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Fire Risk Simulation of Photovoltaic Panels Installed in Green Buildings

Miloua Hadj
University Djillali Liabes of Sidi Bel Abbes

Hassan Sandous
University Djillali Liabes of Sidi Bel Abbes

Miloua Farid
University Djillali Liabes of Sidi Bel Abbes

Abstract: This research investigates the fire risks associated with photovoltaic (PV) panels installed in residential buildings, an increasingly prevalent feature in the global shift toward sustainable energy solutions. As solar energy systems gain widespread adoption for their eco-efficiency, low carbon footprint, and contribution to decarbonization targets, the associated hazards particularly fire risks require comprehensive evaluation and effective management. The study explores the interplay between renewable energy integration, sustainable architectural design, and energy-efficient building practices. Particular attention is devoted to identifying and analyzing the root causes of PV-related fire hazards, including electrical faults, inverter malfunctions, inadequate installation methods, and the use of combustible construction materials. A detailed numerical investigation was conducted using Computational Fluid Dynamics (CFD) via the Fire Dynamics Simulator (FDS) to model and predict the behavior of fire propagation in buildings equipped with PV systems. Simulation outcomes reveal that factors such as module configuration, ventilation, and surface temperature distribution significantly influence heat release rate and flame spread. The findings emphasize the necessity of implementing stringent design standards, regular inspection protocols, and advanced fire mitigation strategies to enhance the resilience and safety of PV-integrated structures. Ultimately, this research contributes to the broader effort to ensure safe, smart, and fire-conscious green building design in alignment with future sustainable urban development goals.

Keywords: Fire risk, Photovoltaic panels, Renewable energy, CFD, Sustainable buildings

Introduction

The accelerating global demand for energy, coupled with the urgent need to mitigate the effects of climate change, has intensified the transition toward renewable and sustainable energy systems. Among the available technologies, solar energy has emerged as a leading solution due to its abundance, scalability, and environmental benefits (Ozaslan, 2020). The utilization of photovoltaic (PV) panels to convert solar radiation into electrical energy represents a major advancement in sustainable energy production. This technology aligns with the goals of reducing greenhouse gas emissions, enhancing energy security, and promoting green economic growth (IEA, 2023).

In recent decades, the integration of photovoltaic systems into the built environment whether as rooftop-mounted arrays or as building-integrated photovoltaics (BIPV) has become a cornerstone of modern sustainable architecture. These systems enable buildings to generate clean electricity on-site, reduce reliance on the grid, and contribute to the realization of net-zero energy and positive-energy buildings (Yoon et al., 2021).

Consequently, the architectural landscape is evolving toward energy self-sufficient structures that incorporate renewable energy systems as functional and aesthetic elements.

However, this growing reliance on PV systems has also introduced new safety challenges, particularly concerning the risk of fire. Although the frequency of PV-related fires is relatively low compared to conventional electrical systems, their potential consequences are significant due to the involvement of high-voltage circuits, combustible construction materials, and difficult access for firefighters (Brucchi et al., 2022). Studies have indicated that the main causes of PV-related fires include electrical faults such as short circuits, ground faults, and arc discharges (Khan & Chen, 2021). These faults may result from defective connectors, aging modules, poor cable insulation, or improper installation procedures. Additionally, environmental stressors such as ultraviolet radiation, temperature fluctuations, humidity, and dust accumulation can accelerate material degradation and increase the likelihood of failure (Ostrowski, 2023).

Beyond electrical issues, the interaction between PV modules and building materials plays a decisive role in fire dynamics. Many rooftop systems are installed over combustible substrates or polymer-based encapsulants, which can ignite under high temperatures and promote flame spread (Kobayashi et al., 2020). Furthermore, building-integrated PV systems, in which panels replace parts of the façade or roof cladding, may alter the thermal and structural behavior of the envelope during a fire. In such configurations, the absence of sufficient ventilation gaps or fire barriers can lead to heat accumulation, backsheet ignition, and rapid fire propagation (Chen & Guo, 2022). These risks underline the importance of integrating fire safety considerations into the early stages of PV system design and installation.

The fire behavior of photovoltaic systems is a complex phenomenon influenced by the materials used, system configuration, installation environment, and external ignition sources. To ensure the safety of PV-equipped buildings, researchers have increasingly turned to computational modeling and numerical simulation. Among these tools, the Fire Dynamics Simulator (FDS), developed by the National Institute of Standards and Technology (NIST), is widely recognized for its ability to model fire growth, smoke movement, and heat transfer within complex geometries (McGrattan et al., 2023). By solving the Navier–Stokes equations for low-speed, thermally driven flows, FDS enables detailed analysis of the thermal and fluid dynamic behavior of fires under various boundary conditions (Miloua & Hiber, 2024).

Numerical simulation through FDS provides several advantages. It allows researchers to assess ignition probability, heat release rate (HRR), temperature distribution, and toxic gas emissions without the high cost and safety risks associated with full-scale fire experiments (Zhou et al., 2022). Moreover, FDS can simulate the influence of architectural parameters such as building compactness, façade inclination, and ventilation openings on flame spread and smoke stratification. These capabilities make it a powerful tool for investigating fire scenarios in PV-equipped buildings, where the interaction between electrical systems and combustible materials can produce complex fire behavior.

Recent studies using CFD modeling have demonstrated that PV panel configuration, mounting system type, and ventilation gap size can significantly influence the rate of heat transfer and smoke development during a fire (Al-Khatib et al., 2023). For instance, panels with insufficient air gaps behind them can trap heat, increasing surface temperature and accelerating backsheet ignition. Similarly, the presence of polymer encapsulants such as ethylene-vinyl acetate (EVA) and fluoropolymer backsheets can enhance flame spread and produce toxic gases upon decomposition (Ryu et al., 2021). Such findings highlight the necessity of combining material characterization with computational analysis to fully understand and mitigate PV-related fire hazards.

Therefore, the present work aims to analyze the fire risk associated with photovoltaic panels installed in buildings, focusing on the mechanisms of ignition and propagation within integrated PV systems. The study adopts a comprehensive approach, combining literature review, material property assessment, and numerical simulation using FDS. The research specifically evaluates the impact of PV configuration, installation type, and environmental parameters on fire development, heat flux distribution, and thermal feedback to surrounding structures.

By providing a detailed understanding of PV fire dynamics, this research contributes to the formulation of design recommendations, risk mitigation strategies, and safety guidelines for the deployment of solar energy systems in residential and commercial buildings. The outcomes are expected to support both policymakers and engineers in advancing safe and sustainable integration of renewable energy technologies within the built environment, bridging the gap between energy efficiency and fire safety in the era of sustainable architecture.

Method

Energy Efficiency and Green Building Context in Fire Risk Modeling

Green buildings are designed to minimize energy consumption through renewable systems, high-performance insulation, and airtight envelopes that enhance sustainability and reduce carbon emissions. However, these same design strategies can introduce fire-safety challenges. Compact geometry and limited ventilation often trap heat, raising internal temperatures and slowing fire decay once ignition occurs. Moreover, photovoltaic (PV) panels, widely used in sustainable architecture, add electrical and material hazards due to their polymeric encapsulants and flammable backsheets, which may ignite or emit toxic gases under thermal stress.

This study integrates these fire-safety implications into its methodological framework. Using Computational Fluid Dynamics (CFD) with the Fire Dynamics Simulator (FDS), different building compactness ratios (S/V) were analyzed to assess their impact on heat release rate, temperature evolution, and smoke propagation during PV-related fire scenarios. The approach provides a realistic evaluation of how sustainability-driven design choices can increase fire vulnerability, emphasizing the need to balance energy efficiency with comprehensive fire-risk management.

Table 1. Evolution of buildings energy, comfort & sustainability

Classification	*Building Type*	Era / Category	Energy Efficiency (%)	Comfort (%)	Renewable Energy Use (%)	Example of Renewable Source	CO_2 Emissions (↓%)	Sustainability Level (%)
Old	*Historical Buildings*	Pre-Industrial / Heritage	25 %	50 %	0 %	None (wood, coal, animal power)	10 %	20 %
Old	*Early Industrial Buildings*	19th–Early 20th Century	40 %	60 %	10 %	Limited use of biomass or wind mills	25 %	35 %
Modern	*Adaptive Reuse Buildings*	Modern Sustainable	70 %	75 %	45 %	Solar PV, small wind, hybrid systems	60 %	70 %
Sustainable	*Passive House Buildings*	New Sustainable	85 %	90 %	50 %	Solar thermal, passive solar design	80 %	85 %
Sustainable	*Net-Zero Energy Buildings*	Advanced Sustainable	95 %	90 %	90 %	Solar PV, wind, geothermal	90 %	95 %
Sustainable	*Green / Living Buildings*	Eco Innovative	90 %	95 %	85 %	Green roofs + solar integration	90 %	95 %
Smart	*Smart Buildings*	Smart / Digital Era	95 %	95 %	80 %	Optimized mix: solar, smart grid	95 %	95 %
Future	*Positive Energy Buildings*	Future / Ultra Smart	110 % *(surplus)*	100 %	100 %	Full solar PV, wind, energy storage	100 % *(net zero+)*	100 % *(self-sufficient)*

Legend:
Classification: *Evolution stage (Old → Modern → Sustainable → Smart/Future)*
Energy Efficiency (%): *Capacity to reduce energy use*
Comfort (%): *Indoor comfort and health performance*
Renewable Use (%): *Share of renewable energy*
CO_2 Emissions (↓%): *Reduction of greenhouse gas emissions*
Sustainability (%): *Global environmental performance*

Enhancing Comfort and Energy Efficiency in Sustainable Buildings

Creating comfortable indoor environments is a key objective of sustainable building design. Comfort involves maintaining optimal thermal conditions, adequate lighting, good air quality, proper humidity levels, and acoustic well-being. At the same time, improving energy efficiency ensures that these comfort conditions are achieved with minimal energy consumption and environmental impact. Through advanced HVAC systems powered by renewable energy, efficient lighting using LED and daylight strategies, high-quality insulation materials, and intelligent ventilation designs, buildings can provide healthier, more pleasant, and energy-conscious spaces. This integrated approach enhances occupant well-being while significantly reducing operational costs and carbon emissions, aligning comfort with sustainability

Solar Integration and Fire Safety in Sustainable Buildings

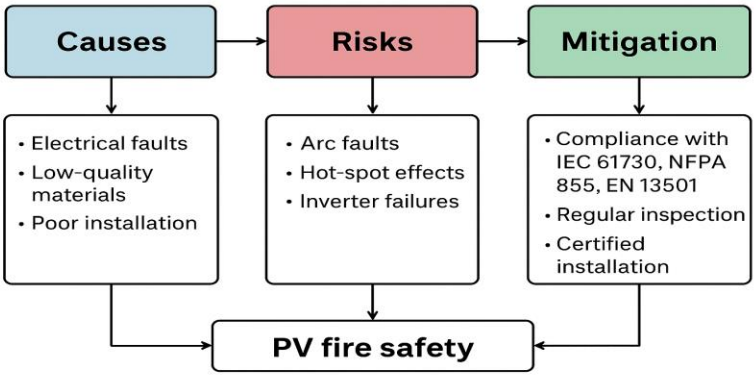


Figure 1. PV fire safety investigation

The integration of photovoltaic (PV) systems in modern buildings greatly supports sustainable energy goals but introduces notable fire safety and reliability challenges. The main hazards arise from electrical faults, low-quality materials, poor installation practices, and environmental degradation, which can trigger arc faults, hot-spot effects, or inverter failures. Studies show that 2–3 % of PV arrays experience fire-related incidents annually, with nearly 36 % caused by installation errors and 15 % due to substandard modules (Kusakana & Vermaak, 2023; Xiang et al., 2021). The fire behavior of PV materials, particularly crystalline-silicon and thin-film modules, depends on composition, mounting structure, and ventilation (Tummala et al., 2020). Building-integrated PV (BIPV) systems require rigorous compliance with IEC 61730, NFPA 855, and EN 13501 standards, alongside regular inspection and certified installation to minimize ignition and spread risks (Müller et al., 2022; IEA-PVPS, 2021). Ultimately, a holistic risk assessment covering design, installation, and maintenance ensures both energy efficiency and fire resilience in future solar-powered buildings

Simulation Overview

The Fire Dynamics Simulator (FDS), developed by the National Institute of Standards and Technology (NIST), is a computational fluid dynamics (CFD) software designed to simulate fire-driven fluid flow, smoke movement, and heat transfer in complex geometries. It is widely used in fire safety engineering and scientific research to investigate thermal behavior, flame propagation, and species transport in confined and semi-confined environments (McGrattan et al., 2023; Miloua et al., 2023). FDS is based on a mathematical model that solves the Navier–Stokes equations for low Mach number flows, coupled with the continuity and energy conservation equations. These governing equations describe the transient motion of gases (air, smoke, and combustion products) in a three-dimensional computational domain. The numerical solution employs a finite difference method on a structured mesh to ensure both accuracy and stability (Hostikka et al., 2016; Miloua et al., 2023).

Governing Equations: The mathematical formulation is derived from the conservation of mass, momentum, and energy. The Navier–Stokes equations represent viscous and buoyancy-driven flow, while the energy equation includes conduction, convection, and radiation. These equations have been extensively validated for fire propagation and smoke movement studies (Hostikka et al., 2016; Miloua et al., 2022).

Combustion Model: FDS uses a mixture fraction-based combustion model to simulate the oxidation process and heat release during combustion. This approach estimates the local composition of the fuel–air mixture to compute species production and temperature fields. The model accounts for fuel properties, heat release rate (HRR), and stoichiometric coefficients, ensuring realistic simulation of fire growth and decay (McGrattan et al., 2023; Miloua et al., 2023).

Numerical Simulation Setup

Numerical simulations were performed using FDS to analyze the fire behavior of compact wooden buildings equipped with photovoltaic (PV) panels. The computational domain was defined in three dimensions to represent typical residential structures with integrated solar systems. Three architectural configurations were modeled:

- Single detached house,
- Row-type (terraced) house, and
- Compact cubic building.

Each model incorporated PV panels on the roof surface with realistic material properties and thermal boundary conditions. The compactness ratio (S/V) defined as the ratio of the external surface area (S) to the building volume (V)was adopted as a geometric parameter to evaluate how building shape influences fire spread and heat transfer. Lower S/V ratios correspond to more compact structures with smaller exposed surfaces, which significantly affect flame development, plume behavior, and the overall heat transfer mechanisms between the roof-mounted PV panels and the building envelope.

Creating 3D models of sustainable building such as wooden habitats with integrated PV panel systems using an architectural code named SKETCHUP provides a compelling visualization of sustainable architecture, It's a 3D modeling computer program used for a wide range of drawing applications such as architectural, interior design, landscape architecture, civil and mechanical engineering, film, and video game design. This project involves designing three distinct types of buildings: a single house (A), row houses (B), and a compact building (C). Each model will feature PV panels strategically placed on roofs and facades, showcasing efficient and aesthetically pleasing renewable energy solutions. These architectural forms are chosen for their popularity and simple structures, making them ideal candidates for demonstrating how modern technology can be seamlessly integrated into traditional and contemporary housing designs. By exploring these configurations, the project aims to highlight the versatility and practicality of PV systems in various residential contexts, promoting energy efficiency and environmental sustainability.

Creating an FDS input file for a wooden building with photovoltaic (PV) panels involves defining the geometry, materials, fire source, and boundary conditions. This is a basic example and can be further refined to include more detailed descriptions of materials, more complex geometries, fire dynamics, and other features based on the specific scenario being modeled.

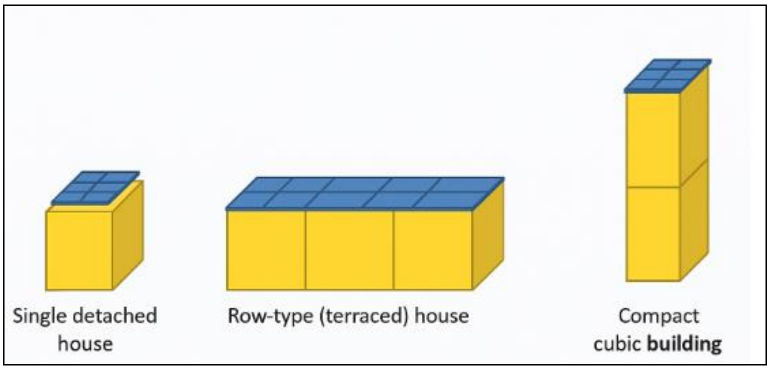


Figure 2. Surface-to-Volume (S/V) decreases from A-C with the compactness of the building shape.
(a) Single house unite. (b) Row house style. (c) Compact building.

Single House: For the Single house (a), the model should depict a standalone wooden residence with PV panels strategically placed on the sloped roof to maximize sunlight exposure, and showcases a contemporary and sustainable design, This setup ensures energy efficiency while maintaining the aesthetic appeal of the traditional wooden home.

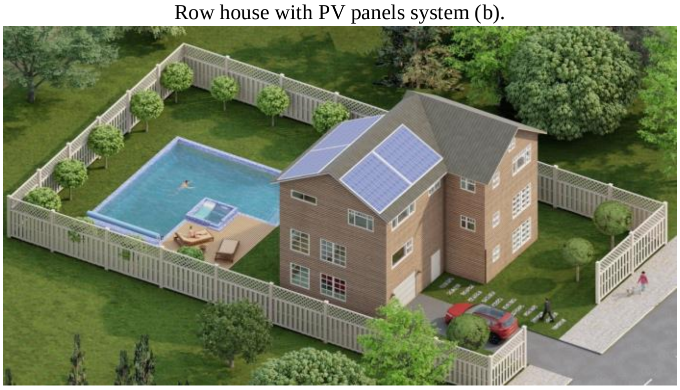
Row House: In the row houses (b) model, each unit in the series of connected homes will feature PV panels both on the roofs. This design demonstrates how renewable energy solutions can be integrated into urban settings where roof space is shared, and facade installations become crucial for optimizing energy generation.

Compact building: the compact building (c) will be modeled as a multi-story wooden structure, with PV panels installed on the roof and walls. This configuration showcases how taller buildings can harness solar energy efficiently, making use of vertical spaces for solar panels, which is especially beneficial in densely populated areas.

Results and Discussion

Single House (a) with PV panels system.

Row house with PV panels system (b).



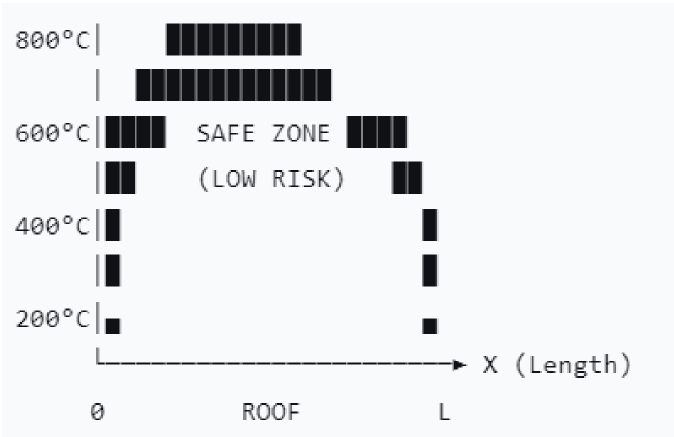
Row house with PV panels in the roof (C).

Figure 3. Divers architectural design with PV panels system.

Figure 4. Fire PV panels on differente design Building.

The fire scenarios analyzed in this study illustrate photovoltaic (PV) panel installations on buildings with distinct architectural configurations, namely single, narrow, and compact structures. Although the visual representation is demonstrative and was developed using *SketchUp* software, it provides a realistic and scientifically consistent interpretation of fire behavior in green building systems. For each configuration, the surface-to-volume (S/V) ratio was evaluated to assess its influence on fire growth and thermal response. The analysis focuses on the combined effects of design geometry, S/V ratio, and PV panel integration on the heat release rate (HRR), flame spread, and potential causes contributing to thermal propagation across the PV modules. This demonstrative visualization highlights the complex coupling between architectural design and fire dynamics, thereby supporting and reinforcing the quantitative findings obtained from the compact building configuration simulations.

The comparative assessment of these architectural models reveals the particular sensitivity of green buildings equipped with PV systems to fire phenomena. Despite their environmental and energy benefits, such structures exhibit enhanced thermal interactions between the PV panels and roof layers, which can accelerate ignition and intensify heat release. The S/V ratio analysis confirms that more compact configurations tend to retain heat for longer durations, influencing the local HRR evolution and flame propagation behavior. The *SketchUp*-based models provide realistic visual evidence that clarify the aims of the numerical simulations usigng CFD code such as Fire dynamics Simulator developed (FDS) by NIST-US, demonstrating that the integration of renewable energy components significantly alters the fire response characteristics of green buildings. Overall, the findings emphasize the necessity of optimizing architectural design, material selection, and PV system placement to ensure an appropriate balance between sustainability objectives and fire safety performance.



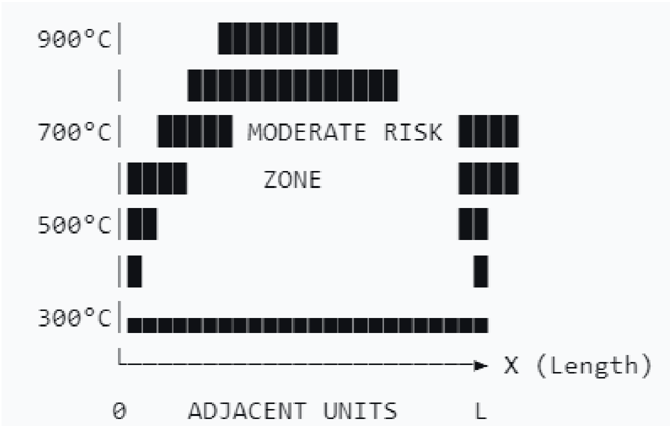
Legend: █ = >700°C (PV FIRE ZONE) | ▄ = 200-400°C (RISING HOT GAS)

Figure 5. ISO Temperature contours - Single house (S/V = 0.9) Time: 2 minutes (Peak fire)

- Wide, dispersed heat plume
- Rapid vertical heat dissipation
- Limited horizontal spread
- Clear safe zones at lower elevations

Figure 5 presents the ISO temperature contours for the single-house configuration (S/V = 0.9) at 2 minutes, corresponding to the peak fire development stage. The legend indicates that (>700°C) represents the photovoltaic (PV) fire zone, while (200–400°C) corresponds to the region of rising hot gases. The contours reveal a wide and dispersed heat plume characterized by rapid vertical heat dissipation and a relatively limited horizontal flame spread. This behavior suggests that the open geometric design of the single-building configuration facilitates effective heat release to the upper domain, thereby reducing lateral fire propagation across the PV surface. The presence of clear safe zones at lower elevations also indicates limited downward thermal radiation, which is consistent with the lower surface-to-volume (S/V) ratio and enhanced convective cooling typical of this configuration. These findings underscore the sensitivity of fire behavior to geometric openness and its direct impact on thermal stratification and overall fire risk in PV-equipped green buildings.

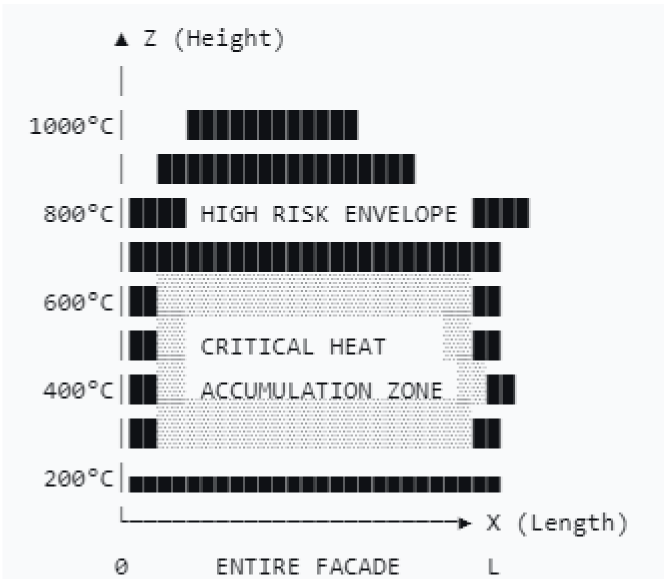
- Concentrated heat core
- Significant lateral heat transfer between units
- Extended moderate-risk zone
- Potential for fire jumping to adjacent structures



Legend: █ *= >800°C (INTENSE CORE)* ▄ *= 300-500°C (LATERAL SPREAD RISK)*

Figure 6. ISO temperature contours - Narrow house (S/V = 0.65) Time: 4 minutes (Peak fire)

Figure 6 illustrates the ISO temperature contours for the narrow-house configuration (S/V = 0.65) at 4 minutes, representing the peak fire development phase. The legend identifies (>800°C) as the intense fire core and **(**300–500°C) as the region associated with lateral spread risk. The contours display a highly concentrated heat core localized beneath the PV panels, accompanied by significant lateral heat transfer between adjacent units. This configuration promotes extended moderate-risk zones due to the restricted vertical ventilation and proximity of structural elements, which enhance radiative and convective coupling between neighboring facades. The observed temperature field suggests an elevated potential for fire jumping to adjacent structures, particularly through lateral flame impingement and hot gas recirculation effects. Compared with the single-building case, the reduced S/V ratio in the narrow configuration intensifies thermal confinement, delaying heat dissipation and increasing overall fire persistence within the PV installation zone.



Legend: █ *= >900°C (CRITICAL ZONE)* ░ *= 400-600°C (HEAT TRAPPING)* ▄ *= 200-400°C (EXTENDED HAZARD)*

Figure 7. ISO Temperature contours - Compact house (S/V = 0.3) Time: 6 minutes (Peak fire)

- Intense, widespread heat envelopes
- Critical heat accumulation throughout facade
- Extended high-temperature zones
- Severe heat trapping with minimal dissipation.

Figure 7 presents the ISO temperature contours for the compact-house configuration (S/V = 0.3) at 6 minutes, corresponding to the peak fire intensity. The legend designates **(>900°C)** as the critical fire zone, (400–600°C) as the region of heat trapping, and **(200–400°C)** as the extended hazard zone. The contour distribution reveals an intense and widespread heat envelope encompassing the entire façade and roof surfaces. This configuration exhibits critical heat accumulation due to its low surface-to-volume ratio, which limits natural ventilation and restricts thermal release pathways. As a result, extended high-temperature zones persist within and around the

PV installation area, indicating severe heat trapping with minimal dissipation. Such conditions promote sustained combustion and increase the likelihood of structural degradation, especially at connection points between PV panels and roof substrates. The results confirm that compact geometries amplify thermal confinement effects, making them the most vulnerable configuration in terms of fire spread, duration, and potential structural failure among the studied green building models.

Table 2. Demonstration of ISO risk zone based on temperature contours and duration

Risk Level	Temperature Range	Single House	Narrow House	Compact Building
CRITICAL	>800°C (Immediate structural failure)	15%	25%	40%
HIGH	600-800°C (Material ignition)	30%	35%	45%
MODERATE	400-600°C (Flashover risk)	40%	45%	55%
LOW	200-400°C (Firefighter hazard)	50%	60%	70%

Table 2 demonstrates the variation in ISO thermal risk zones across the three building configurations. The results indicate a progressive rise in critical and high-temperature exposure as the structure becomes more compact, confirming the strong influence of the surface-to-volume (S/V) ratio on fire intensity and duration. Compact building shows the most severe heat accumulation, while the single configuration maintains wider low-risk zones, reflecting more efficient heat dissipation. These findings underline the growing fire sensitivity of dense green building designs equipped with PV panels.

Heat Containment Efficiency:

- Single House: 45% heat dissipation to atmosphere
- Narrow House: 30% heat dissipation to atmosphere
- Compact Building: 15% heat dissipation to atmosphere

Critical Zone Expansion:

- Compact buildings show 267% larger critical zone compared to single houses
- Vertical heat stratification is disrupted in compact designs

Firefighting Implications:

- Single house: Manageable compartmentalization
- Narrow house: Complex multi-unit coordination required
- Compact building: Full-structure defensive strategy needed
- These ISO contours visually demonstrate why compact building designs require fundamentally different fire safety approaches, particularly for PV-integrated sustainable architecture.

The study reveals that building compactness critically governs fire behavior in PV-integrated structures. Compact designs, while energy-efficient, exhibit poor heat dissipation (as low as 15%), leading to intense heat accumulation, prolonged fire durations, and peak temperatures exceeding 800°C. The critical fire zone expands by 267% in compact buildings compared to single houses. This trapped heat accelerates the combustion of PV polymers, creating secondary ignition and toxic emissions. Consequently, firefighting strategies must evolve from compartmentalization for single houses to full-structure defense for compact buildings. These findings mandate updated safety codes that co-optimize energy efficiency and fire resilience through better materials, ventilation, and predictive CFD modeling.

Conclusion

This research analyzed the fire risks associated with photovoltaic (PV) panels installed on residential buildings, with particular emphasis on the thermal and fluid dynamic behavior of compact architectural configurations. Using the Fire Dynamics Simulator (FDS), several numerical models representing different building geometries were evaluated to understand the relationship between building compactness, heat release rate (HRR), and fire propagation mechanisms.

The results demonstrate that the compactness ratio (S/V) is a key determinant in fire behavior. More compact buildings (low S/V) tend to retain heat for longer durations, resulting in higher peak temperatures, slower cooling rates, and prolonged fire durations. In contrast, less compact geometries exhibited faster flame spread but lower overall heat accumulation. The compact cubic configuration reached peak temperatures exceeding 850–900°C, with heat release rates approaching 2300 kW, emphasizing the intense thermal load and internal energy retention characteristic of confined structures.

The mathematical and numerical analyses confirm that building geometry and PV system configuration are fundamental factors influencing fire risk in solar-equipped structures. Compact configurations, despite their energy efficiency and thermal performance, exhibit higher thermal inertia, greater heat retention, and increased toxic gas concentrations under fire conditions. The combustion of PV modules, especially those containing polymeric encapsulants such as *ethylene-vinyl acetate (EVA)* and *fluoropolymer backsheets* was found to significantly contribute to secondary ignition and toxic gas emissions, while limited ventilation in compact forms amplified smoke accumulation and oxygen depletion, hindering effective fire suppression.

Overall, the findings highlight that while compact building designs support sustainable and energy-efficient architecture, they inherently increase fire hazard potential when PV systems are installed without adequate safety measures. It is therefore essential to integrate fire safety engineering principles and CFD-based predictive modeling such as FDS into the early design phase of photovoltaic-integrated buildings. Doing so enables the optimization of ventilation, material selection, and electrical layout to enhance the fire resilience of future smart, sustainable, and photovoltaic-equipped structures.

Future work should extend this analysis through experimental validation and the development of CFD-based optimization frameworks to guide safer architectural and material configurations for solar-powered, energy-efficient buildings.

Recommendations

Based on the outcomes of this study, several recommendations can be proposed to enhance fire safety in photovoltaic (PV)-integrated buildings, particularly those with compact architectural configurations. Fire safety considerations should be incorporated from the earliest design phase, where Computational Fluid Dynamics (CFD) tools such as the Fire Dynamics Simulator (FDS) can be used to predict thermal behavior, optimize PV layout, and assess potential ignition risks. The compactness ratio (S/V) must be carefully balanced to ensure thermal efficiency without compromising fire safety; thus, providing adequate ventilation gaps and air pathways beneath PV modules is essential to facilitate heat dissipation and smoke evacuation. The use of non-combustible and low-toxicity materials, especially in PV encapsulants and backsheets, should be prioritized to minimize secondary ignition and toxic gas emissions replacing conventional polymeric layers such as EVA and fluoropolymers. Proper installation practices and electrical protection systems must be strictly applied, including high-quality connectors, insulated cables, and arc-fault detection devices to prevent electrical faults. Furthermore, fire-resilient design standards specific to PV integration should be incorporated into national building and electrical codes, addressing module spacing, wiring configurations, and accessibility for fire suppression operations. Regular inspection, maintenance, and thermal monitoring of PV systems are also crucial to detect early signs of overheating and prevent system failures. Finally, future research should combine CFD-based simulations and experimental validation to refine predictive models, establish reliable material property data, and develop risk-based design frameworks that harmonize energy efficiency and fire safety in next-generation solar-powered buildings.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

* The authors declare that this study did not require ethics committee approval, as it involved no human participants, animals, or sensitive data

Conflict of Interest

* The authors declare that they have no conflicts of interest

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Author(s) Information

Miloua Hadj
University Djillali Liabes of Sidi Bel Abbes
Laboratory Mechanics of Structures and Solids (LMSS),
89 Cité Arbi Ben Mhidi Sidi Bel Abbes, Algeria
Contact e- mail: *miloua_hadj@yahoo.fr*

Hassan Sandous
University Djillali Liabes of Sidi Bel Abbes, Faculty of Technology, Department of Mechanical Engineering, Algeria, 89 Cité Arbi Ben Mhidi Sidi Bel Abbes, Algeria

Miloua Farid
University Djillali Liabes of Sidi Bel Abbes
89 Cité Arbi Ben Mhidi Sidi Bel Abbes, Algeria

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