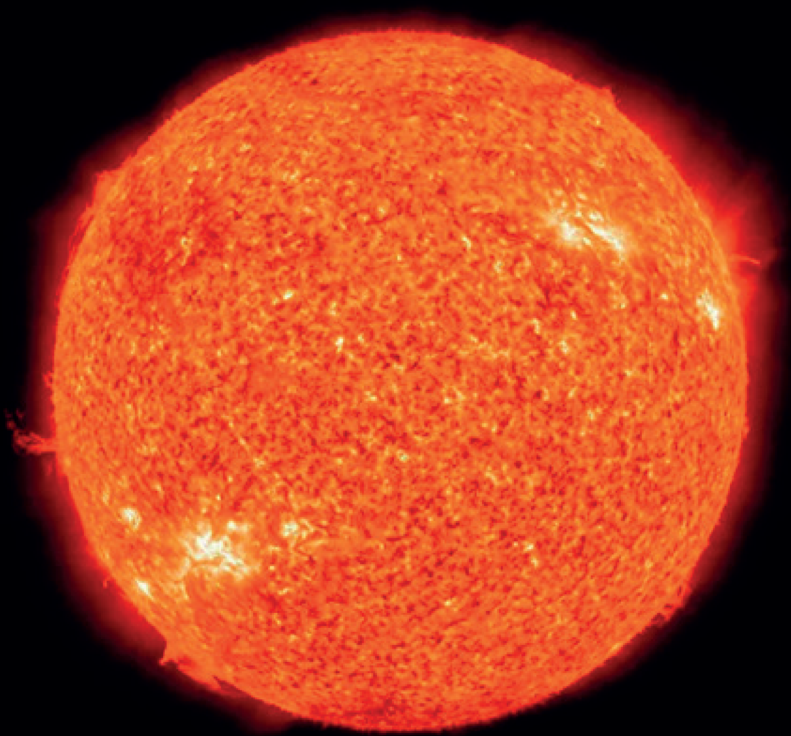

# First-year 3FiRES Booklet

• Workshop and network updates about • Research on BIPV Photovoltaic Facades for Fire Spread Mechanisms, Structural Failures and Resilience Improvement Methodologies

• edited by **Chiara Bedon** & **Yu Wang** •

EUT

[…] There are no doubts that the first-year of scientific activities for the running 3FiRES project represented a powerful opportunity of scientific network and growth for the members of research units on both the Italian and Chinese sides, as well as a unique international experience to share methodologies and discuss new strategies for the analysis of BIPV components and facades in fire […]
**Chiara Bedon, Yu Wang**

[…] Talking about the optimization of novel prototypes, for example, robust standardized methodologies of experimental investigation are of utmost importance. However, the same consideration can be extended to in-service plants, where efficient diagnostic strategies have a primary role for the analysis of photovoltaic components and systems, both under ordinary and accidental operational conditions. […]
**Chiara Bedon, Yu Wang**

[…] solar energy has become part of the building fabric as a sustainable alternative, and then it has become obligatory and, today, increasingly indispensable. This is a great opportunity for architectural, urban and landscape design, but let us not forget that when we use and transform this technological device in architecture, solar is synonymous with happiness and beauty […]
**Adriano Venudo**

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**EUT** EDIZIONI UNIVERSITÀ DI TRIESTE

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Editors: Chiara Bedon, Yu Wang
Contributors: Olaia Aurrekoetxea-Arratibel, Chiara Bedon, Thomas Bisiani, Nicola Blasuttigh, Nicola Cella, Haonan Chen, Riccardo Del Bello, Mariacristina D'Oria, Alberto Dolara, Francesco Frontini, Yiyang Hu, Andrea Lucherini, Michela Lupieri, Alessandro Massi Pavan, Adel Mellit, Elisabetta Nascig, Ainhoa Odriozola-Alberdi, Emanuele Ogliari, Xabier Olano-Azkune, Nerea Otano-Aramendi, Fabio Parolini, Giombattista Traina, Adriano Venudo, Lorenzo Veronese, Yu Wang, Chengming Xiao, Liaoying Zhou

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This volume collects some scientific research results from the first year of activities and Workshop contributions (October 7th, 2024, Trieste & online) of the running "Particular Relevance" Italy-China bilateral project 3FiRES - "Research on BIPV Photovoltaic Facades for Fire Spread Mechanisms, Structural Failures and Resilience Improvement Methodologies" (2024-2025). 3FiRES research partners are the University of Trieste, Department of Engineering and Architecture (Principal Investigator Prof. Chiara Bedon) and University of Science and Technology of China, State Key Laboratory of Fire Science (Principal Investigator Prof. Yu Wang). The scientific activities of 3FiRES project are partly financially supported by the Italian Ministry of Foreign Affairs and International Cooperation (grant number CN24GR03) and National Key R&D Program of China (grant number 2023YFE0116700).

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# Understanding the failure mechanisms of building-integrated photovoltaics (BIPV) under different thermal and mechanical conditions

**Andrea Lucherini** *(1)** **, Chiara Bedon**
*(1) Department for Fire-Safe Sustainable Built Environment (FRISSBE), Slovenian National Building and Civil Engineering Institute (ZAG), Slovenia*
*(2) Department of Engineering and Architecture, University of Trieste, Trieste, Italy.*
**Corresponding author: andrea.lucherini@zag.si*

**Abstract**
Sustainability drivers are pushing the built environment to increasingly rely on renewable energy resources and, accordingly, photovoltaics panels are more and more installed into the building envelope, particularly in facades and roofs. The presented experimental study investigates the failure mechanisms of building-integrated photovoltaics (BIPV) under different thermal and mechanical conditions. Using high-performance radiant panels, commercial BIPV modular units are fire tested under a range of thermal and mechanical conditions of practical interest: at the exposed surface, at the unexposed substrate, and at the BIPV mechanical boundaries. The typical failure mechanism is studied analysing the temperature evolution at specific control points, as well as deflections and strains over the BIPV units. The overall goal of the research project is understanding the failure mechanisms of BIPV modular units to provide design and testing recommendations to increase the safety of these systems under combined fire and mechanical loads.

**Keywords**
Building-integrated photovoltaics; fire safety; fire testing; failure mechanism; thermal boundary conditions; mechanical boundary conditions.

## Introduction

Building-integrated photovoltaics (BIPV) have emerged as a prominent solution for integrating energy generation into the building envelope, particularly in facades and roofs, where they replace conventional materials (see Figure 1). BIPV systems offer substantial contributions towards achieving net-zero energy buildings, while also posing complex challenges related to multifunctional optimal design, encompassing structural safety, architectural impact, energy efficiency, and other factors [01].

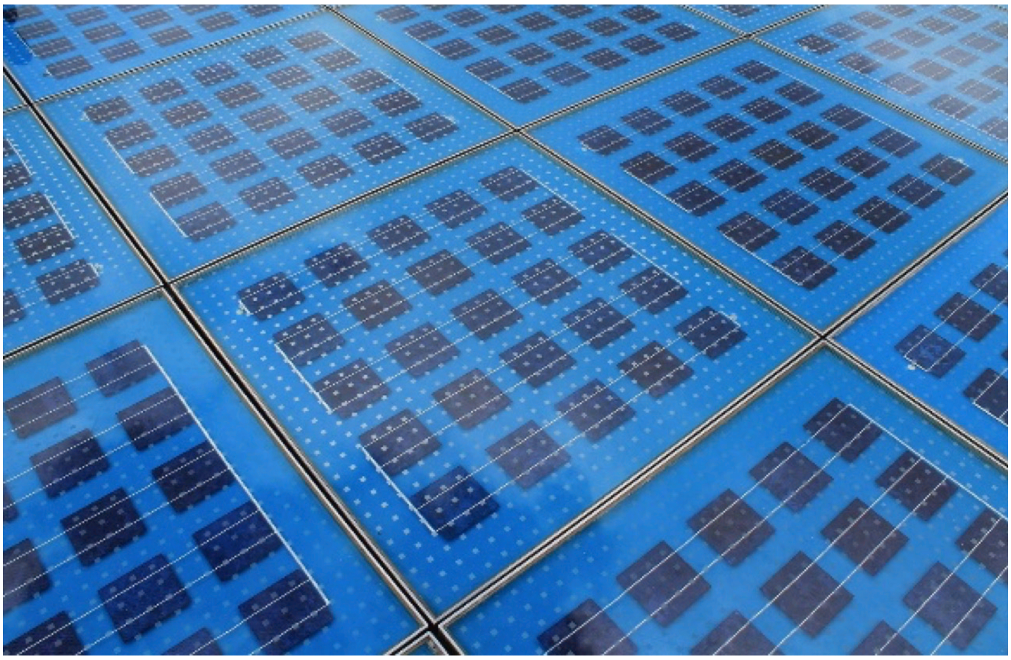

Figure 1. *Building-integrated photovoltaics (BIPV)* [02].

Among others, one of the most pressing concerns in the development of innovative BIPV systems is fire safety [03-05]. Indeed, by being building products and key components of the building's envelope, fire safety requirements apply to these systems. In particular, it must be ensured that BIPVs in facades and roofs do not promote fire spread and compromise the fire safety strategy, as well as they are capable of withstanding the thermal and mechanical loads caused by a post-flashover fire.

Despite the growing adoption of BIPV technologies, several challenges remain in ensuring that these multifunctional products can meet fire safety requirements across multi domains (e.g. electrical, structural, flammability) [03-05]. More specifically, there is a significant gap in standardized protocols, methodologies, and performance indicators for assessing the behaviour of BIPV systems when exposed to fire, more generally elevated temperatures. These standards vary across different countries, and they are often based on existing frameworks (i.e. reaction to fire and fire resistance). However, there is confusion about which fire scenario and performance criteria can be applied to these new composite systems. These gaps create a barrier to the widespread market adoption of BIPV technologies and addressing them is critical to advancing the field.

**Project objectives**
The overall goal of this research project is to experimentally investigate and analyse the behaviour of commercial BIPV modular units under a range of fire conditions. The primary goal is the thermo-mechanical analysis and characterisation of failure mechanisms for glass-glass BIPV modular units with variable geometrical sections, as well as different thermal and mechanical boundary conditions.

This research is carried out in connection with a 2-years Italy-China bilateral project related to the behaviour of BIPV facades under accidental actions (3FiRES, https://3fires.dia.units.it/). The Department of Engineering and Architecture of the University of Trieste (Italy) and the State Key Laboratory of Fire Science of the University of Science and Technology of China (China) are the main investigators. This experimental investigation aims at contributing to the overall objectives of the 3FiRES project.

**Methodology**
The experimental campaign foresees a series of fire tests on building-integrated photovoltaics (BIPV) units using a high-performance radiant panels testing apparatus, recently developed and assembled at the ZAG Fire Laboratory (see Figure 2). The radiant panel system was designed in line with the Heat-Transfer Rate Inducing System (H-TRIS) test method

developed at the University of Edinburgh [06]. The testing apparatus is first calibrated to qualify the incident radiant heat flux received by test samples at different stand-off distances between the radiant panel's surface and the sample's exposed surface. Based on the obtained calibration curve, a number of constant incident heat fluxes imposed on the exposed surface of test samples and test duration are chosen.

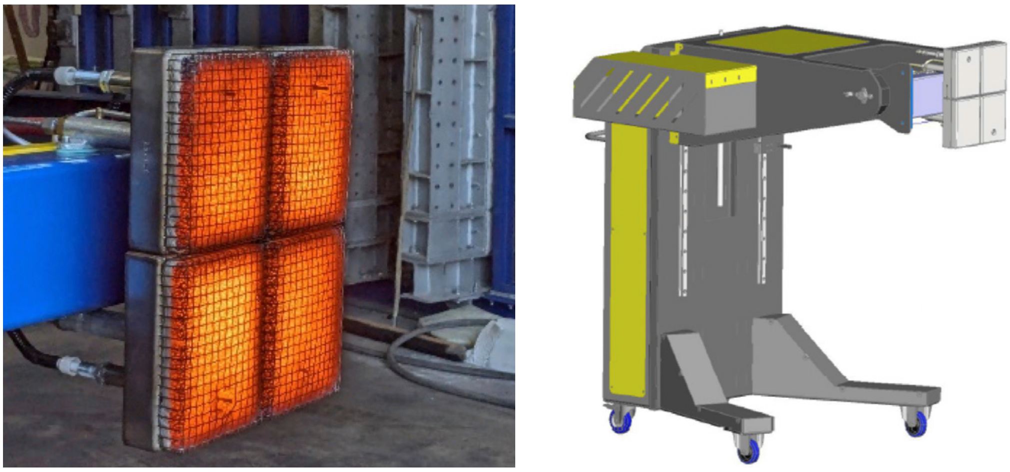

Figure 2. *ZAG high-performance radiant panels testing apparatus.*

The test specimens are commercial building-integrated photovoltaics (BIPV) modular units, manufactured by GruppoSTG (see Figure 3). The typical BIPV units consist of two tempered glass layers, each 4 mm thick, and a thin PVB encapsulant including solar cells. The reference product (1025 x 1000 mm in standard size, 36 monocrystalline cells) is of typical use for facades, and it is usually mounted using metal point fixing connectors.

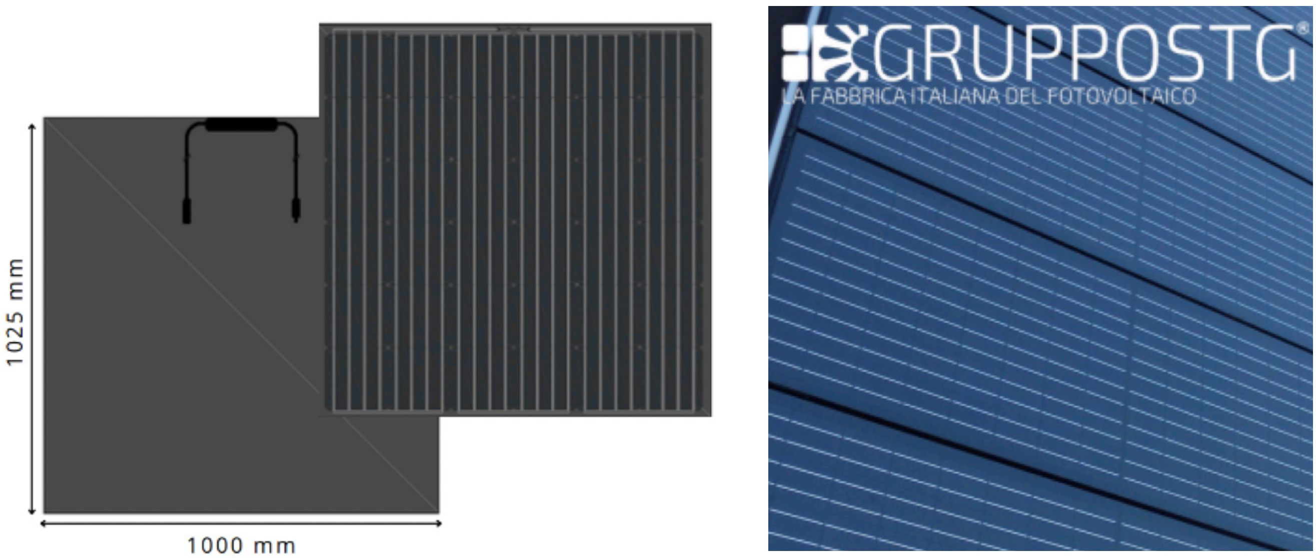


Figure 3. *Test specimens: commercial BIPV modular units.*

The experimental campaign focuses on understanding and quantifying the influence of the following experimental variables on the failure mechanism of single BIPV modular units:

- Thermal boundary conditions at surface: different constant incident radiant heat fluxes imposed at the exposed surface of the BIPV units (e.g. 25, 50, 75 $kW/m^2$).
- Mechanical boundary conditions: the BIPV units are tested with or without the metal frame and point fixing connectors at their boundaries.
- Inclination: the BIPV units are tested in different orientations (vertical, horizontal, inclined at 45°).
- Thermal boundary conditions at substrate: different thermal boundary conditions at the unexposed surface of the BIPV units are imposed (e.g. with or without thermal insulation).

For each experimental condition, three repetitions are foreseen. The BIPV units are instrumented to measure:

- Temperatures at selected control points over the BIPV units using type-K thermocouples.
- Deflections (and deflection rates) in the centre of the BIPV units using linear variable differential transformers (LVDT).
- Strains at the surface of BIPV units using strain gauges.

During the experiments, special attention is paid on the failure mechanism of the fire-exposed BIPV units by observing and reporting the glass failure time, cracking behaviour (e.g. first cracks, first and second glass layer, at the centre and at supports) and post-cracked response.

**Expected results**
From the described experimental campaign, the expected results to be obtained are the following:

- Development and commissioning of an experimental methodology to test BIPV units with various geometries, as well as different thermal and mechanical boundary conditions.

- Obtain high-fidelity experimental data (e.g., temperatures, deflections, strains, cracks).
- Understanding the effects of thermal boundary conditions at surface, mechanical boundary conditions at boundaries, inclination, and thermal boundary conditions at substrate on the failure mechanisms of BIPV modular units.
- Definition of design suggestions and testing parameters to consider the governing factors that influence the failure mechanisms of BIPV modular units in fire conditions.

**Concluding remarks**

The described research project aims at experimental analysing the failure mechanisms of building-integrated photovoltaics (BIPV) under different thermal and mechanical conditions. The outcomes of this research will provide essential data that can inform the development and calibration of standardized assessment procedures, ultimately supporting the creation of safer and more reliable BIPV systems for widespread use. The project will help to develop simplified strategies for the detection and assessment of failure modes in BIPV facades under combined fire and mechanical loads. The research will also serve as a basis to implement and calibrate numerical Finite Element Models (FEM) aimed at predicting the failure of BIPV modular units in specific thermal and mechanical conditions.

**Acknowledgements**

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**References**

**[01]** The International Energy Agency. (2023). Snapshot of Global PV Markets. Report IEA-PVPS T1-44:2023.
**[02]** https://pixabay.com/it/users/pruzi-179411/; accessed on October 2024.
**[03]** N.A.F.M.N. Ong, M.A. Sadiq, M.S.M. Said, G. Jomaas, M.Z.M. Tohir, J.S. Kristensen, *Fault tree analysis of fires on rooftops with photovoltaic systems*, in: "Journal of Building Engineering", n. 46: 103752, 2022.
**[04]** Slovenian National Building and Civil Engineering Institute (ZAG), *Fire Safety Guideline for Building Applied Photovoltaic Systems on Flat Roofs*, 2024.
**[05]** Y. Wang, C. Xiao, C. Bedon, *Performance of photovoltaic panels with different inclinations under uniform thermal loading*, in: "International Journal of Thermal Sciences", n. 208: 109489, 2025.
**[06]** C. Maluk, L. Bisby, M. Krajcovic, J.L. Torero, *A heat-transfer rate inducing system (H-TRIS) test method*, in: "Fire Safety Journal", n. 105, 2019, pp. 307-319.

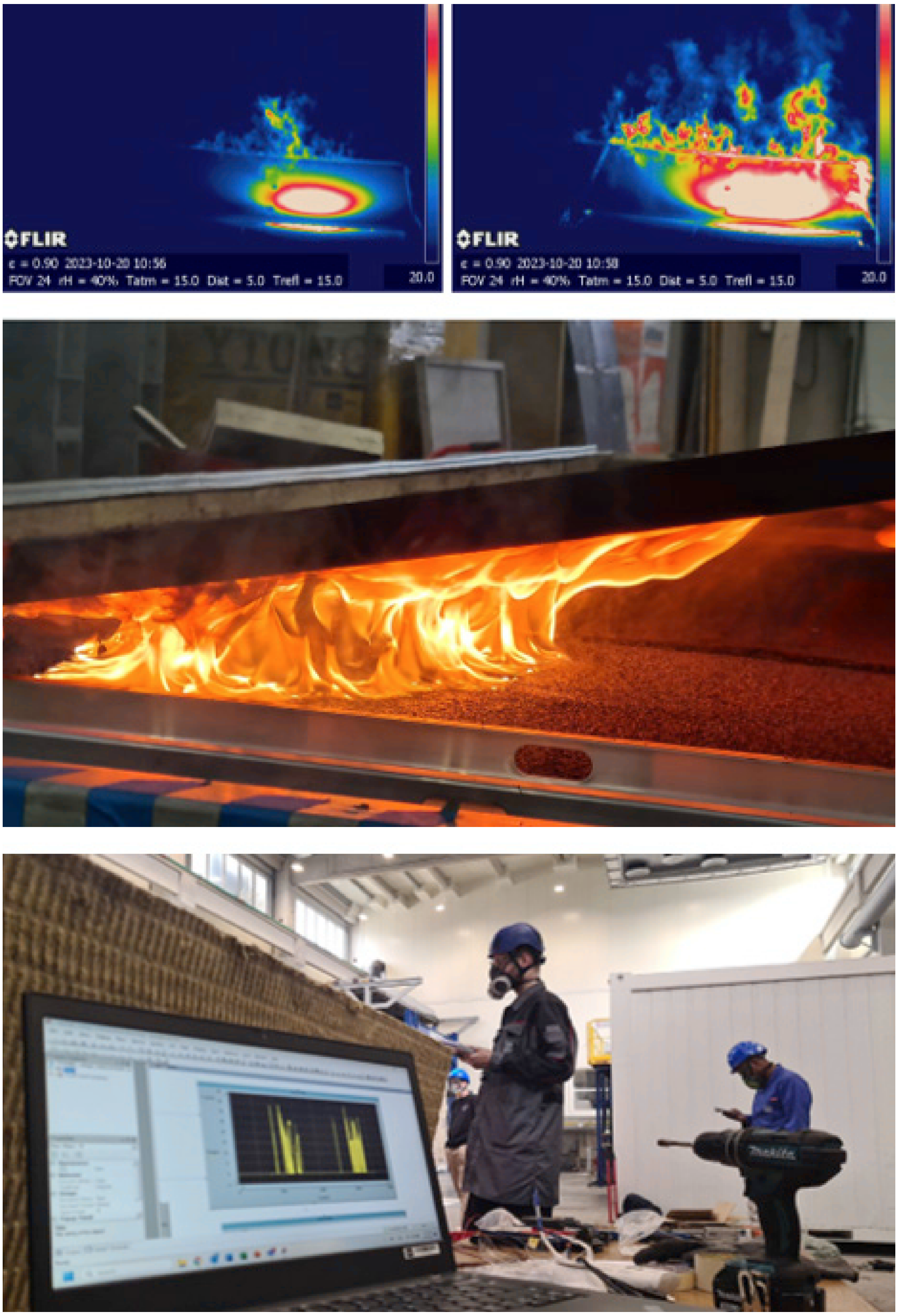


Figure 4.
*FRISSBE team members and fire experiments on PV specimens at the ZAG Fire Laboratory*
(photo © Grunde Jomaas).