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FOREWORD

The European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC) stands as the world's leading and most renowned forum for photovoltaic research and development and the largest international conference dedicated to PV solar energy. In 2026, celebrating its 43rd edition, the EU PVSEC once again served as an essential meeting and exchange point for the global PV community, bringing together experts from research, development, industry, policy and related fields.

Held from 14–18 September 2026 in Rotterdam, The Netherlands, the EU PVSEC 2026 brought together more than 1,400 participants from 54 countries and featured more than 1,000 scientific presentations covering the latest developments across the photovoltaic value chain. Bringing together the Conference and Exhibition, the event provided an essential platform for exchanging knowledge and ideas on photovoltaic research, innovation, manufacturing, applications and deployment. In the exhibition area, **57 companies** presented their latest products, technologies and services, strengthening the connection between scientific advances and their industrial implementation.

Conference Highlights

The EU PVSEC covered a broad range of topics through an extensive programme, providing an opportunity for experts from across the entire field of photovoltaics to share their findings and supporting multidisciplinary exchange. The 2026 programme reflected both the rapid technological development of PV and the increasingly important role of photovoltaics within the wider energy system. It was arranged into five topics as follows:

- Silicon Materials and Cells;
- Perovskites and Other Thin-Films; Tandems; New Concepts;
- Photovoltaic Modules;
- Systems Design and Operation; Applications;
- Photovoltaics in the Energy Transition

Communicating the key messages from the conference, not only to participants but also to other researchers, key stakeholders, policy makers and the general public, represents an important added value of the EU PVSEC. We thank the Highlights Committee, composed of selected members of the Scientific Committee, as well as the Session Chairs, for providing a comprehensive overview of the findings and state-of-the-art research presented during this year's event. Some key highlights are listed below, while further details may be found in the dedicated highlights presentation in the annex of these Proceedings.

Cross-cutting themes:

Reliability, stability and durability are receiving increasing attention across PV technologies, reflecting the importance of ensuring high performance over increasingly long operating lifetimes.

Sustainability and circularity remain central across the PV value chain, including efforts to reduce the use of critical materials, develop Ag-lean and Ag-free approaches, improve resource efficiency and advance recycling and end-of-life solutions.

The transition from lab to fab is becoming increasingly prominent, particularly for emerging technologies, with greater emphasis on scalability, manufacturability, standardisation and industrial compatibility alongside efficiency.

Artificial intelligence, advanced modelling, digitalisation and new characterisation and metrology approaches are increasingly supporting PV research, manufacturing, system design, monitoring and operations and maintenance.

Latest Solar Innovations in Materials, Cells, Modules and PV Systems

Crystalline silicon remains at the heart of global PV research and industrial development. TOPCon and heterojunction technologies featured prominently, alongside continued progress in efficiency, advanced processing, metallisation and light management. At the same time, degradation and reliability are becoming increasingly important research priorities for these mature high-efficiency technologies. New approaches to understanding degradation mechanisms, including UVID and hydrogen-related effects, were presented together with innovative cell concepts and manufacturing routes. Reducing silver consumption also remains a major priority, with significant work on Ag-lean and Ag-free metallisation and alternative materials and processes.

Perovskites and tandem solar cells continue their rapid development, with strong progress in both efficiency and scale. Several noteworthy results and world records were presented during the conference. These included a 34.21% III-V terrestrial PV module, a 30.2% triple-junction perovskite/perovskite/silicon cell developed within a European project, and a 32.37% triple-junction result. Progress towards larger-area devices was also demonstrated, including a 907 W perovskite-silicon tandem module.

Alongside these efficiency advances, increasing attention is being given to stability, scalability and manufacturing processes. Advanced characterisation, modelling, outdoor testing and measurement techniques are becoming increasingly important for understanding complex material and device behaviour, including metastability and ion migration, and for supporting the transition of emerging technologies towards commercial deployment.

At module level, outstanding efficiency advances were presented, including a 31.2% III-V-on-silicon module, alongside impressive results for emerging technologies. Reliability remained a major focus, particularly the impact of encapsulation materials and advances in testing and modelling of ageing behaviour. Further developments included design-for-recycling concepts, innovative anti-glare solutions, wireless in-situ monitoring and improved modelling of PV systems, highlighting the growing integration of performance, reliability and circularity in module research.

Applications, Grid Integration and Storage

"PV everywhere" continues to become a reality, with applications expanding from BIPV and agrivoltaics to floating PV and space, while the combination of PV and storage increasingly points towards "PV whenever". Advances in high-resolution solar resource datasets and modelling are improving yield prediction and long-term energy planning, while research on BIPV, floating PV and agrivoltaics demonstrated increasingly sophisticated approaches to integrating PV into buildings, land and water use while balancing energy production with other functions.

Storage will be essential for the next phase of PV growth: batteries can provide daily flexibility, while longer-term storage can support seasonal balancing and system reliability. PV+BESS projects are therefore shifting from maximising PV yield alone towards optimising the system as a whole, balancing storage, power conversion, grid services, safety and economics. In highly renewable systems, even curtailment may increasingly become an economically rational part of system design rather than simply a loss to be avoided.

Photovoltaics in the Energy Transition

The growing interaction between PV, digitalisation and the wider energy system was an important theme. Artificial intelligence is increasingly being applied to optimise the PV value chain and system integration, while PV itself can help supply the rapidly growing electricity demand of AI data centres. At the same time, studies highlighted the substantial additional deployment potential of PV, including through greater utilisation of rooftops and façades, alongside ambitious national targets and evolving frameworks for applications such as agrivoltaics.

Sustainability and circularity also featured prominently, with excellent progress in innovative, high-value recycling and reuse technologies. Advanced processes demonstrated high yields and high-purity material recovery with strong potential for industrial scale-up, including progress in polymer recycling. Mobile pre-treatment of end-of-life modules was also presented as a promising approach to reducing recycling logistics costs, although challenges remain for some module designs.

The 2026 conference also marked the launch of the EU PVSEC Observatory of Photovoltaic Research, presented by WIP Renewable Energies. The Observatory will provide an analysis of the scientific content of the EU PVSEC to identify emerging research signals, evolving priorities and connections across technologies and along the PV value chain, helping to strengthen the links between research, industry and policy.

EU PVSEC 2026 Proceedings

Selection for inclusion in the conference was made by the Scientific Committee's paper review experts and Topic Organisers (see the listing on pages **010002-001-005**), to whom we express our sincere gratitude for their comprehensive review work and overall contribution to the success of the conference.

The EU PVSEC 2026 Proceedings contain the full papers covering many of the highlights described above and more. The Proceedings provide a comprehensive overview of the PV solar sector, its current status and future prospects in science, research, innovation, development and deployment, extending to **3629 pages**. In addition to the **225 submitted papers**, the Proceedings include **119 presentations (slides)** shown during the plenary and oral presentations as well as **134 poster files** from the visual presentations. In total, this amounts to **478 publications**. Selected papers presented at the conference are also published in extended form in special issues of scientific journals.

The Conference Proceedings are published as downloadable files and are also fully accessible online. A DOI code (Digital Object Identifier) has been assigned to each paper. This ensures unequivocal and permanent identification and full citability. The EU PVSEC 2026 papers can be viewed and downloaded in full free open access from the EU PVSEC Proceedings website.

The Proceedings of the EU PVSEC 2026 strengthen the commitment to providing quick and open access to high-quality scientific results. They constitute a powerful resource for targeted and efficient information search and retrieval, enabling users to search by topic, keywords, paper title, DOI, author or organisation.

We are confident that these Proceedings will play an important role in providing a comprehensive overview of the current actors and activities in the global PV sector and in disseminating information on the state of the art in photovoltaic technologies and applications. In doing so, they can stimulate further research, add momentum to innovation and promote interest in photovoltaics worldwide.

We would like to cordially thank all authors and participants of the EU PVSEC 2026 for their contributions and look forward to welcoming you in **Freiburg, Germany, from 20–24 September 2027** for the next European Photovoltaic Solar Energy Conference and Exhibition.

The Editors

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Kristijan Brecl[1], Špela Tomšič[1], Miha Kikelj[1], Gašper Matič[1], Marko Remec[2], Carolin Ulbrich[2], Lisa Champault[3], Quentin Jeangros[3], Marko Topič[1], Marko Jošt[1], Mark Khenkin[2]

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Ana R. Pires[1], André F. Violas[1], João B. Vilão[1], Rui Bastos[1], Andrés P. Perdomo[1], António J. N. Oliveira[1], Ricardo M. L. Silva[1], Xavier L. Pinheiro[1], Bárbara L. Sieira[1], Diogo F. Carvalho[1], Jennifer P. Teixeira[1], Paulo A. Fernandes[1], Pedro M. P. Salomé[1]

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2BV.2.7 How the Molybdenum Process Influences the Growth of CZTSSe: a Comparative Study of Different Lab-Grown and Commercial Molybdenum Substrates 020053

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2BV.2.8 Numerical Simulation of CIGS/Si Tandem Solar Cells 020054

Alejandro Garcia[1], Juan Carlos Jimeno[1], Nekane Azkona[1], Vanesa Fano[1], Aloña Otaegi[1], Eneko Cereceda[1], Rubén Gutiérrez[2], Federico Recart[1]

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2BV.2.9 Comparison of Sb2Se3 Thin Films Deposited by Vacuum Evaporation and Vapor Transport Deposition 020056

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2BV.2.10 CdCl2 Treatment for Either Doping or Alloying Cu2ZnSn(S,Se)4 to Enhance 020057

the Solar Cell Performance.

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2BV.2.14 Metallic Nanoparticles Through Solid State Dewetting for Light Trapping in Ultrathin Solar Cells 020058

Antonio J. N. Oliveira[1], Bruna S. Tinoco[1], Enzo J. Ribeiro[1], André F. Violas[1], Vitor Lopes[1], Bárbara L. Sieira[1], Victor Silva[2], D. Rocha[1], Paulo A. Fernandes[1], Pedro M. P. Salomé[1], Jennifer P. Teixeira[1]

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2BV.2.15 Broad Spectrum Absorption Enhancement in GaAs-based Quantum Dot Solar Cells with the Two-Dimensional Photonic Crystal Trapping Layer 020059

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2CV.2.27 Varied Intensity I-V Measurement of the Emerging PV under Indoor Lighting 020061

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Eugenia Zugasti[1], Alicia Buceta[1], Cristina Pinto[1], Iñaki Cornago[1], Asier Murillo[1], Jaione Bengoechea[1], Antonio Urbina[2]

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2CV.2.31 Advanced Synchrotron X-Ray and Neutron Techniques to Reveal Early-Stage Degradation Mechanisms in Photovoltaic Devices 020066

Hugo Lajoie[1], Tristan Gageot[1], Romain Couderc[1], Pierre Everaere[2], Thu Nhi Tran Caliste[2], Edward Mitchell[2], Thomas Saerbeck[3], Mark Robert Johnson[3], Ioannis (John) A. Tsanakas[1]

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Branoosh Afshari[1], Negin Nezamlou[2], Mohammad Moaddeli[1], Mansour Kanani[1], Mohammadreza Aghaei[3]

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2CV.3.12 Fast Reverse Bias Characterization of Perovskite-Silicon Tandem Solar Cells 020068

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2CV.3.14 Laser Processes for Perovskite and Organic Solar Cells and Modules for Large Substrates with Multi-Wavelength at Film Side and Glass Side Processing 020069

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2CV.3.23 Development of Inverted Perovskite Solar Cells for Perovskite–Silicon Tandem Applications and their Evaluation via Hyperspectral Photoluminescence Imaging 020070

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2CV.3.26 Developing Sub-micron Pyramidal Texturing Approach on Large Area for Next-Generation Perovskite/Silicon Tandem Cells 020071

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2CV.3.46 2D Perovskite Formation at the EDAI2-passivated Surface of a Triple-cation Triple-halide Perovskite Resulting in High Efficiencies 020072

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2CV.3.47 Influence of Bromide Substitution on the Environmental Stability of Aziridinium Perovskite Thin Films 020073

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2CV.3.50 Insights into the Degradation of Hybrid Lead Halide Perovskite Thin Films and Devices During Outdoor Exposure 020075

Maria Hadjipanayi[1], Vasiliki Paraskeva[1], Aliki Souzou[1], Modestos Athanasiou[1], Aranzazu Aguirre[2], Anurag Krishna[2], Tamara Merckx[2], Alexandros Themistokleous[1], Sophia Hayes[1], Grigorios Itskos[1], Sumeet Mujumdar[1], Elias Peraticos[1], George E. Georghiou[1], Tom Aernouts[2]

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2CV.3.51 Impact of Water Ingress and Damp Heat on POE-Encapsulated Perovskite Solar Cells 020077

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2CV.3.59 Experimental and DFT Studies on the Kesterite-CZTS Nanoparticles as Hole Transport Material for Perovskite Solar Cells 020078

Mehr Un Nisa[1], Giorgio Tseberlidis[1], Vanira Trifiletti[1], Michael Zambrano[2], Adriana Pecoraro[2], Michele Pavone[2], Ana Belén Muñoz García[2], Simona Olga Binetti[1]
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2CV.3.61 Engineering Compositional Homogeneity and Stability in High Efficiency FA–Cs Perovskite Solar Cells 020079

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2DO.8.5 Process-driven Material Selection of Encapsulants for Perovskite-Silicon Tandem Module Lamination 020080

Chiara Barretta[1], Petra Christoefl[1], Marcel Kuehne[2], Markus Franke[2], Frans Op den Buijsch[3], Roland Milatz[3], Lisa Champault[4], Quentin Jeangros[4], Quiterie Emery[5], Mark Khenkin[5], Carolin Ulbrich[5], Gernot Oreski[1]
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2DO.9.2 Multiphysics Design and Optimization of Dual-Source Close-Space Deposition for Scalable Perovskite-Silicon Tandem Manufacturing 020081

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3AO.4.5 UV-Induced Degradation in TOPCon Modules: Linking Accelerated Testing and Field Evidence 020082

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Aksel Kaan Öz[1], Angelika Beinert[1], Laura Stevens[1], Meric Caliskan Arslan[2], Cansel Düz[2], Christine Wellens[1], Martin Heinrich[1]

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3AV.1.7 Effect of Silicone Repair Coating on Degradation of PV Modules with Faulty Backsheet 020084

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3AV.1.9 Scalable Electrospun PVA/SiO_2 Nanofiber Mats Enabling Daytime Passive Radiative Cooling 020085

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3AV.1.11 Integrated Photovoltaic Façades for Industrial Buildings: Adhesion Approaches between Backsheet and Galvanized Steel 020086

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3AV.1.12 Investigation of P1/P2/P3 Laser Patterning Using Femtosecond and Nanosecond Regimes in Kesterite Thin-Film Solar Cells 020087

Fernando Zahid Anguiano[1], D. Canteli[2], Cristina Muñoz-García[2], David Muñoz-Martín[2], Jacob Antonio Andrade-Arvizu[3], Victor Izquierdo-Roca[3], Pedro Vidal-Fuentes[3], Gilberto Gomez-Rosas[1], Miguel Morales[2], Carlos Molpeceres[2]

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3AV.1.13 Ultrasonic Monitoring of Encapsulants During Glass–Glass PV Module Lamination 020088

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3AV.1.15 A Self-Healing and Self-Cleaning Transparent Coating for Photovoltaic Solar Panels 020089

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3AV.1.18 Understanding & Mitigating Encapsulation-Induced Voltage Losses in PSC 020092

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3AV.1.19 Platform for Process Development for Glass Cutting, Glass Drilling, Glass-Glass and Glass-Metal Welding on 1m2 Substrates 020093

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3AV.1.20 Flexible Lamination Concepts for Durable CIGS Photovoltaic Modules 020094

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3AV.1.21 New Developments of Transparent Polymer Materials in Frontsheet Films as Valid Alternatives to Glass 020096

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3AV.1.22 Implementation of an Industrial Process for Interconnection of Busbarless IBC ZEBRA Cells using Ribbons with Electrically Conductive and Non-Conductive Adhesive Pads 020098

Tudor Timofte[1]*, Simon Emmerich*[2]*, Susana Soto*[3]*, Jean Philippe Aguerre*[3]*, Xabier Hernandez*[3]*, Noelia Lorenzo*[3]*, Maximilian Pospischil*[4]*, Andreas Dörflinger*[4]*, Jonas Albrecht*[4]*, Maximilian Weil*[4]*, Stephan Großer*[5]*, Giuseppe Galbiati*[6]*, Tobias Nitsche*[6]*, Daniel Buckland*[6]*, Thomas Buck*[1]*, Dominik Rudolph*[1]*, Mertcan Comak*[1]*, Joris Libal*[1]*, Matthias Helbig*[1]*, Jolina Schmid*[1]*, Tobias Messmer*[1]
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3AV.1.23 Multi-Wire Module Modeling, Measuring and More 020100

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Visual SESSION 3AV.2 PV Module Durability and Reliability

3AV.2.3 Integration of Electrical Circuit Simulations for PV Degradation 020104

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3AV.2.4 UVID Test Results and Early Indicators 020105

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3AV.2.6 UV-Induced Degradation of PV Modules: A Comparative Study of Light Spectra and Encapsulants 020107

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3AV.2.7 Evaluation of a Custom-built Integrated Setup for Microscopic Characterization of the Mechanical Stability of Flexible Perovskite Solar Cells 020109

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3AV.2.8 Outdoor Degradation Assessment from Field Measurements: Isolating Irreversible Degradation from Measured Performance Indicators 020110

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3AV.2.9 Indoor Characterizations of PV Modules Fabricated Using Recycled Silicon - Representative Materials 020111

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3AV.2.11 PVcracks: Python Repository for Electroluminescence Image Processing, Current-voltage Curve Fitting and Power Loss Estimation 020112

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3AV.2.12 Acceleration of Thermal Cycling Test for PV Modules 020113

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3AV.2.13 Reliability Comparison of P-Type PERC and N-Type TOPCon PV Modules Based on IEC Testing and Encapsulation Materials 020114

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3AV.2.19 Two Years Outdoor Performance Measurement of Two Different 781 cm² Perovskite Mini-Modules 020115

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3AV.2.20 Beyond EVA: Screening Encapsulants for Durable and Recyclable PV 020116

Modules

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3AV.2.23 Strength Testing of Full-Size Solar Glass 020118

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3AV.2.24 Non-Destructive Detection of Moisture Ingress in PV Modules using NIR Spectroscopy and Hyperspectral Imaging 020120

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3AV.2.25 Characterization Methods for Perovskite Mini-Module Analysis 020121

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3AV.2.27 Reliability Assessment of Mainstream Encapsulants Laminated Cu-Metallized Si Heterojunction Solar Modules 020122

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3AV.2.28 Mechanical Behaviour of Framed Glass/Backsheet PV Modules: Influence of Frame Geometry and Mounting Configuration 020123

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3AV.2.29 Reverse-Bias Onset under Bird-Dropping Soiling: A Parametric Electrical Model for PV Module Hotspot Risk 020124

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3AV.2.31 Novel Encapsulant Polymers for Photovoltaic Modules 020125

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3AV.2.34 New Methods for Evaluation of Resistances Inside PV Modules 020126

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3AV.2.35 Increased Degradation of N-type PV Modules in Field Operational Systems 020127

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3AV.2.39 Development of Polymer-Modified Polyvinylidene Fluoride and Glass Fiber Composites for the Functional Repair of Photovoltaic Backsheets 020128

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3AV.2.40 Investigating Liquid vs Vapor Moisture Ingress and Resulting Degradation in TOPCon Modules 020130

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3AV.2.42 Field Assessment of Glass Breakage Severity and Electrical Performance in Large-Format Bifacial PV Modules 020131

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Simon Karl[1], Jens Schneider[2], Jens Froebel[1], Matthias Pander[1], Pouya Pourshafi[3], Andreas Maixner[3], Bengt Jaeckel[1], Hamed Hanifi[3]
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José Angulo[1], Juan de la Casa[2], Jan Amaru Töfflinger[1]
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Matthias Pander[1], Stephan Grosser[1], Tudor Timofte[2], Tobias Nitsche[3], Daniel Buckland[3], Giuseppe Galbiati[3], Bengt Jaeckel[1]
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Dominik Bagrowski[1], Dirk Stellbogen[1], Jonathan Kriening[1], Philipp von Bismarck[1], Wolfram Hempel[1], Maximilian Engel[1], Theresa Magorian Friedlmeier[1], Roland Einhaus[1]
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(Snow-PV)

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Paul Gebhardt[1], Angelika M. Beinert[1], Esther Fokuhl[1], Mariella Rivera[1], Florian Schindler[1], Ingrid Haedrich[1]

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Chencheng Xu[1], Andrej Wentnagel[1], Michael Siebert[1], Marc Köntges[1]
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Ayyoub Ahar[1], Camilo Velázquez-Rodríguez[1], Pieter-Jan Delvaux[1], Pol Bikhan[1], Steven Sagaert[1], Laurent Declercq[1], Abdellatif Bey-Temsamani[1], Raf Vranken[1]
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Diego Pavanello[1], Stefano Alessandrini[1], Davide Tomè[1], Sylwia Anita Walczak[1], Antonio Romano[2], Luigi Stingo[2], Elisabetta Canuti[1], Edoardo Celi[3], Alessandro Minuto[3], Rodrigo Costa[4], Andre Goncalves[4], Sylvio Luis Mantelli Neto[5], Fernando Martins[6], Flavio Valoti[7], Juan Jose Stivanello[8], Pietro Raffaelli[8], Marco Potenza[9], Luca Teruzzi[9], Fabio Fribbi[9], Leonardo Longo[9], Stefano Rimoldi[9], Aziz Nairi[10], Paola Russo Ganon[11], Kevin Murray[12], Aodhan Murray[12], Fatemeh Behrouznejad[13], Tobias Weigner[14]

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3DO.18.2 A Comparison of Direct Sunlight Method and Sunlight Simulator for Measuring PV Module Power 020205

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3DO.20.3 Impact of Photovoltaic Module Degradation on the Temperature Coefficients 020215

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4AO.7.4 Uncertainty Propagation from Irradiance Measurements to Simulated Rear Side Irradiance and Bifacial Gain 020219

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Claudio Francesco Nicolosi[1], Giuseppe Marco Tina[1], Amr Osama[2], Sara Golroodbari[3]

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Zain Ul Abdin[1], Friso Lems[1], Farnaz Pourbarghisofiyani[1], Olindo Isabella[1], Rudi Santbergen[1]

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Marko Turek[1], Robert Maßmann[1], Stefan Eiternick[1], Sina Swatek[1], Stefan Lange[1], David Adner[2], Christian Hagendorf[3], Syed Mubeen[4]
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Baris Dai[1]
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Ricardo Velasco[1], Imke Meyer[2], Jose Muñoz[3]
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Anja Neubert[1], Camélia Farchado[2], Javier Lopez-Lorente[3]
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Erlend Hustad Honningdalsnes[1], Erik Stensrud Marstein[1], Helge Bonesmo[2], Dag Lindholm[1], Jonathan Rizzi[3], Heine Nygard Riise[1]
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Joseph Vernier[1], Baptiste Berlioux[2], Baptiste Amiot[1], Sylvain Edouard[3], Eric Dupont[1], Vincent Trotin[4], Didier Combes[3], Patrick Massin[1]
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Anna J. Carr[1], Latifa El Boujdaini[1], Bas B. Van Aken[1]
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Ricardo Nery de Castro[1], Victor Eduardo Cauvilla de Oliveira[2]

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Matthew T. Sivewright[1], E. Ernest Van Dyk[1], Frederik J. Vorster[1]
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Rodrigo del Prado Santamaría[1], Aysha Mahmood[1], Mahmoud Dhimish[1], Luca Oneto[2], Antonio Sgorbissa[2], Gisele Alves dos Reis Benatto[1], Thøger Kari[1], Peter B. Poulsen[1], Sergiu V. Spataru[1]
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Heidi Kalliojärvi[1], Kari Lappalainen[1]

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Jikai Wang[1], Kingsley Oluah[1], Herbert A. Zondag[1], Silvia V. Nedea[1], Angèle H.M.E. Reinders[1]

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4DV.4.53 Optimized Machine Learning Framework for Predicting Photovoltaic Soiling in Arid Desert Climates 020377

Usman Zafar[1], Dhanup Somasekharan Pillai[1], Farhat Mahmood[1], Mohamed Abdelrahim[1], Brahim Aissa[1], Tareq Al-Ansari[1]

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Magnus Moe Nygård[1], Jonas Gran Melandsør[1], Marie Syre Wiig[1]

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4EO.2.3 Benchmark of VIPV Versus Static PV 020379

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4EO.2.6 Impact of Reverse Current on CPV Module Degradation 020380

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4EP.1.3 Reframing PV Inspections at Scale: Techno-Economic Benchmarking and a Roadmap for Intelligent PV O&M and Market Transformation 020382

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Pierre-Jean Alet[1], Giovanna Adinolfi[2], Grazia Barchi[3], Venizelos Efthymiou[4], Marion Perrin[5], Maximilian Schönau[6], Elham Shirazi[7]

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5AP.2.2 Welcome Message - Jon de Gregorio, WIP Renewables Energies 020385

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Max Mittag[1], Pamela Molina[1], Peter Brailovsky[1], Sebastian Nold[1], Holger Neuhaus[1]

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and the Associated Policy Costs

Tommaso Ferraresi[1], Renato Paniccià[1], Leonardo Piccini[1], Giulio Mela[2], Andrea Danelli[2], Pierpaolo Girardi[2], Elisabetta Brivio[2], Nicola Baggio[3]
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5CO.3.3 From Sites to Industrial Ecosystems: Applying Gibrat's Law to Photovoltaic Manufacturing Growth 020389

Pietro P. Altermatt[1], Hannes Wagner-Mohnsen[1], Ye Xu[1], Jing Pan[1], Yao Wang[1], Yifeng Chen[1]
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Johan Lindahl[1], Jens Holm[1], Christoph Podewils[1]
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5CO.4.1 System Economics of Flexibility, Storage, and Curtailment in Renewable Grids 020394

Jan Remund[1], Marc Perez[2], Richard Perez[3], Marco Pierro[4]
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Micke Talvi[1], Kari Lappalainen[1]
[1] Tampere University, Tampere, Finland

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Cristóbal Parrado Riquelme[1], Juan Sebastián Gómez Quintero[1]
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5CO.4.4 Assessing the Reliability of PV + BESS Power Plants in Operation 020398

Erik Stensrud Marstein[1], Christian Messner[2], Patrik Ollas[3], Jonathan Fagerström[1], Mengjie Li[4], Dan-Eric Archer[5], Roger H. French[6]
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5CO.4.5 PV and Energy Storage Capacity Needed to Replace other Electricity Sources in Finland 020399

Evgenia Okhotnikova[1], Kari Lappalainen[1]
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5CO.4.6 How Firm Is Firm Enough? PV+BESS as a Fast-Deployment Option for Clean Firm Power and Data Center Energy 020400

Harry Apostoleris[1], Ali Saberi Derakhtenjani[2], Kareem Younes[3], Matteo Chiesa[3]
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5CO.5.3 Recycling of Polymeric Backsheets from PV Modules 020402

Katrin Nord-Varhaug[1], Tina Kristiansen[1], Iselin Grauer Moen[1], Asbjørn Iveland[1], Wolfram Palitzsch[2]
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ABSTRACT: Agrivoltaic (Agri-PV) deployment requires support structures that satisfy mechanical and agricultural constraints while limiting long-term material demand. This paper evaluates the circularity of a representative overhead Agri-PV support structure designed to carry 28 m² of photovoltaic modules, comparing a hot-dip galvanized steel baseline with a timber-based alternative. Circularity is assessed through the Integrated Value Model for Sustainable Evaluation (MIVES), restricted here to a dedicated circularity requirement structured into design, use and end-of-life criteria. Six indicators quantify non-sustainably sourced virgin material, global resource availability, resource duration, utility, unrecoverable waste and recycling. Indicator values are transformed into dimensionless satisfaction scores and aggregated with equal criterion weights. Timber performs better at design (0.68 vs. 0.16), whereas steel performs better during use (0.93 vs. 0.74); end-of-life scores are equal (0.78). The resulting circularity index is 0.73 for timber and 0.62 for steel, showing that material sourcing and resource criticality can outweigh recycling advantages alone.
Keywords: agrivoltaics, circular economy, MIVES, support structure, material circularity

1 INTRODUCTION

Agri-PV systems co-locate photovoltaic electricity generation and agricultural production on the same land, providing a pathway to reduce direct competition between energy and food uses [1], [2]. In the European Union, Agri-PV has gained policy relevance because relatively small shares of agricultural land could host substantial Photovoltaic (PV) capacity while maintaining agricultural activity [3]. Overhead Agri-PV configurations are particularly compatible with mechanized farming because PV modules are elevated to provide sufficient vertical clearance for conventional agricultural operations and machinery circulation [4]. However, the greater installation height and structural complexity associated with elevated configurations can substantially increase material demand in the balance-of-system support structure. A recent comparative life-cycle assessment of different European Agri-PV configurations showed that overhead systems, particularly elevated dual-axis designs, required considerably more structural steel and consequently exhibited higher environmental burdens associated with mounting structures than less material-intensive configurations [5]. As Agri-PV deployment expands, material selection for these structures therefore becomes relevant not only from a mechanical and environmental perspective, but also in terms of resource circularity.

Recent works have framed sustainability and circular economy as complementary dimensions for Agri-PV development [6] and has shown that support-structure material choices can materially influence life-cycle impacts alongside the PV modules themselves [7]. However, environmental performance and circularity are not interchangeable. Circularity indicators describe how effectively resources are retained and circulated within economic systems, whereas life-cycle environmental assessment addresses the environmental consequences associated with those resource flows; consequently, a higher level of circularity does not necessarily result in lower environmental impacts [8]. A structure may, for example, exhibit high recycling potential while still depending on virgin or critical resources, since resource performance is also influenced by scarcity, recyclability, and geopolitical availability [9]. Conversely, bio-based alternatives such as timber can reduce dependence on virgin non-renewable feedstocks, but their circular performance remains contingent on durability, service life, deconstruction, reuse, and feasible end-of-life pathways [10]. Circularity should therefore be assessed from a life-cycle perspective that considers not only how resources enter and leave a system, but also how long they remain in productive use through initial use, refurbishment, reuse, and recycling [11]. Circularity metrics developed for products and construction increasingly combine material sourcing, resource retention, design for disassembly and end-of-life recovery [11], [12], [13]. Yet Agri-PV support structures remain underrepresented in this literature, despite their long service life and material-intensive elevated geometry. This paper addresses that gap by applying the Integrated Value Model for Sustainable Evaluation (MIVES), a multi-criteria value-function method used in architecture and civil engineering [14], to compare the circularity of galvanized steel and timber support alternatives. The contribution deliberately isolates the circularity requirement from broader sustainability dimensions. Specifically, it asks: how does the material ranking change when design-stage sourcing and resource availability, use-stage retention, and end-of-life recovery are evaluated together rather than through recycling alone?

2 MATERIALS AND METHODS

2.1 Case study and alternatives

The case study is a representative overhead Agri-PV row developed from background work of GRIC within the SYMBIOSYST project [15]. The evaluated structure (Fig. 1) supports 28 m² of PV modules and consists of four foundations, four columns and three beams, with a tracker height of approximately 2.9 m. To preserve functional equivalence, only the primary structural elements that can technically be substituted are changed between alternatives; fastening and tracker-rotation components remain identical. The steel alternative is the baseline hot-dip galvanized configuration. In the timber alternative, the principal above-ground steel members are replaced by

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German pine, while steel is retained where required for ground contact, connections and moving components.

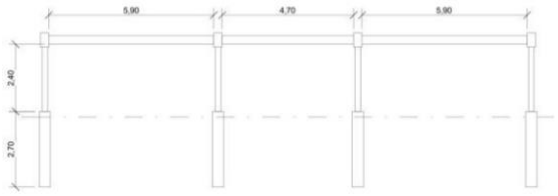

Figure 1. Structural section analyzed [6]

The resulting structure masses are 624.69 kg for the steel alternative and 350.69 kg for the timber alternative. Table I presents a summary of the main characteristics of the alternatives.

Table I. Main characteristics of structural alternatives

Characteristic	Galvanized steel	Timber alternative
PV area supported	28 m²	28 m²
Primary members	Steel	German pine + retained steel
Total structure mass	624.69 kg	350.69 kg
Assumed structural service life, L	50 years	25 years
Industry reference life, L_{av}	25 years	25 years

2.2 MIVES circularity assessment

MIVES converts indicators expressed in different units into a common satisfaction scale from 0 to 1 using value functions, after which indicator, criterion and requirement scores can be aggregated through weights [14]. In the present paper, only the circularity requirement is retained. It is divided into three life-cycle criteria: design (C1), use (C2) and end-of-life (C3). Each criterion contributes one third of the final circularity requirement score, and the two indicators within each criterion receive equal weight. This phase-resolved organization avoids collapsing circularity into a single recycling-dominated metric and is consistent with construction-oriented circularity frameworks that emphasize early design decisions and recoverability [12], [13]

The case study uses linear value functions in MIVES, with increasing or decreasing direction depending on whether a higher raw value represents improved circularity. The normalization bounds follow the underlying model. This approach provides traceability because each criterion can be interpreted independently before aggregation.

2.3 Circularity indicators

Six indicators (I1-I6) operationalize circularity across the three phases (see Table II). I1 measures the mass-weighted share of non-sustainably sourced virgin material entering the structure and is adapted from construction circularity approaches derived from the Material Circularity Indicator [12], [13]. The underlying case study assumes 30% recycled content for steel, sustainably sourced renewable timber, and no recycled or sustainable fraction for the remaining virgin inputs unless explicitly identified. Lower I1 values are preferable.

I2 uses the Global Resource Indicator (GRI), proposed by Adibi et al. [9], to combine scarcity (X), recyclability (Y) and geopolitical availability (Z): GRI = X/(Y·Z). The calculation is performed at material level and aggregated by mass; long-term characterization values are used because the evaluated infrastructure operates over several decades. In the adopted MIVES normalization, the raw GRI is mapped so that the timber alternative receives a higher satisfaction score than the steel alternative, reflecting its more favorable resource-availability profile in the case-study dataset.

The use-stage indicators capture retention of value over time. I3 is based on the Resource Duration Indicator of Franklin-Johnson et al. [11], which combines initial lifetime with additional time associated with refurbishment/reuse and recycling pathways. I4 is a utility factor adapted from circularity applications in the built environment [13]. Because a passive support structure has no meaningful hourly use-intensity differential, utility is simplified to $X=L/L_{av}$. The model assumes L=50 years for steel and L=25 years for timber, with L_{av}=25 years. The steel lifetime assumption follows evidence on long-lived steel products [16], whereas the timber case is conservatively reduced relative to protected timber structures because moisture exposure can degrade mechanical performance [17].

At end-of-life, I5 represents the fraction of unrecoverable waste, including disposal and non-recoverable municipal routes; lower values are preferable. I6 represents the mass fraction routed to recycling and is adapted from recycling-rate concepts discussed by [18]. The end-of-life shares are applied at component level and aggregated by total structure mass.

Table II. Circularity indicators used in MIVES

Criteria	Indicator	Preference
C1	I1 Virgin input	Lower is better
C1	I2 GRI	Higher is better
C2	I3 Resource duration	Higher is better
C2	I4 Utility	Higher is better
C3	I5 Unrecoverable waste	Lower is better
C3	I6 Recycling	Higher is better

3 RESULTS AND DISCUSSION

3.1 Indicator-level results

The raw and normalized results show that the two alternatives obtain their circularity performance through different mechanisms (see Table III). At design stage, the timber alternative contains a lower mass-weighted fraction of non-sustainably sourced virgin material (0.30 versus 0.71 for steel), producing satisfaction values of 0.70 and 0.29, respectively. The GRI raw values are 0.34 for timber and 0.97 for steel; under the adopted MIVES value function these correspond to satisfaction values of 0.66 and 0.03. Consequently, C1 is 0.68 for timber and only 0.16 for steel. This is the largest criterion-level difference and establishes the principal advantage of timber in the overall circularity ranking.

Use-stage performance reverses the ranking. The raw resource-duration values are 29.8 years for steel and 34.4

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years for timber in the underlying calculation, but both alternatives map to the same satisfaction level (I3=0.85) under the selected value function. Utility is decisive: steel reaches I4=1.00 because its assumed lifetime is twice the 25-year reference (X=2), whereas timber reaches I4=0.50 (X=1). The resulting C2 values are 0.93 for steel and 0.74 for timber. This outcome illustrates how durability assumptions can compensate for weaker upstream circularity performance and why service-life evidence is critical when comparing bio-based and metallic structures.

Table III. MIVES satisfaction scores for the case study

Element	Steel raw	Timber raw	Steel score	Timber score
I19	0.71	0.30	0.29	0.70
I20	0.97	0.34	0.03	0.66
C5	—	—	0.16	0.68
I21	29.8	34.4	0.85	0.85
I22	2	1	1.00	0.50
C6	—	—	0.93	0.74
I23	0.19	0.14	0.81	0.86
I24	0.76	0.69	0.76	0.70
C7	—	—	0.78	0.78

End-of-life results are effectively tied. Timber performs better for unrecoverable waste (I5=0.86 versus 0.81 for steel), while steel performs better for material routed to recycling (I6=0.76 versus 0.70). Equal weighting gives C3=0.78 for both alternatives. The result demonstrates the limitation of using recycling alone as a proxy for circularity: steel's stronger recycling pathway is counterbalanced by the unrecoverable-waste indicator, while the larger design-stage differences remain invisible if only end-of-life metrics are considered.

3.2 Aggregated circularity and design implications

With equal weights for C1, C2 and C3, the overall circularity requirement is R=0.73 for timber and R=0.62 for galvanized steel (see Figure 2). The 0.11-point difference is driven primarily by the design criterion, where timber gains 0.52 points relative to steel. Steel recovers 0.19 points during use, and end-of-life contributes no net difference. In other words, the ranking is not determined by whether a material is commonly recyclable, but by the combined effects of sourcing, criticality, retention in use and recovery routing.

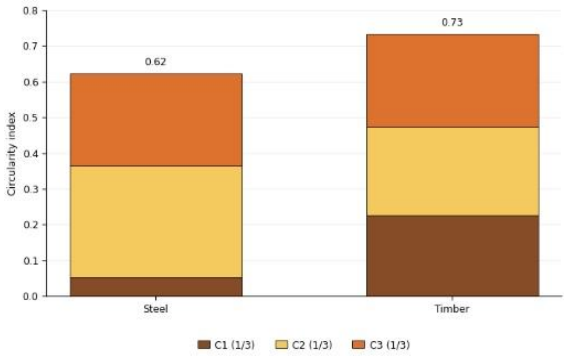

Figure 2. Results of the MIVES application.

This result is consistent with a broader circular-construction perspective in which decisions taken before construction can determine later recovery options and dependence on virgin resources [12]. For Agri-PV, the implication is particularly relevant because support structures are replicated over large land areas and must accommodate machinery clearance. Small improvements in material efficiency, responsible sourcing or component reuse can therefore scale across many repeated structural bays. The MIVES structure also makes trade-offs explicit: a designer can see whether a change improves design-stage circularity but reduces expected service life, rather than receiving only a single opaque score.

The analysis should nevertheless be interpreted as a comparative case study rather than a universal material ranking. First, the timber result depends on the assumption of sustainably sourced wood. Second, the utility indicator is highly sensitive to the 25-year timber and 50-year steel service-life assumptions. Third, end-of-life routing is scenario-based and can change with local collection, reuse and recycling infrastructure. Finally, the GRI values depend on the selected characterization data and normalization. These limitations point to the most useful next steps: project-specific durability data for exposed timber in Agri-PV microclimates, explicit design-for-disassembly scenarios, and updated regional recovery pathways.

4 CONCLUSIONS

A MIVES-based circularity assessment was applied to functionally equivalent galvanized-steel and timber alternatives for an overhead Agri-PV support structure. Timber achieves the higher overall circularity score (0.73 versus 0.62) because its design-stage advantage in virgin-material dependence and resource availability outweighs steel's use-stage durability advantage. End-of-life performance is tied at 0.78, despite steel having the higher recycling score, confirming that recycling alone is insufficient to characterize circularity.

For Agri-PV system design, the main contribution is a transparent, phase-resolved decision framework that identifies where circularity is gained or lost. The results prioritize three practical levers: reducing non-sustainable virgin inputs, improving material and supply-chain selection at design stage, and validating service-life assumptions under agricultural exposure conditions. The framework can be extended to alternative materials, connection strategies and reuse scenarios while preserving the same functional basis.

5 ACKNOWLEDGEMENTS

Authors are thankful to Government of Panama's National Secretary of Science, Technology and Innovation (Grant agreement SENACYT-BIDP-2023- 36), and the Horizon Europe project SYMBIOSYST (Grant agreement No. 101096352), for supporting the actual results and future work. The authors also acknowledge the background work developed within GRIC-UPC that supported the case-study inventory and circularity model.

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Testing Multi-Level Co-Design Approaches in Agrivoltaic Systems: learnings from the Symbiosyst Research Project



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etaflorence renewable energies

Symbiosyst

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1. State of the art on Agri-PV and co-design;

- Agri-PV systems represent a concrete opportunity to integrate solar energy generation into local landscapes;
- landscape is intended here as a multi-specific infrastructure for life, and not a merely visual or aesthetic aspect in planning;

(Belanger, 2009; Toledo and Scognamiglio, 2021, Sirnik et al., 2023, Kitti Biró-Varga et al., 2024; Fatturoso et al., 2024; Troccoli et al., 2024; Picchi et al., 2025)


Credit: Eurac Research

1. State of the art on Agri-PV and co-design

- Through the physical environment where people "live, work and recreate" (Stremke et al., 2022), citizens come in contact with the energy transition; this therefore plays a fundamental role in the decision-making process;

- Local community engagement is widely used in landscape studies and this has been successfully applied in the planning and design of renewable energy systems integrated in the local landscapes (Arler, 2011; Picchi et al., 2021, 2025).


Credit: ETA Florence

1. State of the art on Agri-PV and co-design;

- Agri-PV systems research and implementation is in an early stage and there is a need to empower the main actors and stakeholders, first of all farmers, with the available knowledge;

- In literature, apart from studies in social sciences investigating social attitudes towards Agri-PV systems (e.g. Pascaris et al., 2022; de Falco et al., 2025; Torma et al., 2026) there are no examples of approaches and methods **in design** to incorporate such knowledge in Agri-PV systems projects.;

- A first methodological approach has been described in Picchi et al. (2025).


Credit: ETA Florence

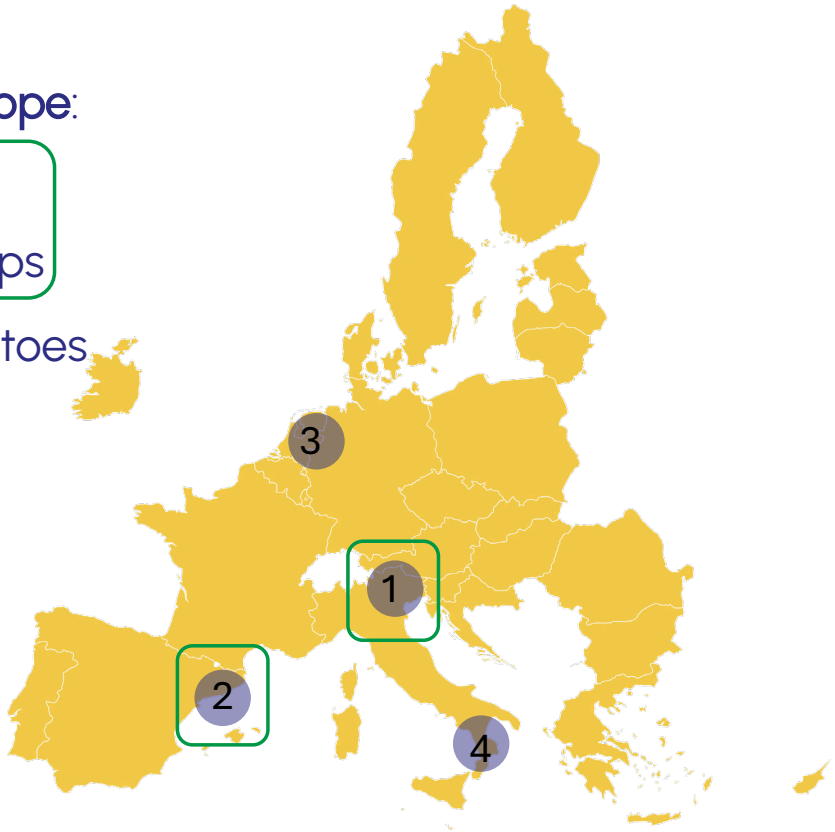
2. The Symbiosyst project and the main Research objectives

Symbiosyst is a Horizon Europe Innovation Action (2023-2026) aimed at developing innovative agrivoltaic (Agri-PV) systems.

- Integrating photovoltaics and agriculture in a mutually beneficial way
- Developing sustainable Agri-PV solutions
- Testing systems through real demonstrator projects
- Supporting social acceptance and stakeholder engagement through the testing of co-design activities

Symbiosyst is testing in **4 Agri-PV Demonstrator Sites in Europe**:

- 1 Ora/Auer (Italy) – open agri-PV with apple orchard
- 2 Viladecans (Spain) – open agri-PV with vegetable crops
- 3 Schipluiden (Netherlands) – closed agri-PV with tomatoes
- 4 Scalea (Italy) – closed agri-PV with lemons



2. The Symbiosyst project and the WP6 and WP8 joint Research objectives

- Symbiosyst WP6 has developed a GIS based methodology for analysing the landscape pattern and suggesting some preliminary features (size, shape) of agrivoltaic patches which can be integrated into the existing landscape structure (Fatturoso et al., 2024);

- WP6 objective is to define landscape suitability criteria to support the decision-making process of different stakeholders (i.e., local authorities in regional planning, and agrivoltaics developers), to best integrate these technologies within the different landscapes;

- Symbiosyst WP8 objective is to test effective methods for engaging local communities in co-designing agrivoltaic systems at multiple levels, from regional to local.

3. Methodological approach in WP6/WP8

- In Symbiosyst the co-design activities are part of WP6 and WP8 and are part of a larger commitment to promote more regional knowledge on agri-PV systems among EU NUTS 2 regions within the European agrivoltaic Network by Sybmbiosyst;
- In Symbiosyst the co-design activities apply to policies and planning at the regional level, while apply to landscape functioning and quality objectives at the local level;
- In the latter case the application considers the landscape as an intermediary between different social profiles and a living environment that unites everyone and invites everyone to dialogue and discussion at the local level, and therefore relevant for community engagement (De Jonge, 2022).

3. Methodological approach in WP6/WP8

Towards a Regional based knowledge on agri-PV



3. Methodological approach in WP6/WP8

- Regional level – supporting policy and spatial planning
- Local level – addressing landscape quality objectives

The multidisciplinary approach promotes synergies between sustainability goals and aims to:

- Increase awareness and social acceptance
- Support the local value chain

3. Methodological approach in WP8 – stakeholder mapping

Local and regional stakeholders

- Trade associations in agriculture
- National and regional/local NGOs active in landscape and environment maintenance and recreation
- Local residents

Policy and Market actors

- Local and regional politicians
- Farmers and farmers cooperatives
- Investment Funds and Development Companies
- Energy communities

Local experts

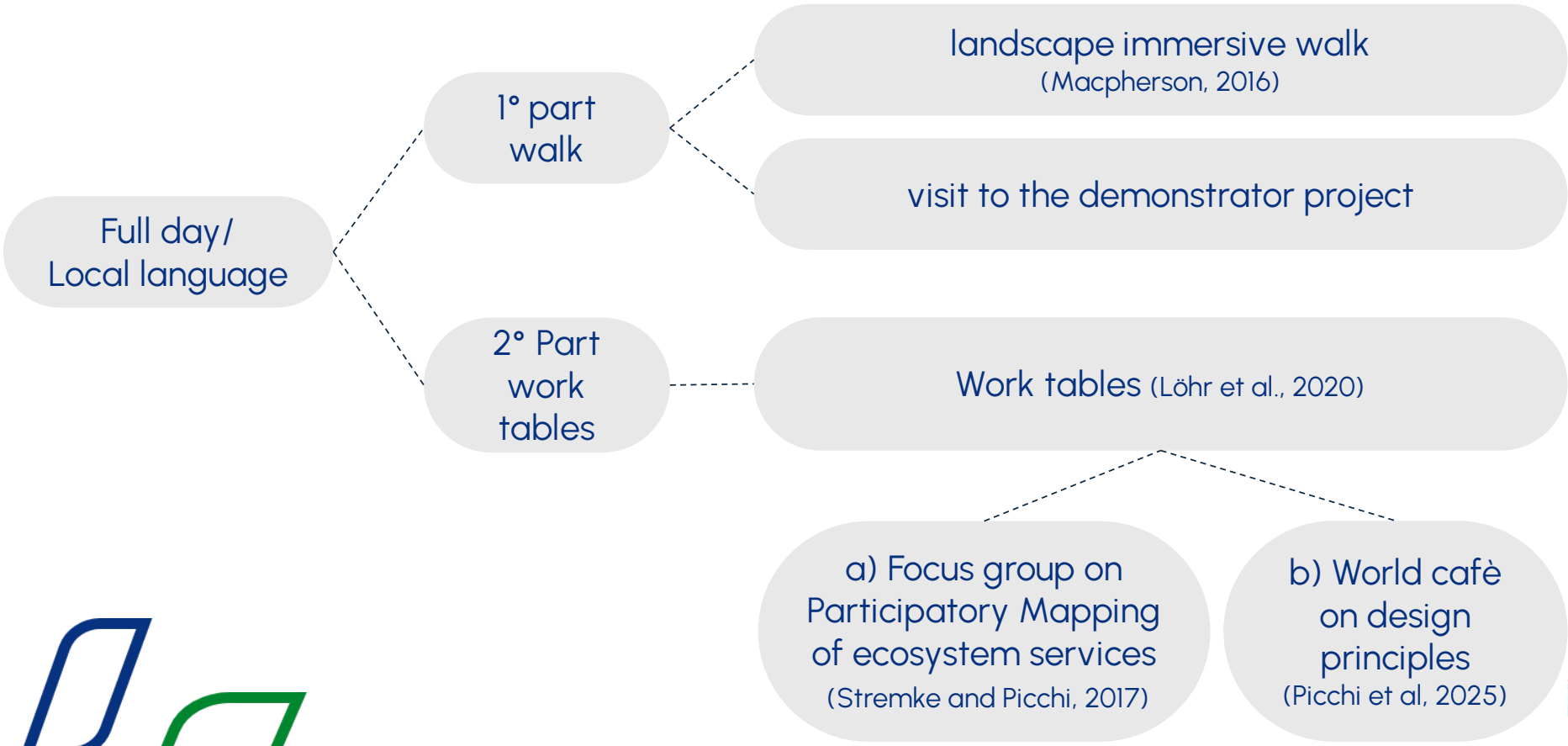
- Community storytellers
- Local experts (historians, archaeologists, agronomists, botanists)
- Local and regional public officer
- Cultural heritage officers

Education and research communities

- High schools
- Universities
- Research Foundations

(adapted from Picchi et al., 2025)

3. Participative Method for co-design framework



3. Method in WP8 – work tables method for maximum 60 participants

2° part

a) Focus Group (30 min) moderated session – **4 groups by 15 p.**

Mapping ecosystem services (ES) values for a shared vision 2050

- ❑ provisioning ES
- ❑ Regulating ES
- ❑ Cultural ES

b) World Cafè (60 min) self-managed session – **5 p. per question**

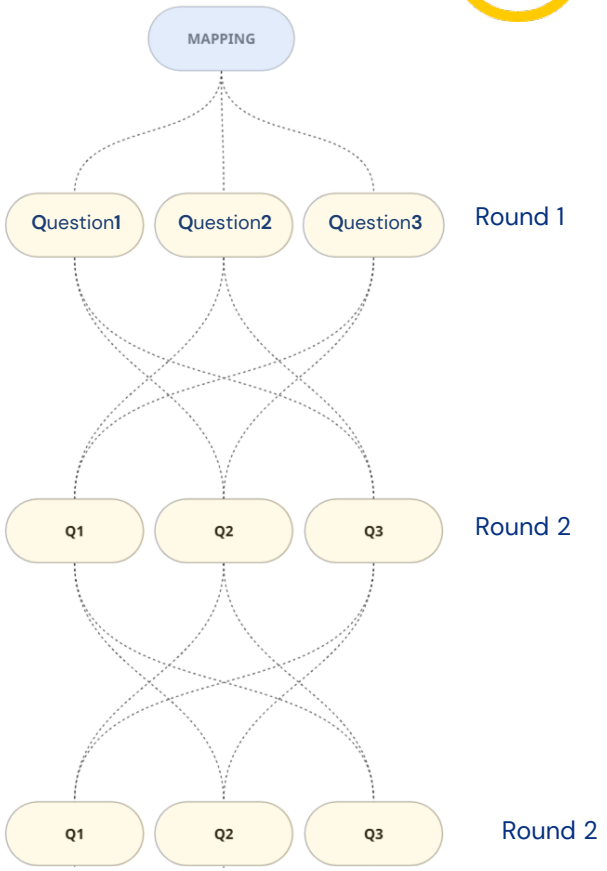
Set of 3 open ended questions

1° Round (20 min)

2° Round (20 min)

3° Round (20 min)

Conclusions (30 min) moderated session



4. Application and Methodological results

1° COMMUNITY WORKSHOP

14 June 2025
Ora/Auer
Bolzano, Italy



PARTICIPANTS

19 participants:

- 5 local and regional stakeholder;
- 4 local experts;
- 4 economic actors;
- 6 representatives of the Scientific Community and the School.

1° part

Landscape immersive walk walk + Picnic



Credit: ETA Florence

Visit to the SYMBIOSYST demonstrator project



Credit: ETA Florence

2° part

Participatory Mapping of Ecosystem Services:

- Focus Group (30 min)
  Moderated session

  2 Groups by 6 participants



2° part

Group A

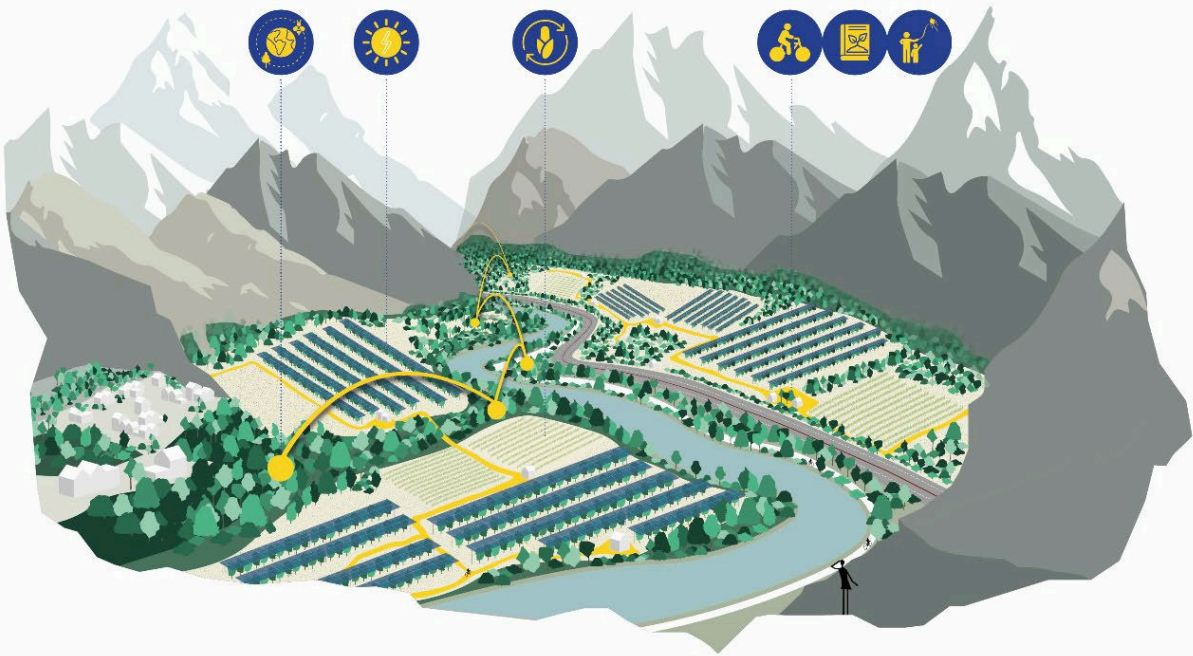

Credit: ETA Florence

Group B


Credit: ETA Florence

Substantive results Sample – Group B

- ➔ Reintroduce arable and forage crops, linked to historical agricultural heritage
- ➔ Create new nature areas to connect existing natural habitats
- ➔ Develop educational pathways on agrivoltaics and sustainability
- ➔ Use Agri-PV energy to support sustainable tourism activities



4. Application and Methodological results

2° COMMUNITY WORKSHOP

22 November 2025
Agropolis, UPC
Viladecans, Spain



PARTICIPANTS

22 participants:

- 5 Local and Regional stakeholder;
- 3 Local experts;
- 4 Market actors;
- 9 Education and scientific community;
- 1 Policy actor.

1° part

Immersive landscape walk in the Agrarian Park of the *Baix Llobegrat*



Field visit to the Symbiosyst demo project



2° part

Participatory Mapping of Ecosystem Services:

- Focus Group (30 min)
  Moderated session

  2 Groups b 9 participants



2° part

Group A



Credit: ETA Florence

Group B



Credit: ETA Florence

Substantive results Sample in Viladecans, Spain – Group B

Through agri-PV systems developing sustainable territorial strategies that enhance strategic agricultural areas and biodiversity:

- ➔ Guiding cultivation towards less saline zones, farther from the sea and closer to peri-urban areas;
- ➔ Strengthening native flora and fauna through vegetation belts, wetlands, and beekeeping, creating ecological corridors;
- ➔ Promoting good practices through communication and outreach, tourism, and environmental education, fostering greater awareness and ecological responsibility within communities.



Conclusions

Visit to an existing Agri-PV demonstrator was relevant to understand agri-PV systems

- Direct experience of a real functioning system
- Improved understanding of dual use
- Supported participants in imaging local application

Landscape exploration walk was relevant for co-design agri-PV systems in the local context

- Better understanding of landscape characteristics
- Increased awareness of agricultural production and natural habitats
- Encouraged discussion and shared reflections among participants

European Agrivoltaic Network

European Agrivoltaic Network
is a European platform dedicated to agrivoltaics for multidisciplinary and crossdisciplinary knowledge exchange.

Initiative of Symbiosyst

with etaflorence renewableenergies

Join the network and express your opinion!



Objectives of the network

- Search for relevant agrivoltaic experiences and pilot plants in all European regions.
- Good practices sharing and spillover effects among difference disciplines.
- Setting a European community on agrivoltaics based on the differentiation of regional knowledge.
- Fostering the knowledge transfer in new agrivoltaic experiences.
- Making European regions emerge as main actors in the regulation and planning of agrivoltaic systems.
- Organization of network events such as webinars, workshops, and field visits.

Project information

SYMBIOSYST – Create a Symbiosis where PV and agriculture can have a mutually beneficial relationship, is an Horizon Europe Innovation Action started in January 2023 that will continue through December 2026
The consortium consists of 18 partners from 6 European countries, including the United Kingdom, and is coordinated by EURAC Research.

Symbiosyst

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SYMBIOSYST Project

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Thank you!

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Partners

Coordinator

eurac research, 3E, EF Solare Italia, ENEA, etaflorence renewableenergies, FOTONIQ, KUBO, KU LEUVEN, Laborelec, imec, LAIMBURG, LUCISUN, Südtiroler Bauernbund, TU Delft, Universitat Politècnica de Catalunya BarcelonaTech, valmont SOLAR, above

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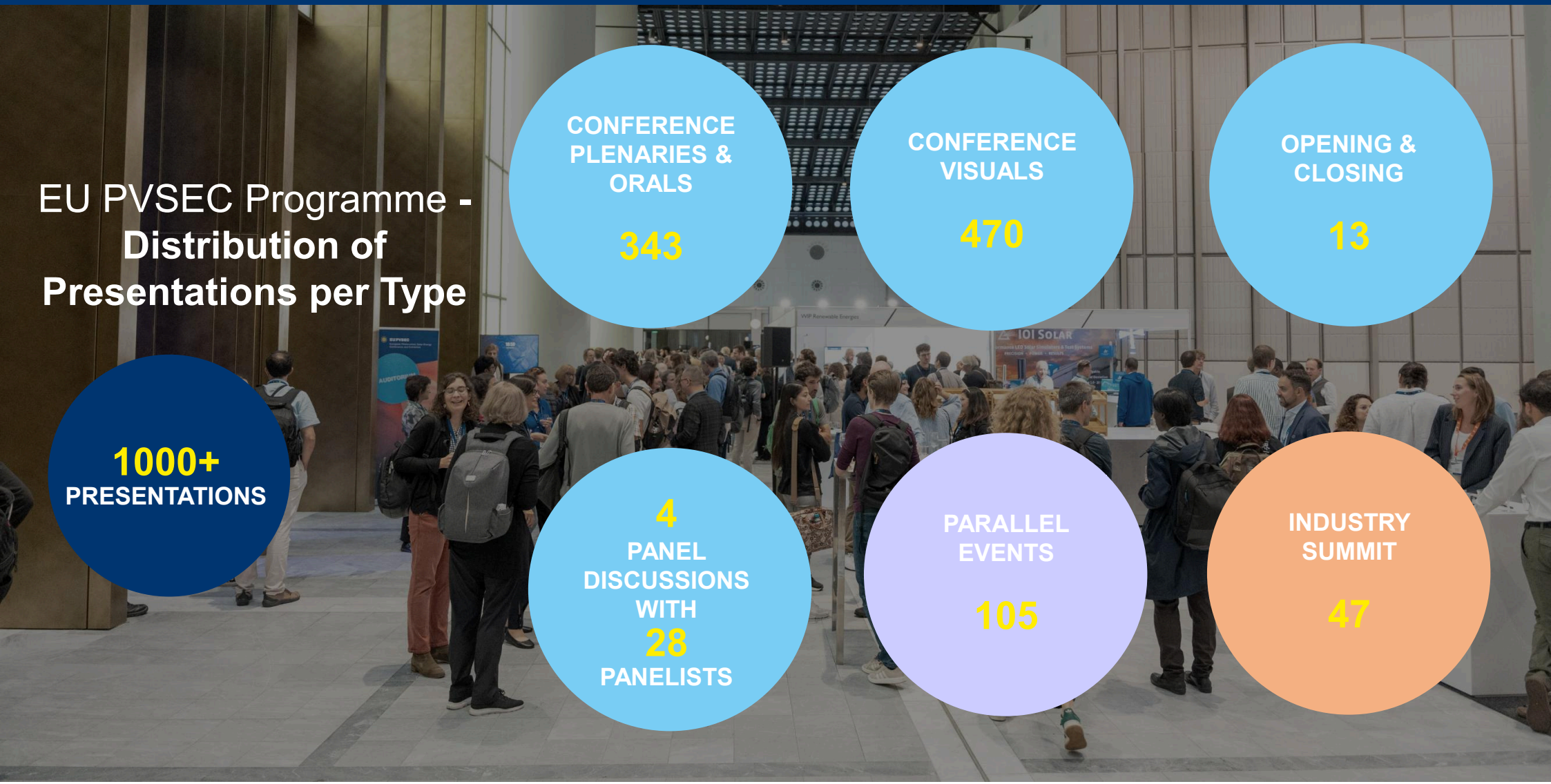
Robert Kenny

European Commission Joint Research Centre

FACTS & FIGURES | Presentations



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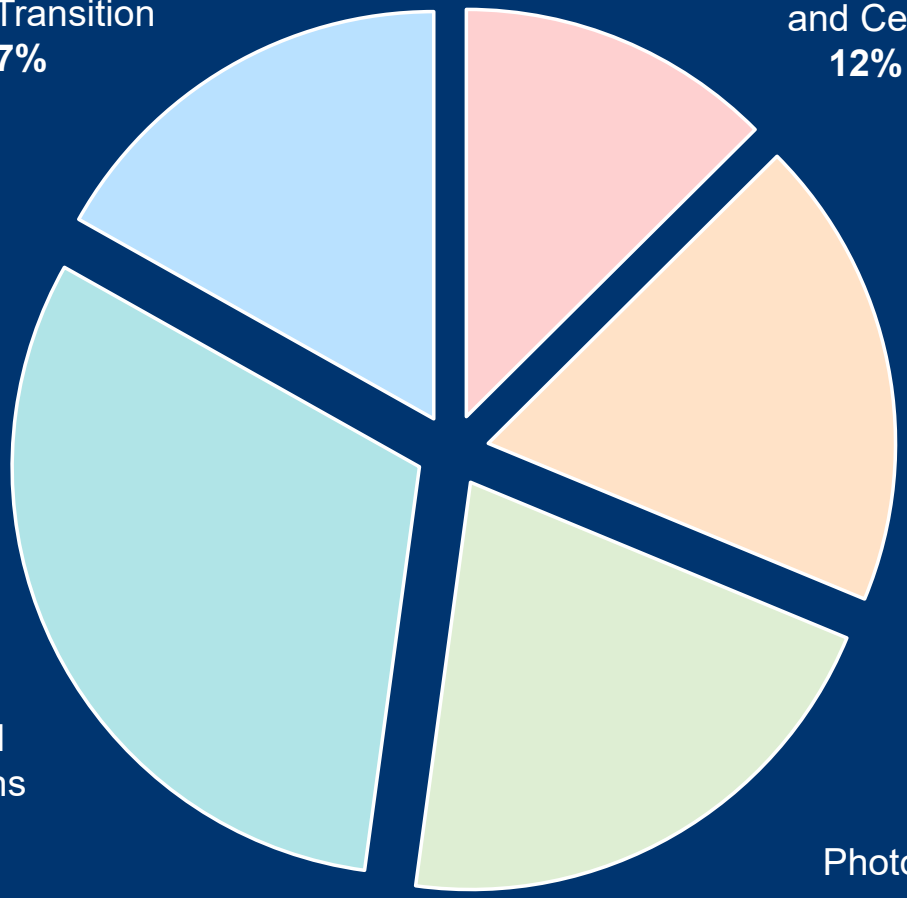
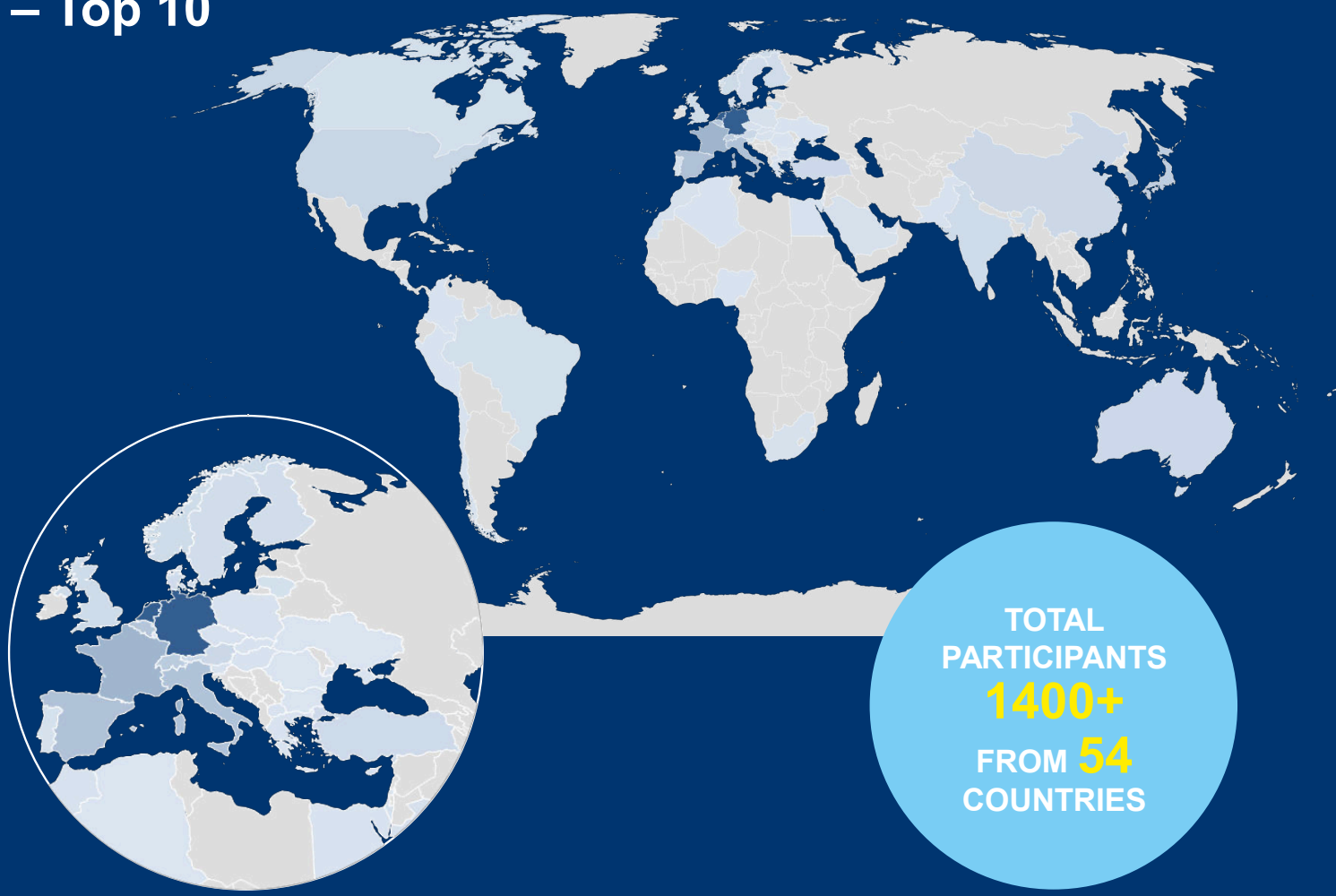


FACTS & FIGURES | Participants

EU PVSEC Programme –
Participants by Countries – Top 10

No	Country	Participants
1	Germany	256
1	The Netherlands	256
3	France	90
4	Spain	65
5	Italy	64
6	Belgium	58
7	South Korea	57
8	Switzerland	47
9	Japan	43
10	United States of America	27



TOTAL PARTICIPANTS 1400+ FROM 54 COUNTRIES

OPENING
Monday, 14 Sept. 2026

Plenary Session
"PV in the Energy System"







Becquerel Prize Ceremony



Welcome Messages





Opening Addresses





Key Note Speech
"Congestion and other Limits in the Electricity System"



Moderated Panel Discussion
"Grid Congestion Management: Enabling the Next Phase of Solar PV Growth – The Dutch Perspective"



PV ACADEMY

Ahead of the conference, the PV Academy once again brought researchers, students and industry professionals together for a day of in-depth learning.

This year's programme covered three very current corners of the PV world:

- **Space photovoltaics**
- **Artificial intelligence applications across the PV value chain and the modelling of PV**
- **Energy storage systems for grid integration.**

Special thanks are due to the PV Academy Chairs, the excellent tutors and the sponsors!

CONFERENCE

Thanks to all members of the Scientific Committee, Awards Committees (Student and Poster), Highlights Committee and Session Chairs to making the conference a success.

2026 Topic Chairs

Topic 1



Dr Olindo Isabella

DELFT UNIVERSITY OF TECHNOLOGY, THE NETHERLANDS

Topic 2



Dr Nicola Beaumont

OXFORD PV, UNITED KINGDOM

Topic 3



Dr Ralf Preu

FRAUNHOFER ISE, GERMANY

Topic 4



Dr Tsvetelina Merdzhanova

FORSCHUNGSZENTRUM JÜLICH, GERMANY

Topic 5



Dr Karsten Wambach

WAMBACH-CONSULTING, GERMANY

CONFERENCE

The importance of scientific collaboration

Throughout the week, numerous oral and poster presentations reported results from Horizon Europe projects, underlining the benefits of intensive collaboration across Europe and beyond. The research presented at EU PVSEC demonstrated the importance of partnership-driven innovation across the PV value chain, an approach further reinforced through EUPI-PV*

European Partnership for Innovation in Photovoltaics

PANEL DISCUSSIONS



BO.13
Geographical Diversification of PV Manufacturing

CO.7
Perovskites: Evolution or Revolution?

DO.13
Floating PV: Calm Waters or Stormy Seas?

Summaries of all three panels will be published on the EUPVSEC website

CONFERENCE

TOPIC 1: SILICON MATERIALS AND CELLS

UVID & hydrogen evolution in TOPCon and SHJ solar cells

- Cell binning does not predict UVID degradation; temperature and visible light mitigate UV effects (UNSW, ISE)
- Indoor tests validated against outdoor (KIWA)
- New insights on H-related mechanisms in passivation/contact stacks and on UV-ID regeneration behaviour in TOPCon and SHJ (UNSW, ISE, METU)

Localized contacts in TOPCon & SHJ solar cells

- Front TCO-free SHJ with localized contacts exceeds 23% certified efficiency (TU Delft)
- Localized contacts enable higher performance and are the bridging step between front/back-contacted and back-contacted cell architectures (ISC K, TU Delft, Jinko)

Innovative solar cell architectures, manufacturing and metrology

- Hybrid Moly-Poly c-Si cells reached 23.63% with rear hydrogenation and post-processing texturing (TU Delft)
- Physics-informed machine learning for solar cell diagnosis and measurement data compression (ISE)
- PVD route for TOPCon solar cells getting traction (ISE, Von Ardenne)

CONFERENCE

TOPIC 1: SILICON MATERIALS AND CELLS

Sustainable metallization

- Ag-coated Cu, Ni, Al particles (Jinko, UNSW, Wuxi Autowell Technologies) and Ag-lean (ISE-RENA) approaches
- Ag-free metallization pastes providing high-performance alternatives to Ag pastes (ISE, CEA/INES, FZJ, ISFH, CSEM)

Light management toward the Auger-Lambert limit

- Excellent plenary by Daniel McDonalds *who next year will report on advancements towards 29%* (ANU)
- Light trapping highlighted as key pathway to reduce optical losses and push Si cells closer to theoretical limits.
- Photoluminescence technique devised to characterize the absorption of infrared light in silicon (ANU)
- POLO^2 IBC solar cells with front nanotexture surpassed 26% efficiency (TU Delft & ISFH).

CONFERENCE

TOPIC 2: PEROVSKITES AND OTHER THIN-FILMS; TANDEMS; NEW CONCEPTS

Topic 2 plenary session had two world records shared (2CP1)

- Amazing achievement of 34.21% III-V terrestrial PV module demonstrated through controlled improvements in geometric and optical module design. (2CP1.4).

- Looking into the future, another highlight was the 30.2% triple junction PVSK/PVSK/silicon cell by the consortium partners in the Triumph project shared in the Topic 2 plenary session (2CP1.3) – a perfect example of successful European collaboration. A new world record from Trina of 32.37% (2D0.8.1) also shared on triple junction technologies.

Rapid improvements in module power highlighted by then 907 W PVSK-Silicon tandem module shared by Trina (2D0.8.1) as another demonstration of the performance boost for a tandem architecture.

CONFERENCE

TOPIC 2: PEROVSKITES AND OTHER THIN-FILMS; TANDEMS; NEW CONCEPTS

Themes across Topic 2 include the PVSK transition from a lab technology to a commercial one with greater number of talks focused on scalable processing, reliability testing and standardization of testing and protocols.

- On reliability, Prof. Schlatmann presented outdoor PVSK-Silicon industrial module (combined activity between PVComB, HZB and Oxford PV) highlighting the importance for outdoor data. Many studies highlighted the need for outdoor data in session 2B0.9 and the need for standardization for increased confidence in perovskite-based products.
- Session 2D.06 highlights included multiple presentations focused on sequential deposition techniques for scale, including rapid advancements using multiple deposition techniques resulting in efficiencies >30% for PVSK-Si tandems (2D.06.5) with scalable methods and use of green solvents (2B0.10.1)
- Panel (C07) discussed the convergence around shifting the focus from record performance to credible reliability data on PVSK technologies

In session 2A.01 new innovations in CIGS and CdTe tandems were demonstrated in both 2T (2A.01.4) and 4T configurations (2A.01.6) highlighting the prospects of traditional compound thin-film technologies for future tandems.

Advanced characterization is driving innovation with advanced PL and JV measurement techniques (2A.03) discussed to understand complex material challenges such as metastability and ion migration.

CONFERENCE

TOPIC 3: PHOTOVOLTAIC MODULES

Outstanding module efficiency advancements results have been presented

- 31.2% III-V on Si with shingle matrix module design (3 DO.12.2)
- Impressive module level results also obtained in Topic 2

Improved woven-fabric concept adapted for perovskite cell (3CO.12.6)

High number of papers giving insights into impact of encapsulation materials on module reliability with a focus on the shift from EVA to EPE as well as additives (3BO.11.1, 3BO.11.3,3AV.1.2, 3AV.2.46…)

“Design to recycle” easy end-of-life module separation of modules and materials (3CO.11)

Presentation and discussion on Anti-glare glass with deep laser-assisted texturing (3CO.12.4)

Wireless In-situ monitoring of module state and dynamics (3.AV.3.22)

Substantial progress in modelling of systems with variable component design PVMD toolbox (3DP.2.4) as well as testing and modelling for the aging behaviour (3BO.12.4; 3BO.12.6)

CONFERENCE

TOPIC 4: SYSTEMS DESIGN AND OPERATION; APPLICATIONS

- **PV everywhere (Space applications are expending) and soon PV whenever.** PV's next growth phase depends on storage. Batteries can balance daily demand, while long-term seasonal storage in molecules can ensure reliability. Storage is key for PV to scale further and gain trust.
- Curtailment may be a feature not a bug in the future
- PV+BESS projects shift design priorities from maximizing photovoltaic yield to optimizing the PV+BESS system as a whole, balancing storage sizing and cycling, power conversion, grid services, safety, and project economics.

Topic 4

4AO.9: Long-term Solar Resource Datasets
Highlight: There are big improvements in the resolution of satellite/reanalysis datasets. It is now possible to have a 4 km spatial resolution and hourly temporal resolution for some datasets, improving photovoltaic yield prediction and long-term energy planning across complex environments.

4BO.5: BIPV Performance Modelling and Reliability
Highlight: Lightweight, frameless photovoltaic modules with mild curvature enable roof-parallel installation on structurally constrained flat roofs, with validated modelling and field measurements showing only 3–4% annual energy losses at ±2° curvature and half-cut cell architectures reducing electrical mismatch losses by approximately 50%.

CONFERENCE

TOPIC 4: SYSTEMS DESIGN AND OPERATION; APPLICATIONS

4DO.13 (Panel) Floating PV calm water or storm seas?
Highlight: Onshore floating photovoltaic offers lower-cost dual use of inland water bodies, while offshore floating photovoltaic expands solar potential by using existing infrastructure of wind but faces higher CAPEX, harsher conditions, and greater environmental challenges.

4DO.4 Agrivoltaic system: design, monitoring and digital modeling
Highlight : **Vertical agrivoltaic systems** can maintain agricultural productivity at scale, with global satellite observations and crop modelling indicating neutral or positive effects on vegetation through reduced wind stress and evapotranspiration.

Computational fluid dynamics and machine learning show that agrivoltaic panel geometry can reduce evapotranspiration by up to 40% and alter plant and photovoltaic temperatures by up to 5°C, highlighting the need to optimize geometry for both crop resilience and energy yield.

Other session Agri PV- Japan's agrivoltaic development is moving toward adjustable, tracking, and vertical systems, with crop-specific designs increasingly focused on balancing energy yield and agricultural productivity.

CONFERENCE

TOPIC 5: PHOTOVOLTAICS IN THE ENERGY TRANSITION

- Excellent progress in innovative and high value PV recycling methods including high scale-up potential: High yield and quality of materials reported;
- AI applications help optimising the value chain and system integration. PV can power AI data centres;

5AP.1: PV in the Energy System

PV Systems provide electricity for AI Data Centres and AI application is a powerful tool to optimize the PV value chain and system integration

5CO.3: Raw Material Recovery and Utilisation from End-of-Life PV Modules

5CO.5 : Recycling and Reuse of PV Modules

Advanced recycling methods provide high-purity material recovery with excellent potential for industrial scaling including polymer recycling.

CONFERENCE

TOPIC 5: PHOTOVOLTAICS IN THE ENERGY TRANSITION

5DO.11 Supporting innovative PV Development for the TW area

A large portion of future European electricity demand could be covered with full utilization of rooftop and façades; Ambitious Japanese targets to 2040; Italian regulatory landscape for Agri PV – 80% of “value” should be from the agricultural production.

5DV.2 Sustainability of PV

Mobile Pretreatment of PV modules can reduce logistic costs of recycling. Good progress in polymer recycling presented though some module types may still be hard to recycle.

CONFERENCE KEY TAKEAWAYS

- The next stage of the growing market is to make sure electricity is available where and when it is needed by focusing on the grid and flexibility enablers (in particular battery storage) - “PV everywhere and PV whenever.”
- According to Solar Power Europe, PV generation has avoided more than 30 billion EUR in EU gas imports since the start of the 2026 Middle East War.
- Crystalline silicon remains at the heart of global PV research and industrial development. Research priorities are addressing efficiency improvements, reducing the use of silver, and long-term reliability.
- Perovskites and tandem solar cells continue their rapid development, with strong progress in efficiency accompanied by increasing efforts to improve stability, scalability and manufacturing processes, supporting the transition towards commercial deployment.
- Reducing material consumption and replacing critical resources, including efforts to substitute silver with copper, remain important areas of innovation for PV modules. Circularity is becoming increasingly relevant, with research addressing recyclability, repair, reuse and improved end-of-life management.
- The diversity of PV applications continues to expand. In agrivoltaics, regulatory approaches combined energy production with agricultural productivity. Floating PV, building-integrated PV and vehicle-integrated PV further demonstrate the growing range of environments in which photovoltaic technologies can be deployed.
- Socio-economic aspects address the wider societal dimension of the energy transition. The critical role of PV in providing electricity to the millions of people who still lack access, especially in parts of Africa was highlighted.
- Digitalisation and AI are established tools throughout the PV value chain, including in system design, modelling and forecasting, performance analysis, fault detection and automated O&M. At the same time PV has been identified as the only real solution to provide the green energy needed by the rapidly increasing number of data centres.

SESSION HIGHLIGHTS – TOPIC 1

1AO.4	UV-Induced Degradation: From Cell Level Mechanisms to Module Reliability	Further advanced understanding of UVID. Common themes included: 1. Cell binning doesn't predict UVID; 2. Temperature and visible light can mitigate UV alone; 3. Indoor tests validated against outdoor testing.
1AO.5	Silicon Solar Cells; Hydrogen and Stability & Reduction of Silver Consumption	Understanding of H-related mechanisms in passivation stacks / contact structures important regarding stability aspects -> thorough characterization studies have been presented. Ag-reduction is very important regarding sustainability aspects -> many creative technological approaches out there to reduce Ag consumption. Ag-coated Ni-particles metallic paste decreases Ag utilization by 24%
1AO.6	Innovations in Passivating Contact Solar Cells	Yingwen Zhao from TU Delft showed development of hybrid Moly-Poly c-Si solar cells. By introducing hydrogenation of the rear side and texturing post rear side processing, the Voc of the device could be improved from 700 to 720 mV leading to a champion device with efficiency of 23.63%. POLO2 IBC cell endowed with front nano-texture breaks 26% barrier
1BO.2	Silicon Heterojunction Solar Cells	It is important to see that thin-film innovations for silicon heterojunction solar technology are still very prominent within European research demonstrating sustainable cell concepts e.g. removing silver and indium. Record efficiency on front TCO-free SHJ solar cell of above 23% was demonstrated.
1BO.4	Manufacturing of Silicon Solar Cells and Technologies to Reduce Ag Consumption	Plasma oxidation: clearly structured talk to realize a tunneloxid by PECVD, by Fraunhofer ISE, relevant for industrial manufacturing. Ag free paste for SHJ cell with clear structures and efficiencies drop of 0,4%abs (good result at this point)
1CO.2	Recombination, Degradation, and Diagnostics in Silicon Photovoltaics	ANU demonstrated a technique for using wavelength dependent PL to characterize the absorption of infrared light in silicon. This is significant given that the Isc due to infra-red leakage out of the solar cell is a limiting factor to limit efficiency in Si.
1CO.1	Optimization of Manufacturing of Silicon Solar Cells	Fraunhofer ISE presented very interesting and convincing method for cell diagnostics based on cell simulation and machine learning. 1CO.1.3 Physics-informed Machine Learning for Solar Cell Diagnosis and Measurement Data Compression.
1DO.6	Silicon Bottom Cells & Perovskite/Silicon Tandems	Deep understanding & characterization of the recombination junction of tandem and its interfaces with SAM and the impact on PK growing. Outstanding result on TCO free devices >30% by EPFL.
1BV.1	Single Junction Silicon Cells | Silicon Bottom Cells for Tandem Photovoltaics | Characterisation & Modelling of Silicon Cells	In-free Si heterojunction (HJT) solar cells advancing indium-free approaches toward more sustainable PV. Reduced-Ag metallization using printed Cu lowering silver consumption.
1BV.5	Silicon Material Science and Technology | Manufacturing of Silicon Cells	Global diversification of Cz wafer production. Some nice high quality Cz silicon wafers produced in Türkiye presented by University of Malta (awarded the poster prize). Development of a European Cz puller for PV enhancing resilience for Europe and the World.

SESSION HIGHLIGHTS – TOPIC 2

2AO.1	New Concepts in CIGS and CdTe Solar Cells	Various exciting cell concept and material innovations were displayed. Innovations included the introduction of novel buffer materials for low and wide band gap CIGS materials, as well as contact passivation materials allowing bifaciality and tandem integration. Tandem integration ranged from 2T Perovskite - CIGS tandems presented by Emilee Fortier to 4T CdTe - cSi tandems presented by Prof. Alessandro Romeo, demonstrating the prospects of the traditional compound thin-film technologies for future tandems.
2AO.2	III-V and Organic Solar Cells | Contactless Measurement Techniques	One of the highlights is the analysis of the resilience of InGaAsP multijuntion solar cells on different illumination angles, this aspect was thoroughly described and highlighted and it is very important for real life conditions as OWPTs will continue to gain more applications in remote power transmission. A second highlight is about the study of contactless measurement for perovskites.
2AO.3	Advanced Characterisation and Simulation of Perovskite and Tandem Cells	Following last years's trends, photoluminescence is established as a powerful tool to identify underlying material and device properties. New developments include the decoupling between surface and bulk recombination. Advanced JV measurements, incorporating temperature and scan-speed variation allow for a deeper understanding of the transport properties of the perovskite absorber, including ion migration.
2BO.1	Novel Materials and Processes for Perovskite Devices	2BO15: Roll-to-roll development 2BO16: Good results on mixed Sn-based perovskite
2BO.8	Novel Architectures and Advanced Materials for Enhanced Efficiency and Versatility	2BO.8.5: This is based on a combined view of applicability (compatibility with existing systems, retrofit), innovation (reduce the angle distribution of diffuse light) and depth of analysis (optical simulation combined with the experimental determination of the angular distribution). The idea of the free-space luminescent concentrator can indeed be used to concentrate the light on a traditional module without further heating the module (there is less thermalisation loss and, if any heating, it is located in the concentrator). The concentration factor is rather low and it remains to be seen how you have to adapt the design of the PV-system to maximally exploit the effect.
2BO.3	Performance Characterisation of Perovskite-based Cells and Modules	The session brought together six presentations addressing the transition of perovskite photovoltaics from laboratory devices to reliable commercial modules. Contributions demonstrated encouraging outdoor energy yields from perovskite–silicon tandems and advances in module testing, while highlighting the importance of stabilization protocols, operating conditions and long-term durability. Together, the presentations showed tangible progress towards commercial perovskite PV, with the dependable performance assessment and sustained outdoor stability remaining central to deployment.
2BO.9	Advanced Characterisation and Stability im Perovskite Devices	As (hybrid) perovskite PV based technology moves to commercialization, stability and degradation studies and related advanced characterization becomes more important. Importantly, new drafts are made for new IEC standards.
2DO.7	Novel Materials and Device Architectures for Perovskite based Multijunctions	2DO7.1 Enhanced current in mid bandgap subcell in triple junction solar cells with a SiO2 nanoparticle based intermediate reflector and increased thickness. 2DO7.2 Two terminal all perovskite tandem solar cells on flexible substrate with 30% bifaciality and upscaling with slot-die coating. 2DO7.3 In-free AZO recombination junction and NiOx-based HTL with SALD with alternative Ni precursor and co-reactant engineering (H2O, O2, O3). 2DO7.4 Green solvent stable ink for inkjet printing in ambient air with GVL and DMSO for perovskite scalability. 2DO7.5 Perovskite passivation with bifunctional groups: understanding of passivation mechanisms and degradation mechanisms. 2DO7.6 Impact of CsI position in the sequential/co-sequential evaporated perovskite stack: co-sequential CsI leads unhomogeneous vertical and horizontal Cs distribution and overall wider bandgap.

SESSION HIGHLIGHTS – TOPIC 2

2DO.8	Scalability and Real-world Performance of Perovskite based Tandems	Rapid improvements in module power highlighted by then 907 W PVSK-Silicon tandem module shared by Trina (2D0.8.1) as another demonstration of the performance boost for a tandem architecture.
2DO.9	Late News: Perovskite and Perovskite-Silicon Tandems	University of Oxford: Presented an innovative graded dielectric layer concept for perovskite/silicon tandem solar cells that suppresses ion accumulation and tunneling currents under reverse bias, enabling markedly improved reverse-bias stability. Smit Thermal Solutions: Showcased a high-throughput close-space deposition platform for inorganic scaffold fabrication, with a strong focus on wafer thermal budget management, coating homogeneity, and industrial-scale throughput. IPVF: Delivered a comparative analysis of LCOE and energy yield for perovskite/silicon tandem PV at residential and utility scales, identifying the key cost and performance drivers for tandem technology. IMEC: Presented a comprehensive assessment of 3T perovskite/silicon modules versus conventional 2T architectures, highlighting potential advantages and predicted real-world performance benefits.
2BO.10	Towards Industrial Processing of Perovskite Devices	2B0.10.1: The use of green solvents in large area modules resulted in 16-17%, which is really up to state-of-the-art. Overall, the session showed that the debate is still open about what processes are most suited for scale up, full solution processing or evaporation based processing. Even the architecture discussion, n-i-p vs p-i-n, is open.
2BV.2	Compound (Chalcogenide, Kesterite, III-V) and Organic Devices	Different materials have been presented for compound chalcogenide materials (Sb2Se3, CZTS, CIGS, CdTe). In particular, we highlight the introduction of ultra thin CIGS materials thanks to nanostructures that allows for light trapping. Also we highlight the raising efficiency of CZTS, over 14% presented by a Korean group and with different post deposition treatments as well as the study of the back contact. New applications of thin films like for example laser conversion efficiency for space applications is also acknowledged.
2CV.2	New Materials, Devices and Conversion Concepts | New Modelling and Characterisation Techniques	There were several excellent presentations about promising new methods for device fabrication to reduce costs for established technologies or to explore new material properties and combinations. From the analysis side there was an in-depth method development for attaining ion mobilities which is particularly interesting for understanding perovskite solar cell behaviour.
2CV.3	Perovskite-based Tandem and Multijunction Devices | Perovskites	Strong discussion on hybrid and adaptive processes for scalable depositions (Uli KIT)
2CV.3	Perovskite-based Tandem and Multijunction Devices | Perovskites	The average of the posters is of high quality. Strong discussion on hybrid and adaptive processes for scalable depositions (KIT) - More attention to scalability of perovskite solar cell and modules. - More attention to sustainability, for example the use of so called green solvents - meaning eco-friendly solvents.

SESSION HIGHLIGHTS – TOPIC 3

3BO.11	Polymers and Encapsulation	Be careful to you additives: B. Hoex. The talks highlighted the importance of additives and low concentrations substances in encapsulant-cell compatibility, adhesion and long-term durability (3BO.11.1, 3BO.11.3). Belferkous (3BO.11.4) showed how non-destructive characterization and AI-assisted analysis provide powerful predictive tool (degradation score) for O&M operations.
3BO.12	Indoor/Outdoor Correlations and Degradation	The overall problem was highlighted by Todd Karin (3BO.12.3) presenting higher failures in their test sequence and no overall top performer (so there is no ideal module). The challenge remains to use indoor accelerated testing to map 30 years of performance. In two presentations (Paul Gebhardt 3BO.12.4; Ismail Kaaya 3BO.12.6) we saw modelling approaches taking into account real mission profiles as well as measured degradation factors. All speakers in excellent talks that we must look beyond the datasheet and take into account the BOM specifics.
3BO.14	Environmental and Mechanical Stresses on PV Modules	The session highlighted the growing need for enhanced mechanical stability of PV modules in emerging applications and challenging climates, emphasizing that standard IEC qualification tests may not be sufficient to capture all relevant failure mechanisms. A keynote contribution by Anika Gassner (OFI) presented and validated application-specific test sequences for alpine PV systems, providing a practical framework for product development and reliability assessment in these demanding environments.
3BO.15	UV-ID; PID and Metallization Reliability	New insights about UV-ID degradation and regeneration behavior linked with preconditionning and temperature understanding on TOPCon and HJT. Allow a better power evaluation of these affected modules compared to field. Improvment on Ag/Cu interconnexion solutions and even full copper in term of reliability compared to pure silver open a door to a cheaper and less silver constraint module. Better realistic PID potential testing method using UV light, more comparable to outdoor behavior
3CO.10	Late News: PV Module Reliability and Degradation	HID - Human Induced Degradation! The most underestimated reason for PV systems failing. From planning, packaging, transport, and installation to O&M.
3CO.11	PV Module Materials and Processes for Sustainability	"Design to Recycle" approaches for encapsulation materials and other polymer or functional layers are presented and highlight the advances in concepts that case module recycling at the end of life, through complete separation of encapsulants from solar glass, as well as solar cell separation from the laminate. Additionally, further trends which contribute to the enhancement of sustainability are explored, such as liquid encapsulation (with a current end-of-life material recovery as high as 92%), for facile dismantling of modules at their end of life, as well as trials for introduction of low temperature, lead free soldering alloys for solar cell interconnection, which target a melting point of 120°C or lower and must compete with current process cost schemes. This circular approach supports photovoltaic module manufacturing at material and process level, as a renewable and sustainable source of energy.
3CO.12	Innovation in PV Module Manufacturing	3CO.12.6: The IMEC presentation on multi-wire interconnection for perovskite tandem solar cells presented an improved woven-fabric concept adapted for perovskite cells, with evaluation on the reliability of low lamination temperaure and short time. It has a potential of fast fabrication process. 3CO.12.4: The presentation from Fraunhofer ISE on anti-glare glass showed strong results on reduction of luminance of reflected light, which reduces the glare effect on PV modules. Results were better than commercial anti-glare glasses (not presented in the presentation). It benefits from potential cheap fabrication process with promising results.

SESSION HIGHLIGHTS – TOPIC 3

3DO.16	Advanced Imaging and AI-Based Diagnostics for Photovoltaic Modules	The research community is becoming increasingly aware of the importance of extracting the right information from luminescence techniques. This includes improving automated defect detection, addressing the limitations, and gaining deeper information from the images.
3DO.12	Circularity and Materials in Modules Design	The session highlighted that the increasing diversification of PV module materials and designs is creating new challenges for processing, characterization, and long-term reliability. As new material combinations and increasingly complex module architectures enter the market, established characterization methods and processing approaches may no longer be sufficient to fully understand their behavior. This becomes particularly relevant when novel material solutions are adopted rapidly, while knowledge of their processing sensitivities and long-term performance is still developing. Overall, the session emphasized that innovation in module materials and design must go hand in hand with adapted characterization methods, robust processing strategies, and a deeper understanding of long-term reliability to ensure that advances in performance and circularity do not introduce new failure risks.
3DO.20	Thermal Performance of PV Modules in Operation	Overall, the session highlighted the importance of accounting for irradiance, degradation, technology, location, and system design when modeling the thermal behavior and performance of PV modules. The temperature coefficients should be verified over time and their change during time is correlated to degradation effects.
3DO.18	Metrology and Performance Characterisation of PV Modules	Advancedment in technology implies challenges in metrology and accuracy in power rating, of commercial modules, the session focused on several relevant aspects such as: -the importance of spectral irradiance, there was also intralaboratory (focucing on indoor and outdoor measurements) and interlaboratory -improvement in the measurement techniques, such as the measurement of AR coating, and the IAM factor, - and meastability of TOPCon
3AV.1	PV Module Design and Manufacturing	This session highlighted PV module technologies from multiple perspectives, featuring innovative approaches in encapsulation, interconnection, materials development, and novel module concepts. The contributions covered solutions both on component and product level and were adressing upcoming developments and currently existing challenges. The presentations demonstrated that Europe remains competitive in delivering innovative contributions across the entire value chain and proving it is not being left behind globally. Europe is not only developing new technologies but it also has the ability to accurately and comprehensively evaluate the value of these developments. This dual capability ensures that Europe can continue to set the right priorities and accents for the future of the PV sector.
3AV.2	PV Module Durability and Reliability	Wide range of development of from larger datasets of field performance to an increased with focus on, nondestructive characterization techniques. Highlight was a weighted risk evaluation for polymer failure in different use scenarios.
3AV.3	PV Module Performance – Modelling, Testing, Standards	The session highlighted the Importance of the comparison between indoor and outdoor reliable characterisation methods focusing on spectral effects, degradation issues and soiling. Ultimate goal is improving the understanding of real world implications in PV energy production.

SESSION HIGHLIGHTS – TOPIC 4

4AO.7	Accuracy of Solar Resource Measurement	Details make the difference in measurements. No high quality timeseries without quality checks. Graphical quality checks provide better understanding of the errors. Satellite images in combination with ground images can provide very high resolution and quality information for albedo.
4AO.8	Solar PV Forecasting	This session focused on recent developments in solar PV forecasting and nowcasting for improved energy system operation and grid integration. Contributions address forecasting methods based on satellite data, sky imaging, machine learning and advanced data processing techniques, with applications ranging from plant-level to national-scale predictions.
4AO.9	Long-term Solar Resource Datasets	There are big improvements in the resolution of satellite/reanalysis datasets. It is now possible to have a 4 km spatial resolution and hourly temporal resolution for some datasets.
4BO.5	BIPV Performance Modelling and Reliability	Modelling can address all the challenges in BIPV and fire safety should be next important topic due to safety reasons
4BO.6	Operational Levers for PV Asset Management: From Layouts to Repowering	A detailed presentation on performance losses due to soiling emphasized that losses increase at high incidence angles, which means losses under diffuse irradiance are higher as well. Current field measurement techniques do not account for this. Two presentations shared improvements in PV shading loss modelling and simulation techniques: one focused on reducing the losses (using backtracking) and one focused on assessing the losses.
4BO.7	Smarter O&M: AI-Driven Inspections and Diagnostics for PV Systems	A common theme was that the industry needs scalable, automatable methods to maintain high performance as PV deployment continues accelerating: “Fleets grow faster than the experts that watch them”. Integrating complementary ML/DL approaches may be a powerful approach to high accuracy in data-driven methods, with two speakers presenting driven fault detection and diagnosis methods using layers of ML/DL models that verify and correct each other’s conclusions. However, high accuracy may come with poor interpretability in some cases. Finally, positive results were presented for advanced methods of analyzing drone imagery (both IR and EL) and field trials for automatic and fast methods of computing solar tracker positions for arrays on nonuniform terrain.
4BO.16	BIPV Module and System Design	Strong focus on facades with also new solutions for both trasparent element and metal lightweigh solutions. Fire performances of facade is still a concern but new tests demonstrate that not only materials are relevant but system design plays a significant role in fire development. There is still need to harmonize standards to support BIPV.
4BO.17	Colour and BIPV	Speakers talk about a broader choice for architects and designer builders, offering more diversity in colors, maintaining high performances and durability. The is a need to predict performances with specific applications, and necessity to adapt or improve simulation tools. In general, all presenters talk of aesthetical aspects solution and try to keep efficiency and performance as high as possible. They brought new combination approches LSC/QD + perovskite in order to promote improved products to meet building needs.
4CO.8	Reliably Assessing PV Plants: Monitoring, Metrics and Field Practices	There are new challenges in calculating performance KPIs (e.g. PR & EPI) of PV plants, due to curtailment, sensor positions in large PV plants, as well as inherent measurement uncertainties and cases of heavily filtered datasets.

SESSION HIGHLIGHTS – TOPIC 4

4CO.9	Understanding and Detecting Degradation and Losses in PV Systems	This session focused on understanding, monitoring and detecting degradation and performance losses in photovoltaic systems under real-world operating conditions. Contributions address degradation assessment methodologies, environmental stress effects on different module technologies, UV-induced degradation prediction, crack evolution and detection techniques
4DO.1	Solar PV Forecasting in Urban Areas | Yield in Bifacial PV Plants	Forecasting: Focus on the usability of the forecasts rather than their accuracy. Every model is wrong; choose the most useful. PV Yield: Despite the significantly higher uncertainty in rPOA models, POA uncertainty remains the dominant source of uncertainty in the overall PV yield simulation due to the low absolute share of rPOA.
4DO.2	Hybrid Systems and Storage; Direct Uses of PV Generated Electricity	Session started with results on investigation of combined systems (PV+WIND+STORAGE+....).Highlights have been the last contributions with simplification of the path from the sun to longterm storable energy like gas and/or hydrogen direct from the sun or immediately after the modules. These developments are on a way from laboratory to industrial use like PV was 25-30 years ago and are promising to fulfil the target of energy independancy from fossil fuels.
4DO.3	Modeling and Optimization of PV Systems / Power Electronics for 4-Terminal Modules	Simulation results presented major achievements in utilizing module level power electronics (MLPE) for 4 terminal tandem PV modules. The importance of using minute scale data for safety dimensioning was highlighted, along with the importance of accounting for electricity price fluctuations in profitability index computation. Solar farmer was validated and ERMESS, an open-source framework for microgrid simulations, was presented.
4DO.4	Agrivoltaic Systems: Design, Monitoring and Digital Modelling	Vertical agrivoltaic systems can support plant growth and reduce wind, helping to counteract the effects of shading, while APV systems can also alleviate extreme ambient conditions by moderating the microclimate beneath the PV panels. Combining ray-tracing tools and crop models can account for APV regulations and crop-yield requirements, while CFD and machine learning can predict convection and air temperature based on system geometry, meteorological conditions, and plant growth.
4DO.17	Floating PV “Onshore"	The Floating Solar community can look forward to a multi-dimensional framework for sustainability and standardised incremental impact assessments through the STEWART project. Quote of the day was: “Bi-directional Floating PV – waterbird interactions”.
4DO.5	Agrivoltaics: Crop Performance, Materials, Field Experiments and Applications	THIN-FILM PV: Strong technical potential, but results are not yet fully convincing and are still largely based on small-scale experiments. STRUCTURAL SYSTEMS:PV structures need to be adapted to agricultural requirements - including height, spacing and tracker configuration - while maintaining PV performance. FROM IMPACT MITIGATION TO MUTUAL BENEFITS: Research still focuses mainly on minimising negative PV impacts on crops and pasture. The next step is to demonstrate clear, measurable mutual benefits for both energy and agriculture.

SESSION HIGHLIGHTS – TOPIC 4

4DO.10	Environmental Impacts on PV Systems Performance and O&M	This session examined how environmental conditions and extreme weather influence photovoltaic system performance, reliability and operations and maintenance strategies. Topics include soiling in desert and floating PV systems, snow and wind impacts in high-latitude regions, machine-learning-based loss prediction and the effects of extreme weather events on PV infrastructure. The presentations highlight the increasing importance of climate-resilient system design, advanced diagnostics and predictive modelling for reliable long-term PV operation.
4EO.2	Floating PV “Offshore”; VIPV; Space PV; CPV	All 5 presentations are of high quality.Two Highlights are: - 4EO.2.2 author Khalid Baig from TNO. In this presentation measured movements of an offshore FPV system are used to compose a movement model that can be applied not only to the current location at sea, but also to other potential locations for future installations. Thereafter the validated movement of the FPV-platform is used to model the electrical output in various levels of MLPM. - 4EO.2.4 author Jelle Westerhof from Twente University. This presentation shows a very innovative design of a 'magic mirror' that can boost (winter) yield on normal PV-panels. The concept has been inspired by radiative cooling coatings. Prototypes have been constructed already to show that the concept is working. Promising technology, if the cost can be kept low enough.
4BV.3	Solar Resource and Forecasting	Many papers about solar forecasting applying mostly standard methods of AI (not too many innovation). Interesting topics aside forecasting within a wide field of work like gap filling methods for one second GHI measurements, quality control of GTI, uncertainty information for satellite based GHI, GHI measurements on cars or spatial smoothing of variability.
4BV.4	PV and Buildings	A clear takeaway from this poster session was the continued focus on coloured BIPV solutions (characterization, color degradation analysis over time, angle-of-incidence effects, ways to achieve coloured samples, etc.) alongside sustained attention to safety issues, mainly those related with fire propagation in roofs and facades.
4CV.1	Design, Engineering and Installation of PV Systems; BoS	The presenters had engaging discussions with the visitors and provided comprehensive explanations. Content-wise, Poster 4.C.V1.1 was very good, but visually less appealing. Overall, Poster 4.C.V.1.9 was the best poster regarding the technical novelty, where shading can be mitigated using low-cost battery balancers.
4DV.1	Agri-PV | Other PV Applications (Floating, Infrastructure, etc.); CPV; PV in Space | Hybrid Systems and Storage; Direct Uses of PV Generated Electricity	In general there were a lot of high quality posters covering Agri-PV, Floating (FPV), VIPV and Space-PV. - Space-PV: (at least) one high quality poster on HJT-cell optimization for space. - FPV: we saw more modelling than field testing. The poster on the combination of offshore PV between the current and planned offshore wind farms in the North Sea of the Netherlands is a kind of runner-up of this session. - VIPV: session winning poster of AIST on retrofitting a minivan with PV on top. Very much experimental work and validation, with impressive results. - AgriPV: a lot of work with pilot sites on many different subtopics (crops, trackers, maintenance, etc.). - Battery Energy Solar System (BESS): the other winner of this session.

SESSION HIGHLIGHTS – TOPIC 5

5CO.4	Combining PV and Energy Storage	Work coordinated through IEA-PVPS Task 16 quantified the optimal oversizing of PV capacity as "implicit storage" to ensure firm renewable production. It evidenced a steep increase in the optimum curtailment fraction up to 20% when the cost of demand-side flexibility increases from 0 to 0.1 $/kWh. Since the study has so far considered the grid as a copper plate, trade-offs with grid reinforcement costs are likely to drive the optimum curtailment fraction up. (Jan Remund, Meteotest + IEA-PVPS T16) . The control logic for hybrid PV+BESS systems has a strong influence on achievable income. Within the presented range of options, a robust model-predictive control logic leads to more than 50% higher revenues than a rule-based logic. (Cristóbal Parrado, Andrés Bello University). Despite the push for data centres to "bring their own power", the optimal solution is not to go off-grid. In case studies in the Middle East, the grid has unused capacity that depends on the season. Dimensioning PV+BESS to serve 98% of the DC load makes good use of this capacity and avoids costly investment in double the battery capacity to cover the remaining 2%. (Harry Apostoleris, EPRI).
5CO.5	Recycling & Reuse of PV Modules	The session focused on innovative strategies for enhancing the sustainability of photovoltaic (PV) modules through advanced recycling and reuse approaches. Key insights included: 1- Advanced recycling methods — Availability of high-purity material recovery techniques and their potential for industrial scaling. 2- Polymer recycling feasibility — Demonstrated that polymers can serve as the final step in recycling, enabling critical material valorization. 3-Re-implementation of PET materials — Innovative use of recovered terephthalic acid (TPA) from PET materials as a sustainable input. 4- Lightweight module development — Proven feasibility of lightweight PV modules, offering design and transport advantages. 5- Reliability of second-life modules — Emphasis on historical data and testing protocols to ensure performance consistency of reused modules from decommissioned plants.
5CO.3	Challenges for Manufacturing in Europe	This session addresses the strategic, economic and policy-related challenges of strengthening photovoltaic manufacturing in Europe. Contributions explore the implementation of the Net-Zero Industry Act, reshoring of PV supply chains, industrial ecosystem development, certification frameworks for European-made content and the market potential of emerging technologies such as perovskite modules. The session highlights how industrial policy, circularity and manufacturing innovation can support Europe’s competitiveness, resilience and long-term leadership in the global PV sector.
5CO.6	Raw Materials Recovery and Utilisation from End-of-Life PV Modules	The session covered raw material recovery across every component of the PV module — silicon, glass, encapsulants, backsheets and frames — and extended to manufacturing residues such as silicon kerf loss and frame offcuts. A common thread was that purity requirements should follow the intended application rather than default to solar grade. A very innovative illustration of this idea inverted the usual logic of silicon recycling: rather than re-purifying contaminated or doped material, it exploits the embodied energy already invested in it, converting the waste into heat and hydrogen with waterglass solutions and metal concentrates as saleable co-products. A second route combined kerf loss with aluminium frame scrap to synthesise zeolites, dispensing with high-temperature activation altogether.
5DO.11	Supporting Innovative PV Deployment for the TW Era	53% of electricity demand in Europe could be covered by rooftop + facade IPV, with the majority of the potential in the residential sector, raising concerns about the high costs of meeting this demand. A presentation on Japan explained the challanges of increasing PV to very high levels uner the constraints of limited flat land.

SESSION HIGHLIGHTS – TOPIC 5

5DO.14	Environmental Impact and Sustainability; Life Cycle Analysis	The session highlighted advances in LCA modeling through dynamic foreground and background modeling, consideration of novel scenarios of PV deployment including sophisticated consideration of repowering as well as agrivoltaic application, and evaluation of environmental impacts of advanced PV cell concepts, especially perovskite-silicon tandems. Whereas life cycle assessment is a mature field of study with codified if general methods, this session demonstrates the continued research innovation in the PV field to advance LCA from a methodological and application perspective providing valuable insights useful for policy and project decision-making, where EUPVSEC remains at the fore.
5DO.19	PV in the Electricity Grid	This session explores the integration of PV into electricity grids, with a focus on forecasting, market participation, and operational impacts. It gave a good overview of the complexity to the energy system and the grid. Presentation #1 considered both risk and bidding simultanously using a probabilistic approach. Presentation #2 used the open-source tools to predict the regional global production. Presentation #3 presented the proof of down sampling of time resolution based on net-meter measurements. Presentation #4 presented accurate forecast results using satellite images and aggregated plants data from grid operators. Presentation #5 was a geographically diverse study about firm power as part of IEA PVPS Task 16, deadling with over capacities. Presentation #6 presented the potential of EV to be used as buffer to increase PV self-consumption in workplaces.
5DO.15	Circular Economy and Waste Streams of PV Modules	Three remarkable aspects emerged: 1. Keep the glass intact if you want to enter high-value recycling! Glass in general played an important role, including with regard to regulations. 2. Currently, the WEEE directive sets a recycling quota based on the total mass of the waste. The discussion with Mattia Gianvincenzi gave hope for an adjustment towards a material-specific quota – i.e., x% of a material contained in an end-of-life PV module – wonderful news for silver hunters. 3. Last but not least, a dashboard for different waste streams was developed within the RETRIEVE project – my personal highlight – and with that, my thanks to Anna Rebecca Siemer for the demonstration.
5EO.1	PV Markets, Value of Storage and Manufacturing Economics	Melodie De L'EPINE talked evolution of the PV market. We startd to market volume with the unit of TW. Kay Ceser presented the benefit of vertical PV integration with BESS. Daniel Chrkavy presennted revenue simulation of PV+ BESS in Germany and Spain using 3 years data. Garvin Heath discussed models for repowering and decomissionning for utility scale power plants. Tools and cases.
5EO.3	Photovoltaics for and with Society	Social dimension is an Unavoidable aspect to be considered: gender, diversity, educational, citizen engagement and social media are keys for the acceptance of PV.
5DV.2	Sustainability of PV	Korean colleagues from Won Kwang S&T presented a wonderful mobile recycling solution for pre-treatment in the field... it helps to minimize dead freight space. The EverPV project, Technalia, presented a viable solution to finally tackle backsheet recycling in a targeted way. And particularly impressive was the courage to face the truth shown by the Polymer Competence Center Leoben, stating that not every PV product can be meaningfully recycled.
5DV.3	Grid Integration and Flexibility Enablers | Scenarios for Renewables, Policy, Resilience, Global Challenges | Costs, Economics, Finance and Markets | Societal Challenges; Citizens' Participation, Awareness	Diverse topics were presented. Economic analysis of PV manufacturing in Europe, Impacts of regulatory change in Costa Rica, analysis of generation and storage. Social acceptance issues and challenges of perovskite technologis are also discussed.

SESSION HIGHLIGHTS – OPENING AND PLENARIES

Opening	Moderated Panel Discussion - Grid Congestion management and the perspective of The Netherlands	While congestion was first seen as a problem, the realization is surfacing that curtailment of PV is a feature of a system with PV, wind, and batteries. Peter Palensky of TU Delft gave a brilliant and inspiring plenary presentation about the huge challenge of energy system integration in which he made a comparison with another big challange faced in the Netherlands: dealing and living with water. Grid congestion is temporary - but it is forcing the sector to build a better-organised energy system.
5AP.1	PV in the Energy System	ETIP PV experts presented nine concrete recommendations to unlock PV capacity integration into the grid and support its adaptation to different deployment phases, and envisioning increasingly flexible, resilient, and grid-supportive PV systems. Jef Poortmans of Imec brought together the worlds of PV and AI: PV4AI and AI4PV. AI can contribute a lot to further development of PV and energy system integration, and PV can contribute greatly to the big and rapidly growing energy demand of AI. PV energy for AI and AI to pave the way for PV along the value chain.
2CP.1	Thin-Film PV Technologies Towards Impact	An exclellent range of broad topics covered by the session from R&D fundamentals (Petrozza) and developing of triple junction technology (Sivaramakrishnan), through module improvements for III-Vs resulting in a world record >34% (Stevens) to an Thin-film technology perspective (Hammer) and what can we learn from CIGS for the future of commercialising PVSK technology.
1CP.2 | 3CP.2 | 5CP.2	Silicon PV Design, Manufacturing and Circularity	Both silicon presentations provided clear insight in the advances for Silicon-based efficiency improvements, both theoretically (Daniel MacDonald) and practically (Menglei Xu), in which the latter presentation by Jinko gave a very good detailed insight in the various options available and used for TOPCon technology improvements. TOPCon is closing the Voc gap with SHJ. Jaione Bengoechea addressed circularity for PV modules and systems based on the R-ladder, which ranks a sustainability strategies based on how efficiently they use resources and retain product value, and includes re-use, re-purpose, re-cycle. Noteworthy is the concept of a circularity index that may support uptake of circularity concepts in PV technology.
5EP.1 | 3EP.1 | 4EP.1	Reliable PV Everywhere	1. Analysis of PV-module manufacturers' financial reports highlights different practices and huge uncertainties. Checking financial risk of suppliers is important. 2. Full overview of IEA-PVPS-T13 (RELIABILITY) activities for PV in extreme climates, under extreme weather conditions and for different applications. 4. A vision for PV O&M activities till 2035: robotics, automation, AI to reduce costs and improve efficiency. 3. Great potential of Floating PV in the oceans (open-seas), particularly around the equator: 30 °S to 30 °N. 4. Overview of the regulatory framework on Agri-PV in Italy, targets and visual examples of projects. 5. PV in Africa (and the global South): challenges (growing populations & low shares of electrcity access) and opportunities (solar lanterns, solar-home systems, mini-grids, ...). Access to electricity is an important economic development enabler.

EU PVSEC

PARALLEL EVENTS

- **PV Reliability in Nordic Climates: Investigating the Impact of Snow**
  Cross-climate research highlighted key degradation mechanisms, the need for more realistic testing, and the strong performance of PV in Nordic climates despite snow-related mechanical stress.
- **Diversity in PV: Embedding Inclusion by Design**
  Inclusive leadership strengthens innovation, collaboration and collective intelligence by creating psychological safety and valuing diverse expertise.
- **Opportunities for Sustainable Perovskite PV Commercialisation**
  European perovskite scale-up requires stronger collaboration, harmonised LCA and data approaches, coordinated material selection and shared pilot-line infrastructure.
- **The PV Plant of 2035: From Design to Daily Operation**
  Reliability and increasingly autonomous, data-driven operation will shape future PV plants, while cost will remain decisive for advanced inspection technologies.

EU PVSEC

PARALLEL EVENTS

- **Regional PV Power Modelling and Forecasting**
  Regional PV modelling is already well recognised, with strong awareness and growing practical use.
- **Advancing LCA & LCI for Photovoltaics**
  Better understanding of recycling offtake markets is needed to improve recycling economics and enable greater reuse of recovered PV materials.
- **PV Integration for Sustainability and Resilience of the Transport Sector**
  Vehicle-integrated PV and PV charging solutions are close to market readiness, but stronger supporting ecosystems are still needed.
- **Shortening the Innovation Cycle: Making EU and National PV Funding Work Together**
  More flexible funding, faster transitions between funding stages and instruments for small, agile consortia could accelerate PV innovation.
- **PV Made in Europe: How Do We Build Competitive Solar Value Chains?**
  European solar policy must reflect current manufacturing capabilities while balancing support for upstream production with the competitiveness of downstream markets.

INDUSTRY SUMMIT

As technology becomes more sophisticated and customized, enhanced quality control is increasingly important.

Global competitiveness & diversification: The EU, India, and the US are driving diversification away from China, highlighting the need for energy-intensive nations to build integrated R&D and manufacturing ecosystems to remain globally competitive.

AI across the PV value chain: AI is expected to become increasingly embedded across processes, from manufacturing to operations and optimization.

Trustworthy AI: Reliable workflows and bounded autonomy are essential to ensure AI remains controllable and dependable.

Scaling with confidence: AI models should be rigorously stress-tested and validated before being deployed at scale.

Strategic partnerships & industrial sovereignty: Equipment choices, manufacturing know-how, and partnerships across Europe, India, Africa, and the US are key to building resilient supply chains and global competitiveness, while avoiding past mistakes in technology and knowledge transfer.

INDUSTRY SUMMIT

Bankability & reliability: Competitive manufacturing must be backed by stable yields, credible business cases, early investor engagement, and reliable products supported by warranties, independent testing, monitoring, and climate-specific performance data.

Market-specific integration & digitalisation: PV solutions increasingly need to be designed around specific applications and market needs, with system integration, storage, forecasting, operational control, and trustworthy AI enabling greater technical and economic value.

INDUSTRY SUMMIT

NZIA feasibility: The policy should reflect Europe's existing industrial capabilities, as fully European-made PV modules are not yet feasible due to gaps across the upstream supply chain.

Industry balance & costs: The focus should be on balancing upstream industrial needs with downstream competitiveness, considering module price differences at the overall system level, where they may be negligible in markets such as BIPV.

LIST OF EXHIBITORS
(in alphabetical order)

Organisation	Country
2nd Cycle FlexCo	Austria
Abet Technologies, Inc.	United States of America
Belga Solar	Belgium
Biosphere Solar	The Netherlands
Delft University of Technology	The Netherlands
DUSTOSS	Israel
DYNVOLT	North Macedonia
ECOPROGETTI SRL	Italy
Eternal Sun I WAVELABS	The Netherlands
EU PVSEC Startup Pavilion	
European Commission - Joint Research Centre (JRC)	Italy
ESMC Pavilion	Belgium
exateq GmbH	Germany
Fronius International GmbH	Austria
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