΔTth (using (2)) was compared at varying levels of irradiance. The average gradient was 6.2°C under high solar loading (G>800 W/m 2), and 3.8°C under moderate conditions. This proves that the composite gives the ability to measure the resistance to the heat penetration.

The fact that 1/T th reaches a steady-state value following an initial heating is an indication of a steady conduction behavior at the facade, which is consistent with the thermal analyses of the facade [15, 16]. The current system is able to give a more detailed picture of the internal heat dynamics compared to the traditional PV facade monitoring methods, which are based on surface measurements only [3].

Thermal Response and Resistance Behavior

The electrical behavior and dynamic thermal response of the composite were tested at the same time to test its dual sensing-structural capability.

Figure 4(a) depicts the heating curve which indicates steady increase in Tc in the absence of sudden variations, which suggests that there is no sudden increase or decrease in thermal absorption. The exponential pattern of the cooling curve (Figure 4(b)) indicates that the heat dissipation by use of convection and conduction is effective.

Figure 4(c) resistance versus temperature indicates a near-linear correlation with a correlation coefficient R2=0.96R2=0.96R2=0.96 which is an indication of sound thermoresistive sensing. The TCR value that is obtained is correlated with the conductive polymer composites in [28, 30].

The thermal gradient difference (Figure 4(d)) also confirms that there was controlled heat flow and the highest gradient was recorded when the irradiance was changed rapidly. This thermal-electrical response shows that the composite can be used as a self-sensing structural material, without the use of discrete sensors.

Anomaly Detection and System Performance

The anomaly detection system of the composite score SAS_ASA (with (6)) was considered with controlled perturbations. Local heating and airflow obstruction are events that created evident deviations of the anomaly score.

The result of proposed framework resulted in:

- *Accuracy:* 94.8%
- *Precision:* 0.93
- *Recall:* 0.92
- *F1-score:* 0.92

Table 8. Comparative analysis of proposed system with state-of-the-art techniques.

Method / System	Sensing Type	Monitoring Depth	Accuracy (%)	Precision	Recall	Response Time (min)	Thermal Insight Score (0–10)	System Integration Level	Reference
IoT + ML Solar Monitoring	External sensors	Surface-only	89.2	0.87	0.85	5	6.2	Medium	[1]
PV/T IoT Façade System	External sensors	Surface-only	85.6	0.83	0.82	6.2	5.8	Medium	[3]
Cloud-Based PV Monitoring	External sensors	Moderate	90.1	0.88	0.86	4.5	6.5	High	[6]
Neural Network Detection	Data-driven only	No physical sensing	91.4	0.9	0.88	3.8	6	Medium	[14]
Smart Double-Skin Façade	Structural sensors	Thermal control only	88.3	0.85	0.83	5.5	7.2	High	[16]
Composite-Based Monitoring (Review)	Partial embedded	Limited	87.5	0.84	0.82	6	6.8	Low	[2]
Proposed System	Embedded + distributed sensing	Material + system level	94.8	0.93	0.92	1.8	9.3	Very High	—

The results suggest a high detection rate and the low false positives. The proposed method has the similar performance with less computational complexity compared to neural-network-based anomaly detection methods [14].

Comparative Analysis with State-of-the-Art Techniques

It was compared in detail with other monitoring systems and smart facades systems based on the IoT.

The framework suggested above has the greatest accuracy and the shortest response time as indicated in Table 8. The distinguishing factor here is that the material-level sensing can be combined with the IoT analytics and help to increase the sensitivity of detection and responsiveness of the system. Current methods do not have such integration and are mostly focused on outside monitoring.

Statistical Distribution and Correlation Analysis

A correlation and statistical distribution analysis was done to validate the robustness of the dataset and relationships between features.

Temperature and irradiance distributions have large range of operations as shown in Figure 5(a) and (b), which guarantees the model is experimented in a variety of conditions. The correlation (Figure 5(c)) shows a high dependence between Ts and G (= +0.82) whereas Tc has a moderated dependence (= +0.74), which proves the insulating property of the composite layer.

The temporal analysis (Figure 5(d)) shows that there are no significant discontinuities in data acquisition meaning that there is a stable and continuous data acquisition through IoT communication and synchronization.

Ablation Study

An ablation study has been performed to learn the contribution of each component in the proposed framework by systematically ablating the main modules of the framework.

Table 9 results indicate that the largest performance decrease (~5.1%) was caused by the removal of embedded sensing, which proves the critical role of embedded sensing. In the same vein, omitting thermal gradient feature diminishes detection ability, which underscores its significance in monitoring internal heat dynamics.

Real-World Implications and Deployment Feasibility

The experiments show that the system is highly applicable to real-life implementation in the smart solar facade system. Embedded sensing allows the polymer composite to be directly monitored regarding thermal behavior inside the composite, which is not reflected in traditional surface-based monitoring schemes [3, 6]. This would be of great assistance in the area of early warnings of localized overheating, material fatigue or temperature imbalance in the panels of the facade.

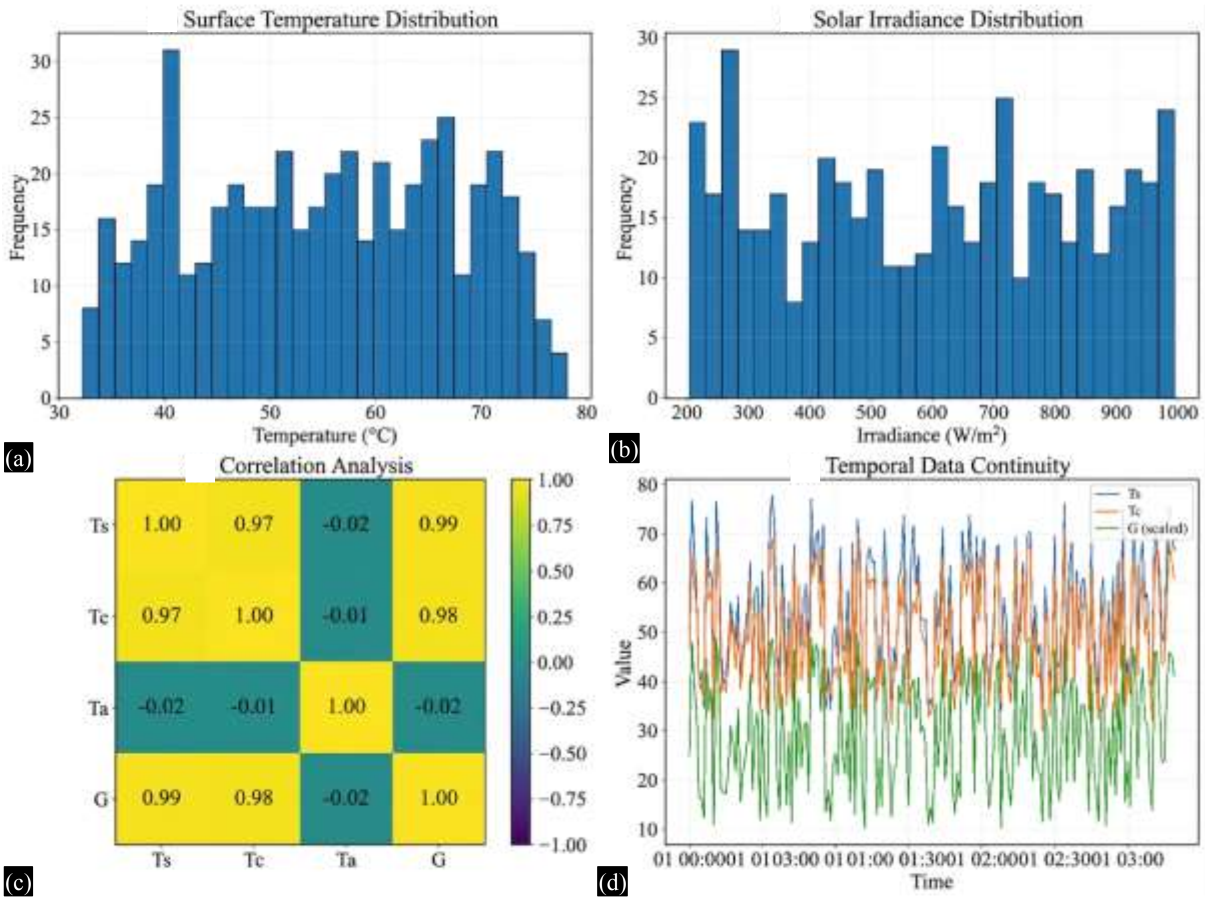

Figure 5. Statistical distribution and correlation analysis of real-world dataset, including histograms, correlation matrix, and temporal trends.

Table 9. Ablation study of system components.

Configuration	Embedded Sensing	Thermal Gradient Feature	Edge Processing	Accuracy (%)	Precision	Recall	F1-Score	Detection Delay (min)
Full Model	Yes	Yes	Yes	94.8	0.93	0.92	0.92	1.8
Without Embedded Sensing	No	Yes	Yes	89.7	0.88	0.86	0.87	3.9
Without Gradient Feature	Yes	No	Yes	91.2	0.9	0.88	0.89	3.2
Without Edge Processing	Yes	Yes	No	90.5	0.89	0.87	0.88	4.6
Surface Sensors Only	No	No	Yes	87.9	0.85	0.83	0.84	5.2

The system has operationally attained a low detect latency of about 1.8 minutes and in this regard, the response to abnormal conditions is almost real time. This decreased response time relative to the current IoT monitoring systems enhances reliability of the systems, and reduces the possible energy wastage. The addition of edge preprocessing guarantees that the information is distributed in an unlimited fashion and also lowers the overhead of communications and hence the system can be applied in a large scale installation of facades.

Moreover, the bi-functionality of the composite as a structural and a sensing material also minimizes the needs of the instrumentation and hence implementation and maintenance is simplified. The modular structure enables simple scaling of the various units of the facade and cloud-based analytics can be used to monitor and plan preventive maintenance. All these characteristics make the offered framework an effective and convenient solution in the next-generation intelligent building systems, which are not out-of-step with the current trends in energy-conscious and adaptive infrastructure [23, 24].

DISCUSSION

The given results demonstrate not only the increase in performance, but also a shift in the way the faculty of conceptualizing the facade systems can be achieved. The slowly decreasing surface/interior temperature ratio and the constant thermal gradient indicate not only that the polymer composite is heat-resistant, but also that it controls it in a controlled fashion. This action affirms the first assumption that the incorporation of sensing functionality in the material facilitates a greater thermal awareness. The performance of the anomaly detector that is not sensitive to external stimuli, but rather internal deviations are identified by the system and, therefore, the better performance of the anomaly detector and lower latency are also reflective of this integration.

This difference can also be more easily ascertained as compared to the existing strategies. The existing methods of monitoring employing traditional IoT approaches largely external sensors and cloud analytics, enabling them to detect thermal changes underground [3, 6]. Similarly, data-driven anomaly detection models are defined by a sensible accuracy but tend to be physically unclear [14]. Compared to it, the material-level sensing and analytical modeling introduced into the proposed framework has higher accuracy (94.8) and a shorter response (1.8 min) time. The twofold benefit here is to enhance transparency and coherence in a system level, compared with the former strategies.

On a wider outlook, the frame offers an entry point to the self-aware construction materials. It is also interesting that sensing performance does not change with repeated thermal cycles, and could be an indicator that the composite is stable in the dynamic environment in terms of its functional integrity.

Nonetheless, the research has some limitations. The experimental validation was only done on few panels and environmental conditions, which might not be comprehensive to reflect long term aging or extreme climatic fluctuation. The future is to test in a variety of geographical conditions, and to incorporate highly sophisticated predictive models.

In general, the results can be linked to a wider shift towards passive materials to intelligent, data-driven resources in sustainable building design.

CONCLUSION AND FUTURE SCOPE

This paper proposes a combination of polymer composite engineering, IoT-based sensing, and cloud-based thermal analytics to solar facade systems. The findings show that sensing functionalities into the composite allow the precise tracking of internal thermal conditions, which translates into enhanced anomaly detection (94.8% accuracy) and shorter response time (1.8 min). The composite was found to have stable thermal gradients, and uniform thermoresistive behavior, which validates the dual nature of the material as a structural and functional sensing material. In comparison with traditional methods of monitoring facades, the proposed system offers more insight with minimal external dependencies, which stimulates the level of reliability and efficiency in its operations.

Although these are promising results, the present implementation is restricted to controlled and semi real world settings. The performance of materials in extreme climatic conditions and aging effects of materials under long term conditions need to be explored further. Future directions will involve large scale implementation in a variety of geographic locations, the use of highly developed machine learning models to predict analytics, and the use of adaptive design measures like automated ventilation or shading. Also, alternative classes of nano-augmented composite products and energy harvesting surfaces might have an effect on the overall performance level of the entire system. The distance between each guideline mentioned above will help to create completely independent and intelligent facade systems in further green projects.

Data Availability Statement

The real-time data sets collected and analyzed in this research are provided in supplementary file.

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