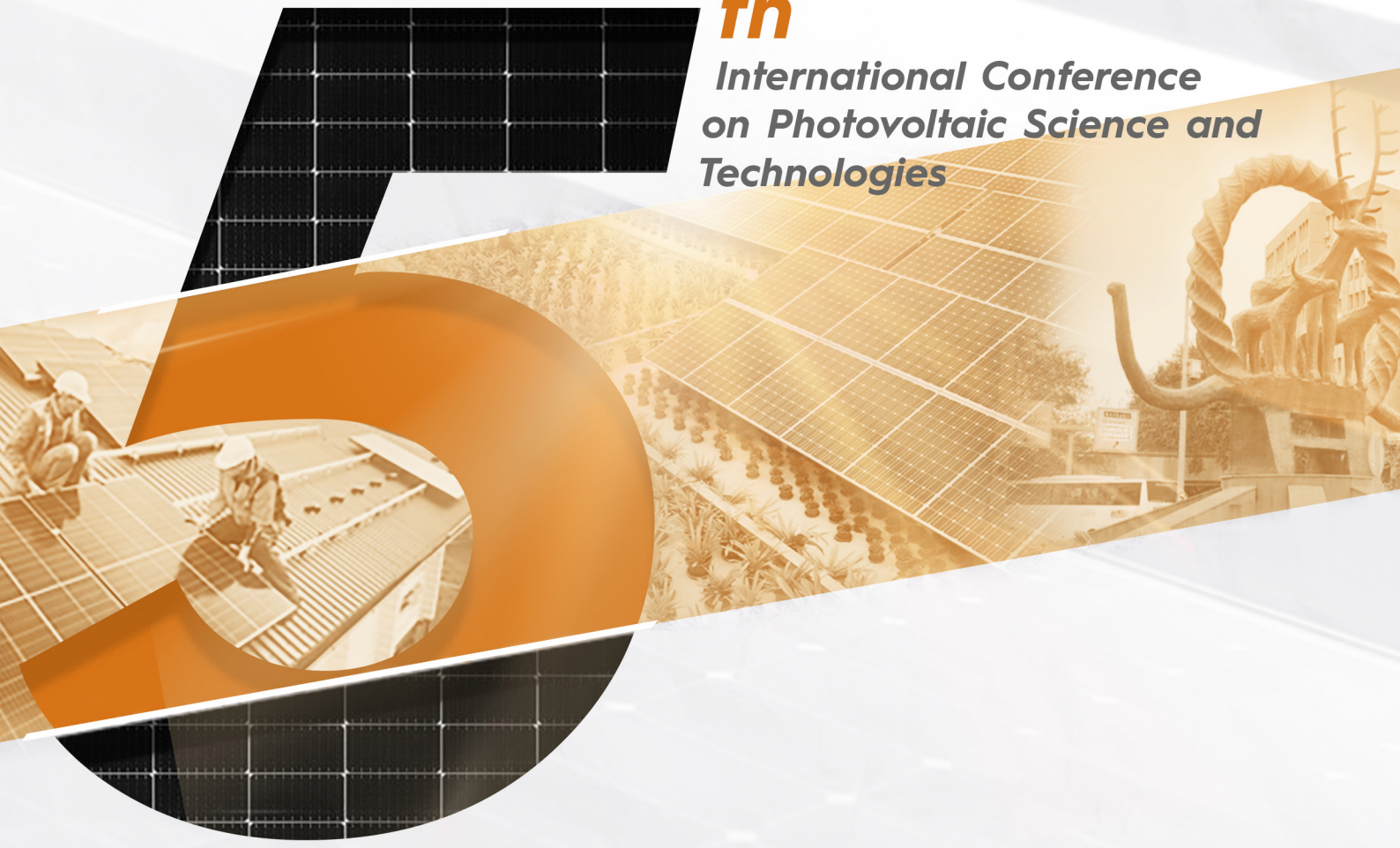
PVCON 2026

PHOTOVOLTAIC CONFERENCE

29 - 30 JUNE / 1 JULY

th International Conference on Photovoltaic Science and Technologies



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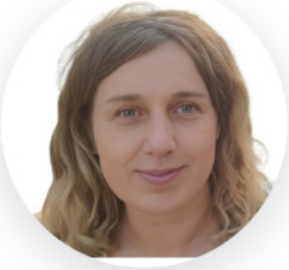
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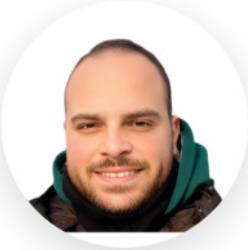
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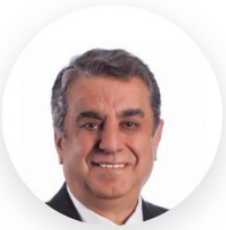
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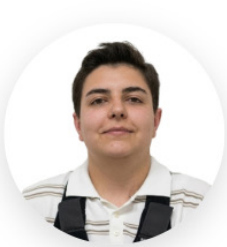
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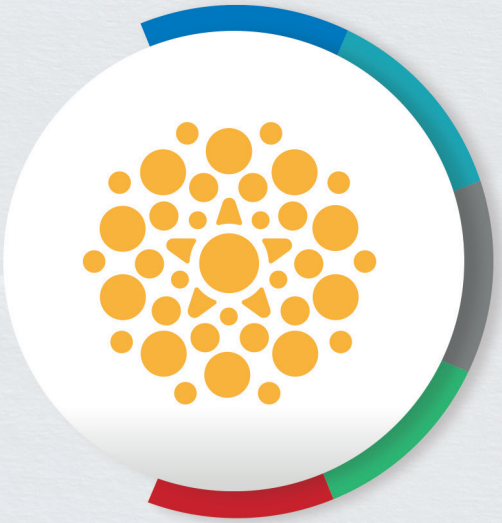
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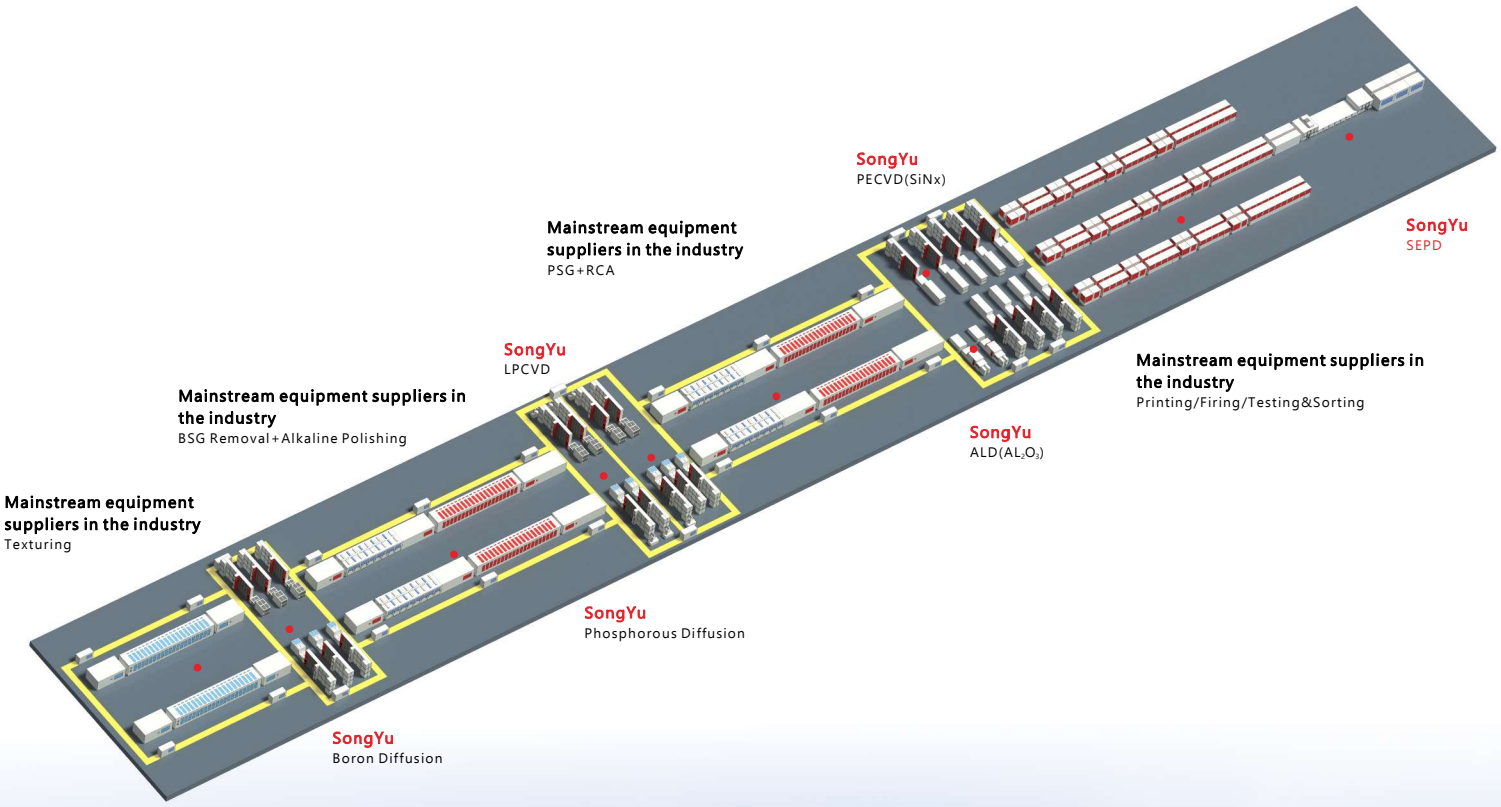
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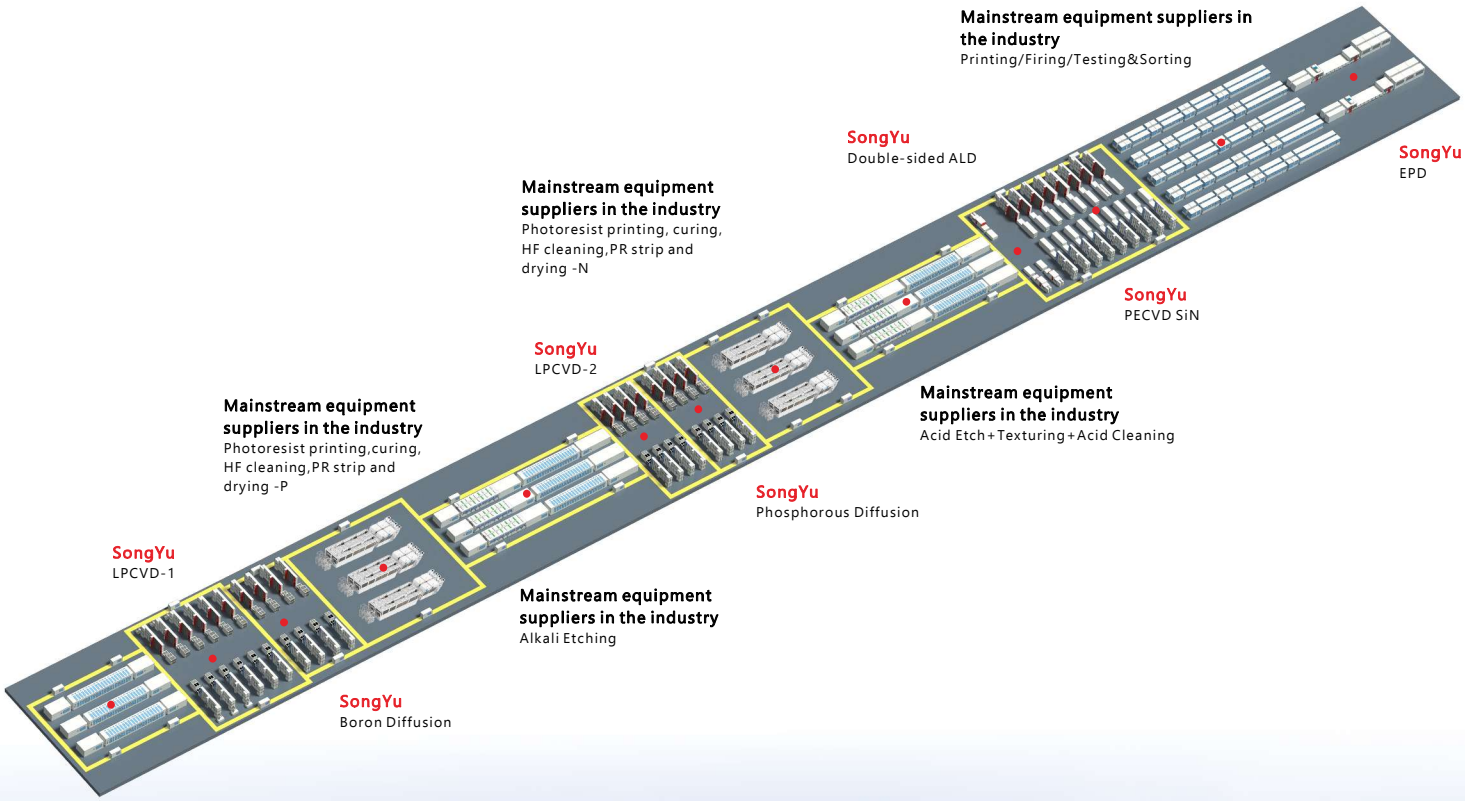
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Chairs Message

It is our pleasure to present the Abstract Book of **PVCon 2026 – the International Conference on Photovoltaic Science and Technologies, held from 29 June to 1 July 2026** at the Middle East Technical University Culture and Convention Center in Ankara, Türkiye.

Photovoltaics is undergoing rapid transformation through advances in solar cells, emerging materials, tandem technologies, module manufacturing, integrated applications, power electronics, and energy systems. At the same time, sustainability, circularity, resilient supply chains, large-scale deployment, and supportive public policies are becoming increasingly important for the future of the sector.

Building on the experience of previous editions, PVCon 2026 brought together researchers, industry professionals, public stakeholders, students, and other members of the photovoltaic community. The conference provided a platform to discuss recent scientific and technological developments while also addressing industrial challenges, commercialisation, system integration, sustainability, and the wider societal and policy dimensions of photovoltaics.

A particular emphasis was placed on strengthening dialogue between academia, industry, and the public sector. Through scientific presentations, invited talks, technical discussions, and thematic sessions, PVCon 2026 supported the exchange of knowledge, the development of new collaborations, and a shared understanding of the opportunities and challenges shaping the future of photovoltaic technologies.

We sincerely thank all authors, speakers, session chairs, reviewers, committee members, sponsors, partners, and participants for their valuable contributions to the success of PVCon 2026. We hope that the ideas and collaborations developed during the conference will continue to contribute to scientific progress, industrial innovation, and the sustainable deployment of photovoltaics.

Conference Chairs
PVCon 2026


PVCON
2026
PHOTOVOLTAIC CONFERENCE
29 - 30 JUNE / 1 JULY

Conference Program - Monday

Monday 2026-06-29 | Tuesday 2026-06-30 | Wednesday 2026-07-01

Show Poster Sessions

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A · Room A
Room A

09:00

09:00 - 10:30 OPENING

Opening Talks

Room A

- Director of ODTÜ-GÜNAM Oya Ertunç Bilgiç
- Conference Chair, Chairman of the Board of Directors of ODTÜ-GÜNAM Assoc. Prof. Dr. Selçuk YERCİ
- Chairman of the Executive Board & President of TENMAK Dr. Abdullah Buğrahan Karaveli
- President of METU Prof. Dr. Ahmet Yozgatlıgil
- Deputy Minister of Republic of Türkiye Ministry of Industry and Technology Dr. Çetin Ali Dönmez

10:00

10:30 - 11:00 BREAK All rooms

Coffee Break

11:00

11:00 - 12:30 TECHNICAL SESSION

Material Development and Circularity in PV

Room A

Chair: **Figen Varlıoğlu Yaylalı** Chair: **Antonin Faes**

AM2.1 **11:00 – 11:30** 30 min
Circular Recycling of Solar Cells
INVITED SPEAKER **Ian Marius Peters**

AM2.2 **11:30 – 11:45** 15 min
Institutionalizing Circularity and Resource Sovereignty in the PV Industry: A Cross-Country Comparative Analysis
Tayfun Hız · ODTÜ-GÜNAM

AM2.3 **11:45 – 12:00** 15 min
Circular Photovoltaics: Low-Temperature Delamination for Glass Substrate Reuse
Doğuşcan Dönmez · ODTÜ-GÜNAM

12:00

AM2.4 **12:00 – 12:15** 15 min
Formulation Strategy for High Performance Silver Paste in Solar Cell Metallization
Duygu Cevher · Nanografi

AM2.5 **12:15 – 12:30** 15 min
Second Life of Silver: From Waste Photovoltaic Pastes to Transparent Conductive Networks
Serdar Güler · METU

B · Room B
Room B

11:30 - 12:30 TECHNICAL SESSION

BIPV & VIPV

Room B

Chair: **Salar Sedani**

BM2.2 **11:30 – 11:45** 15 min
From Architectural Intent to Manufacturable Module: Design-to-Order Digital Workflows as Enablers of BIPV Value Chain Scale-Up
Ahmet Rasim Demirtaş · SolarVIS

BM2.3 **11:45 – 12:00** 15 min
Architectural Integration and Energy Performance Assessment of Building Envelope-Integrated BIPV Systems in Six Provinces of Türkiye's Very Hot, High Solar Radiation Zone Using PVsyst
Ahadollah Azami · Çukurova University

BM2.4 **12:00 – 12:15** 15 min
Multi-Objective Analysis of Semi-Transparent Photovoltaic Façades: Balancing Energy Generation and Indoor Visual Comfort in a Mediterranean Climate
Amirhossein Karimizadeh · Eastern Mediterranean University

BM2.5 **12:15 – 12:30** 15 min
A Multi-Level Design Methodology for Matrix-Shingled Vehicle-Integrated Photovoltaics: From Cell Metallization to Platform-Specific Electrical, Thermal and Energy-Yield Assessment
Parisa Sharif · ODTÜ-GÜNAM

12:30 - 13:30 LUNCH All rooms

Lunch

13:00

14:00

13:30 - 15:00 TECHNICAL SESSION

Tandem PV and Perovskite

Room A

Chair: **Ian Marius Peters** Chair: **Zeynep Gözükara Karabağ**

AM3.1 **13:30 – 14:00** 30 min
Overview of Silicon and Perovskite PV Activities
INVITED SPEAKER
Antonin Faes

AM3.2 **14:00 – 14:15** 15 min
Eliminating P2 Scribes: A New Interconnection Design for Efficient Perovskite Solar Modules Under Indoor Lighting
Bahri Eren Uzuner · ODTÜ-GÜNAM

AM3.3 **14:15 – 14:30** 15 min
Over 33%-Efficient 4 cm^2 Perovskite-Silicon Tandem Solar Cells with Optimized Screen-Printed Metallization
Kerem Artuk · CSEM

AM3.4 **14:30 – 15:00** 30 min
Bridging Efficiency and Stability in Perovskite Photovoltaics
INVITED SPEAKER
Esma Uğur

14:00 - 15:00 TECHNICAL SESSION

Power Electronics

Room B

Chair: **Murat Göl**

BM3.2 **14:00 – 14:15** 15 min
Recent Trends in Fault Detection for PV Power Plants: A Survey
Masoud Emamian Verdi · Middle East Technical University

BM3.3 **14:15 – 14:30** 15 min
A Comparative Analysis of Deep Learning Models and Weather Feature Selection for Accurate Solar Power Forecasting
Somayyeh Rahimi · Middle East Technical University

BM3.4 **14:30 – 14:45** 15 min
Machine Learning-Based Fault Prediction in Electricity Distribution Networks: A Reliability Analysis Framework for Potential Photovoltaic Integration
Mustafa Kemal Ayas · Gazi University

BM3.5 **14:45 – 15:00** 15 min
Rapid Prototyping Workflow for a PV Inverter FPGA-Based Model Predictive Control (MPC)
Robert Balog · Texas A&M University

15:00

15:00 - 15:30 POSTER All rooms

Poster Session 1 with Refreshments — Emerging Technologies & Perovskite Solar Cells

View poster presentations

15:30 - 17:30 TECHNICAL SESSION

CETP TANDEM Workshop

Room A

Chair: **Hisham Nasser** Chair: **Gönül Hızalan Özsoy**

AM4.1 **15:30 – 16:00** 30 min
Scaling up Perovskite Solar Technologies Towards Gigawatt-Manufacturing with Vacuum Deposition Equipment for Evaporation and Sputtering Processes
INVITED SPEAKER
Ruben Seifert

16:00

AM4.2 **16:00 – 16:15** 15 min
Bifacial and Sustainable Tandem PV Technology Using Silicon Cells With TOPCon Front Emitter
L.J. (Bart) Geerligs · TNO

AM4.3 **16:15 – 16:30** 15 min
Insights into the Potential Gettering Effect of n-polySi TOPCon on Recharged Cz Wafers and Degradation Studies of Bottom Cell Substrates for the TANDEM Project
David Fuertes Marrón · UPM

AM4.4 **16:30 – 16:45** 15 min
Mitigating the Optoelectronic Trade-off between Parasitic Absorption and Surface Recombination in TOPCon-based Bottom Cells for High Efficiency Tandem Solar Cells
Yigit Mert Kaplan · ODTÜ-GÜNAM

AM4.5 **16:45 – 17:00** 15 min
Towards Perovskite/Silicon Tandem PV: R&D Activities and Future Perspectives
Özlem Coşkun · Kalyon PV

AM4.6 **17:00 – 17:15** 15 min
Stack of AZO as Recombination Junction and NiO as Hole Transport Layer Employing Spatial ALD for Tandem Solar Cells
Floor Souren · SALD

17:00

AM4.7 **17:15 – 17:30** 15 min
Green-Solvent Based Ambient Air Processed Bifacial Perovskite–Silicon Tandem Solar Cells with 28 mW cm^{-2} Power Output
Radha Krishnan Kothandaraman · TNO

15:30 - 17:15 TECHNICAL SESSION

AgriPV & SSH

Room B

Chair: **Ramazan Sarı** Chair: **Tayfun Hız**

BM4.2 **15:30 – 15:45** 15 min
Agrivoltaics and Sustainable Agricultural Transitions: Farmers' Perceptions and Adoption Constraints in Türkiye
Pinar Derin Gure · ODTÜ-GÜNAM

BM4.3 **15:45 – 16:00** 15 min
Exploring of the Viability of Potential Business Models for Agrivoltaic Systems in Türkiye: A Qualitative Investigation Through Multi-Stakeholder Perspectives
Betül Ergün · Mugla Sıtkı Kocman University

BM4.4 **16:00 – 16:15** 15 min
Environmental Performance and Design Considerations of Agrivoltaic Systems: A Life Cycle Perspective for Photovoltaic-Agricultural Co-Production
İpek Gülçin Uysal · Ege University Solar Energy Institute

BM4.5 **16:15 – 16:30** 15 min
Development of A Photovoltaic Enabler Index (PVEI) and its Effect on PV Adoption in Türkiye
Furkan TÜZÜN · Social Sciences University of Ankara

BM4.6 **16:30 – 16:45** 15 min
The Role of Intellectual Property in Solar Energy Technologies
Şerife Akyıldız · TENMAK - Ministry of Energy and Natural Resources

BM4.7 **16:45 – 17:00** 15 min
Industrial Solar Panel Investments and Sustainability Performance: Evidence from Global Trends and Emerging Economies
Özkan Özkara · Ministry of Industry and Technology

BM4.8 **17:00 – 17:15** 15 min
Analyzing Dynamics in Solar Energy Transition in Developing Economies Using Grounded Theory
Mert Güleç · METU

Conference Program - Tuesday

Monday 2026-06-29 | **Tuesday 2026-06-30** | Wednesday 2026-07-01

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A · Room A
Room A

09:00

09:00 - 10:30 TECHNICAL SESSION

Perovskite: Device Engineering and Stability

Room A

Chair: **Xueqing XU** Chair: **Ian Marius Peters**

AT1.1 09:00 – 09:30 30 min
Strategies for Improving Stability of Perovskite Solar Cells
INVITED SPEAKER **Daniel Prochowicz**

AT1.2 09:30 – 09:45 15 min
Implementation of a Salt-Functionalized Carbon Electrode in Dopant Free HTM Integrated Planar Perovskite Solar Cells
Zeynep Gözükara Karabağ · ODTÜ-GÜNAM

10:00

AT1.3 09:45 – 10:00 15 min
Additive Engineering of PEAI-based Additives for High-Efficiency Indoor Perovskite Photovoltaics
Yagmur Yaren Kurnaz · ODTÜ-GÜNAM

AT1.5 10:00 – 10:30 30 min
Perovskite Solar Cells on Plastic Substrates with Micro-Groove Back Contact Architecture
INVITED SPEAKER **Brian Korgel**

P · Panels
Room B

09:00 - 10:30 PANEL

Entrepreneurship Ecosystem Opportunities for PV

Room B

Moderator: **Hande Eryılmaz** Panelist: **Alp Eren Yurtseven** Panelist: **Hanzade Sarıçiçek** Panelist: **Ümit Çalıkoğlu** Panelist: **Samet Yıldırım**

This panel aims to discuss the PV solar energy entrepreneurship ecosystem in Ankara. The discussion will be enriched with core leading actors TTGV, TEYDEP, TENMAK and SolarVis, representing public, SME and NGO interests. The panel aims to emphasize the roles of the institutions and their value creation for the solar energy community. Discussants will detail future opportunities and also reflect insights to overcome barriers to enrich market, research and societal value creation.

Simultaneous Turkish-English / English-Turkish translation services will be provided.

10:30 - 11:00 POSTER All rooms

Poster Session 2 with Refreshments — Silicon PV, Materials Science & Device Characterization

View poster presentations

11:00

11:00 - 12:15 TECHNICAL SESSION

Emerging PV

Room A

Chair: **Esma Uğur**

AT3.1 11:00 – 11:30 30 min
Wide Bandgap Perovskite Solar Cells and its Tandem Devices
INVITED SPEAKER **Xueqing XU**

AT3.2 11:30 – 11:45 15 min
Development of MXene/PEDOT:PSS Hybrid Electrodes as an Alternative to ITO for Flexible Optoelectronic Devices
Gulsah Yılmaz · Ege University Solar Energy Institute

AT3.3 11:45 – 12:00 15 min
Novel PACz-Derived Self-Assembled Monolayers for Interfacial Engineering and Organic Solar Cell Applications
Shayan Sajedi · ODTÜ-GÜNAM

12:00

AT3.4 12:00 – 12:15 15 min
Resolving Recombination Pathways in Perovskite Solar Cells Using an Impedance Spectroscopy-Based Ideality Factor
M. Cem Şahiner · ODTÜ-GÜNAM

11:00 - 12:30 PANEL

Supply Chain and PV Market Outlook

Room B

Moderator: **Büşra Yılmaz-Depondt** Panelist: **Hamza Memişoğlu** Panelist: **Arda Yalı** Panelist: **İrfan Bıkmaz** Panelist: **İsmail Uslu** Panelist: **Görkem Günbaş**

The panel will go far beyond conventional discussions on cell and module assembly, bringing the localized upstream supply chain ecosystem directly to the table with key decision-makers. As Turkey advances toward its goal of surpassing the 6 GW threshold in cell production, the discussion will evaluate the localization rates, technical standards, supply security, and cost competitiveness—under global price pressures—of critical components such as solar glass, aluminum frames, polymer materials (EVA/POE), and cell manufacturing equipment.

12:30 - 13:30 LUNCH All rooms

Lunch

13:00

13:30 - 15:00 TECHNICAL SESSION

Perovskite: Scaling and Automated High-Throughput Fabrication

Room A

Chair: **Kaining Ding** Chair: **Mustafa Yaşa**

AT2.1 **13:30 – 14:00** 30 min
New Infrastructure for PV Materials in the AI Era – High Throughput Experimentation Platforms and High Fidelity AI Models
INVITED SPEAKER **Yicheng Zhao**

AT2.2 **14:00 – 14:15** 15 min
Inkjet Printing for Mass Production of Perovskite Modules: High-Throughput Patterned Deposition and Enhanced Manufacturing Consistency
Yuelong Huang · Phoenixolar

AT2.3 **14:15 – 14:30** 15 min
Full-Process Development of Large-Area Rigid and Flexible Perovskite Modules Using Scalable Slot-Die Coating and Drying Technologies
Katsumu Araki · SPS

AT2.4 **14:30 – 14:45** 15 min
CleanBot: An Automated Platform for Enhancing Reproducibility in Photovoltaics Research
Frank Stubhan · Sciprios

AT2.5 **14:45 – 15:00** 15 min
Computational Study of Hydrophobic Ammonium Salts for Defect Passivation in $FAPbI_3$-Based Indoor Perovskite Solar Cells
Cem Maden · ODTÜ-GÜNAM

13:30 - 15:00 PANEL

Towards a More Inclusive PV Ecosystem: Visibility, Leadership and Representation in the Energy Transition

Room B

Moderator: **Pinar Derin Gure** Panelist: **Hisham Nasser** Panelist: **Büşra Yılmaz-Depondt** Panelist: **Ezgi Pehlivanlı Yazıcı** Panelist: **Ramazan Sarı**

This session adopts an expanded understanding of "inclusivity" by bringing together sociological perspectives, regional access to clean energy, gender equality, and success stories of migrant and refugee researchers. The objective is to move beyond simply encouraging participation and instead address sectoral diversity through tangible topics such as the economic empowerment of women entrepreneurs, the professional integration of disadvantaged groups, and the diversification of the talent pool within the R&D ecosystem.

14:00

15:00

15:00 - 15:30 POSTER All rooms

Poster Session 3 with Refreshments — Applications: Agrivoltaics, BIPV, Modules & Systems

View poster presentations

15:30 - 17:30 TECHNICAL SESSION

DEPSI

Room A

Chair: **Kerem Artuk** Chair: **David Fuertes Marrón**

AT4.1 **15:30 – 16:00** 30 min
Progress in Perovskite Indoor Photovoltaic Devices and Best Practices for their Measurement
INVITED SPEAKER **Thomas Brown**

AT4.2 **16:00 – 16:15** 15 min
Dual-Environment Perovskite Solar Cells: Powering Sustainable BIPV and IoT Integration
Mustafa Yaşa · ODTÜ-GÜNAM

AT4.3 **16:15 – 16:30** 15 min
Mass-Customized Flexible PV Modules for BIPV: Reliability and Integration
Pierpaolo Spinelli · TNO

AT4.4 **16:30 – 16:45** 15 min
Low-carbon footprint perovskite precursor synthesis and end-of-life management
Görkem Günbaş · Cubichem

AT4.5 **16:45 – 17:00** 15 min
High Throughput Roll-to-Roll Moisture Barriers for Perovskite Solar Cells Using Spatial Atomic Layer Deposition
Hindrik De Vries · SALD

16:00

17:00

AT4.6 **17:00 – 17:15** 15 min
A Physics-Based Digital Twin Framework with Deep Learning for PV Performance Monitoring and 10-Year Aging Prediction in Hot Semi-Arid Climates
Emna Akkari · Centre de Recherches et des Technologies de l'Energie (CRTEn)

AT4.7 **17:15 – 17:30** 15 min
Scalable Operation Window and Color Tunability in Hybrid-Processed Perovskite Solar Cells for BIPV
Elshan Asadi · ODTÜ-GÜNAM

15:30 - 17:30 PANEL

COP-31 Special Session: Green Transition, Energy Efficiency, and Photovoltaic (PV) Technologies

Room B

Moderator: **Sanem Yalçıntaş** Panelist: **Selçuk Yerci** Panelist: **Selen İnal** Panelist: **Sıla Gözlükaya** Panelist: **Mehmet Ali Kahraman** Panelist: **Pinar Derin Gure**

The decarbonization of industry will be discussed not only from an environmental perspective but also through tangible financial and infrastructure-related metrics. In the lead-up to the implementation of the Carbon Border Adjustment Mechanism (CBAM), Carbon Return on Investment (C-ROI) calculations for industrial stakeholders, as well as the capacity planning and grid integration processes associated with variable renewable energy generation, will be evaluated. In addition, the potential of Concentrated Solar Thermal (CST) technologies for hard-to-abate sectors, where emissions reductions remain particularly challenging, will be addressed.

18:00

19:00

19:00 - 22:00 OTHER All rooms

Gala Dinner

Divan Çukurhan

Join us for an elegant dinner at Çukurhan, a renowned historic venue located in Ankara's historic castle district. Guests will enjoy a premium dining experience with unlimited beverages in a unique historical setting that reflects the cultural character of Türkiye's capital. Round-trip transportation from the conference venue is included in the registration fee.

20:00

21:00

Conference Program - Wednesday

Monday 2026-06-29 | Tuesday 2026-06-30 | **Wednesday 2026-07-01**

Show Poster Sessions

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Search by speaker, title, room, poster author, reviewer, topic...

A · Room A
Room A

09:00 - 10:30 TECHNICAL SESSION
Crystalline Silicon and Transport Materials
Room A
Chair: **Milad Ghasemi** Chair: **Bülent Arıkan**

- AW1.2 09:00 – 09:30 30 min — Lightweight Solar Application in Europe — INVITED SPEAKER Yilin Zhao
- AW1.3 09:30 – 09:45 15 min — Optimizing Ag Growth in IZO/Ag/IZO Electrodes Via Seed Layers for High-Efficiency SHJ Solar Cells — Khushi Muhammad Khan · Università di Catania
- AW1.4 09:45 – 10:00 15 min — Picosecond Laser-Assisted Selective Poly-Si Patterning for TOPCon Solar Cells Via Alkaline Etching — Shojaa Abusakha · ODTÜ-GÜNAM
- AW1.5 10:00 – 10:15 15 min — Temperature Stability and Radiation Hardness of Gap/Si Heterojunctions Grown By Pe-Ald — Alexander Gudovskikh · Petersburg Alferov University
- AW1.6 10:15 – 10:30 15 min — Super Edge Passivation Deposition Technology to Improve Solar Cells Performance — Bao Jian · SONGYU TECH

B · Room B
Room B

09:00 - 10:30 TECHNICAL SESSION
Room B - PowerAV
Room B
Chair: **Neslihan Çolak** Chair: **Ramazan Sarı**

- BW1.1 09:00 – 09:30 30 min — System Performance, Techno-Economics, and Operation of Agrivoltaics: Cases from East Africa and Europe — INVITED SPEAKER Richard Randle-Boggis
- BW1.2 09:30 – 09:45 15 min — Integrated Agrivoltaic Design Approaches in Türkiye: From Transmissive PV Systems to Spectral Optimization Using Gcc Panels — Duygu Kuzyaka · ODTÜ-GÜNAM
- BW1.3 09:45 – 10:00 15 min — Stakeholder Perceptions of Agrivoltaics — INVITED SPEAKER Alina Diana Both
- BW1.4 10:00 – 10:15 15 min — A Hybrid Physics and Data-Driven Framework for Modeling Soil Accumulation and PV Performance in Agrivoltaic Systems — INVITED SPEAKER Alfredo Sanchez Garcia
- BW1.5 10:15 – 10:30 15 min — Next-Generation PV Systems: Smart Panel Architecture, Sensor Integration, and Data Analysis — Gokhan Aslan / Serhat Özcan · itechsolar / VSIAS

W · Workshops
Room C

09:00 - 10:30 WORKSHOP
Reaping Entrepreneurial Opportunities in Solar Energy : Business Model Canvas (BMC) Workshop
Room C
Moderator: **Hande Eryılmaz** Moderator: **Derek Baker**

This workshop aims to highlight entrepreneurial opportunities for the solar energy sector through a hands-on BMC exercise. Interested participants will learn basic entrepreneurial practices, understand value proposition decisions and also understand the process of developing their business/academic idea in a more coherent and systematic manner.

10:30 - 11:00 POSTER All rooms
Poster Session 4 with Refreshments - Social, Economic & Environmental Studies
View poster presentations

11:00 - 12:30 TECHNICAL SESSION
Horizon Europe - SiLEAN Workshop
Room A
Chair: **Hisham Nasser** Chair: **Bart (L.J.) Geerligs**

- AW2.1 11:00 – 11:15 15 min — Development of Silicon Heterojunction Solar Cells With Low Environmental Footprint and Advanced Interfaces — INVITED SPEAKER Karsten Bittkau
- AW2.2 11:15 – 11:30 15 min — Development of Highly Transparent and Conductive In-free AZO:H — Gokhan Altiner · ODTÜ-GÜNAM
- AW2.3 11:30 – 11:45 15 min — Indium Reduction in Silicon Heterojunction Solar Cells Using Magnetron-Sputtered SnOX contact layers — Alexandr Zamchiy · FZJ
- AW2.4 11:45 – 12:00 15 min — From Silver to Copper: Reliability of Copper Containing Metallization with Multi-Wire Twill Interconnection — Hamed Javanbakht Lomeri · imec
- AW2.5 12:00 – 12:15 15 min — Beyond Conventional Texturing: A New Regime of Plasma-Driven Shallow Nanotexturing in Silicon — Ozan Aydin · ODTÜ-GÜNAM
- AW2.6 12:15 – 12:30 15 min — Resource-Use Criticality of PV Technologies in the EU27 — Mohammad Abdelbaky · TU Delft

11:00 - 12:30 TECHNICAL SESSION
AgriPV & Floating PV
Room B
Chair: **Duygu Kuzyaka** Chair: **Richard Randle-Boggis**

- BW2.1 11:00 – 11:15 15 min — Mounting Height as a Design Variable in Bifacial Tracked Agrivoltaic Systems: A Simulation Study under Palermo Conditions — Ecem Önen · University of Salerno
- BW2.2 11:15 – 11:30 15 min — Assessment of PAR Distribution in Vineyard Agrivoltaic Systems under Different Panel Density Configurations — Faruk Öner · Ege University Solar Energy Institute
- BW2.3 11:30 – 11:45 15 min — A Fuzzy-Logic-Based Decision-Making Framework for Crop-Environment Management in Agrivoltaic Systems — Mohammad Derogarian Miandoab · ODTÜ-GÜNAM
- BW2.4 11:45 – 12:00 15 min — A Digital Voucher System for Renewable Energy Communities: Applicability Analysis Across Agri-Food Sme Typologies in Türkiye — Harun Gümüş · Ege University / Solar Energy Institute
- BW2.5 12:00 – 12:15 15 min — Meteorological Sensitivity and Production Stability of Rooftop and Floating Photovoltaic Systems: A Comparative Machine Learning Analysis — Bilge Sıla Çevik, Hilal Çapkan · Sakarya University
- BW2.6 12:15 – 12:30 15 min — Pollution Effects on Floating Photovoltaic Systems — Robert Balog · Texas A&M University

13:00

12:30 - 13:30 LUNCH All rooms

Lunch

13:30 - 15:00 TECHNICAL SESSION

PV/T

Room A

Chair: **Yilin Zhao** Chair: **Parisa Sharif**

AW3.1 13:30 – 14:00 30 min

Enhancing Performance of Solar Photovoltaic Through Thermal Management and Intelligent Maintanence

INVITED SPEAKER **Wenye Lin**

14:00

AW3.2 14:00 – 14:15 15 min

Digital Twin–Based Hybrid PV–CSP System for Flexible PV Integration Into Distribution Networks

Rabia Nur Kalem · GDZ Elektrik Dağıtım A.Ş.

AW3.3 14:15 – 14:30 15 min

Architectural Integration and Energy Performance Assessment of Building Envelope-Integrated BIPV Systems in Six Provinces of Türkiye's Very Hot, High Solar Radiation Zone Using PVsyst

Ahadollah Azami · Çukurova University

AW3.4 14:30 – 14:45 15 min

Determinants of Solar Heat For Industrial Processes Adoption in Türkiye

Fatma Ece Demirer · METU

AW3.5 14:45 – 15:00 15 min

International Space Station of Türkiye and Renewable Energy Installation

Bulent Akınoğlu · Middle East Technical University

13:30 - 15:00 WORKSHOP

AgriPV workshop

Room C

Moderator: **Talat Özden** Panelist: **Fatih Özdemir** Panelist: **Hilal Sönmez** Panelist: **Özge Özeke** Panelist: **Bilge Senturk** Panelist: **Duygu Kuzyaka**

The regulatory, technical, and agricultural intersections of dual land use for solar energy generation and agriculture will be analyzed. Discussions will focus on developing a legal framework that maximizes energy production while preserving agricultural yields, including topics such as the classification of marginal agricultural lands. Grid connection procedures and net-metering-related barriers will also be addressed at the highest levels of public administration and policymaking. ODTÜ-GÜNAM's international pilot projects, together with global best practices and case studies, will serve as key references for these discussions.

15:00

15:00 - 15:30 TECHNICAL SESSION

Closing Ceramony with Poster Award

Room A

15:30 - 17:30 OTHER All rooms

Technical Tour – ODTÜ-GÜNAM Research Laboratories

16:00

Participants will have the opportunity to visit ODTÜ-GÜNAM's research laboratories and pilot-scale photovoltaic infrastructure. The GPVL facility at ODTÜ-GÜNAM has an approximately 600 m^2 production area and a production capacity of 100 wafers per hour. It is capable of manufacturing industrial-size silicon solar cells, primarily of the PERC/PERT/PERL/IBC types. With a team of more than 20 researchers, GPVL operates as a fully integrated pilot production line, covering the complete process from silicon wafer to finished solar cell. Due to limited capacity, advance registration and additional fee are required.

17:00

Green-solvent based ambient air processed bifacial perovskite–silicon tandem solar cells with 28 mW cm^{-2} power output

Radha Krishnan Kothandaraman[1], Denise Kreugel[1], Ryley Ratnasingham[1],Felipe Vinocour Pacheco[1], Anuja Vijayan[1], Georgia Gkouzia[1], Marcel Simor[1], Corné Frijters[1], Johannes Lambooij[1],Giulia Lucarelli[1], Ilker Dogan[1], Bart (L.J.) Geerligs[2], Valerio Zardetto[1]

[1] TNO, Solar Technology and Application, High Tech Campus 21, 5656AE Eindhoven, The Netherlands

[2]TNO, Solar Energy, Westerduinweg 3, 1755 LE Petten, The Netherlands

Two-terminal (2T) Perovskite-silicon tandem solar cells have rapidly advanced in the last decade to achieve a certified record efficiency of 34.85% on 1 cm^2. Yet, in most works, the perovskite top cell's development relies on spin-coating process, making it industrially irrelevant. Furthermore, most of the work involves using toxic solvents for perovskite deposition step in an glovebox, making them cost-prohibitive at industrial scale. Efforts to upscale perovskite films using environmentally benign solvents such as dimethyl sulfoxide (DMSO) and γ-valerolactone (GVL) have largely remained limited, and restricted to inert processing conditions due to challenges pertaining to controlling the crystallization kinetics. The high boiling green solvents are difficult to remove from the wet film during quenching process, which suppresses supersaturation and delays nucleation, ultimately leading to suboptimal crystallization. As a result, the resulting perovskite layers often exhibit a higher density of voids and residual intermediate solvate phases, both of which critically degrades film quality. In this work, we overcome challenges related to solvent extraction by fine-tuning the quenching process for achieving high-quality perovskite top cell for tandem integration. We implement a step by step approach (**Figure 1**) by tuning the perovskite ink (**1a**), applying interface & surface passivation (**1b, c**), and optimizing the top cell optics (**1d**). We translated our findings to coat on 15.7 cm x 15.7 cm silicon wafers by slot-die coating, and demonstrate ambient-air processed 2T perovskite-silicon tandem solar cells with efficiency of over 23% under 1-sun illumination on 1 cm^2 by slot-die coating. Furthermore, with optimal choice of bandgap for bifacial application, we demonstrate 2T perovskite-silicon tandem solar cells with over 28 mw cm^{-2} power generation output under 15% albedo conditions, the highest value worldwide to best of our knowledge. Our findings demonstrate that solvent-engineered ambient processing can deliver high-quality perovskite absorbers suitable for bifacial tandem integration, offering a viable route toward commercially scalable, potentially stable and environmentally sustainable perovskite–silicon technology.

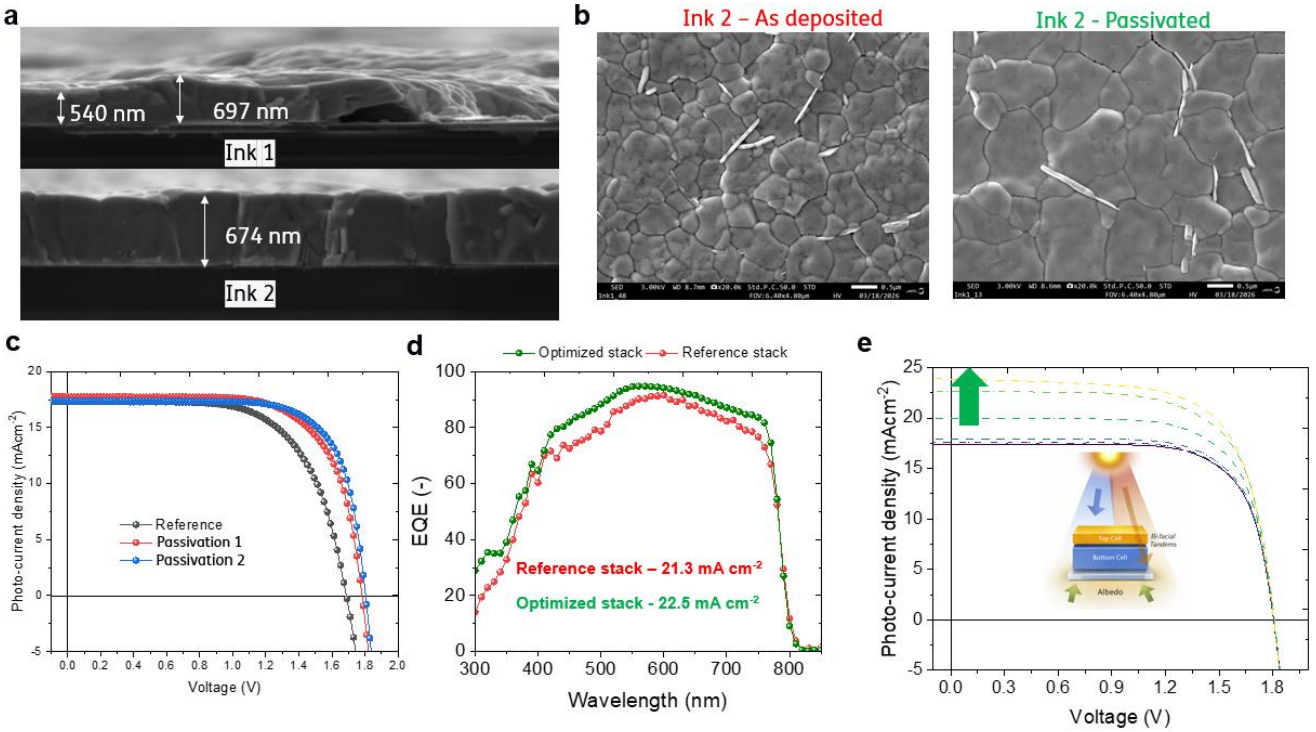


***Figure 1**: Green solvent based ambient processed 2T perovskite-silicon tandem solar cells* **a)** cross-sectional scanning electron microscope (SEM) of reference and target ink based perovskite absorber, **b)** Top-view SEM image comparison of perovskite absorber with and without surface passivation, **c)** JV curve comparison of 2T perovskite-silicon tandem solar cells with different passivation, **d**) EQE plot comparison of spectral response of perovskite top cell after optimized optical design, and **e**) JV comparison of 2T perovskite-silicon tandem solar cells with increase in rear-side illumination.

Bifacial and Sustainable Tandem PV technology using Silicon Cells with TOPCon Front Emitter.

Bart (L.J.) Geerligs[1*], E. Hande Ciftpinar[2], Yu Wu[1], Petra Manshanden[1], Radha K. Kothandaraman[2], Valerio Zardetto[2], Floor Souren[3], Hindrik de Vries[3], Ivo Aretz[3], Jons Bolding[3], David Fuertes Marrón[4], Nerea Dasilva Villanueva[4], Luis Jaime Caballero[4], Carlos del Cañizo[4], Hisham Nasser[5], Yiğit Mert Kaplan[5], Gokhan Altiner[5], Melisa Korkmaz[5], Talat Ozden[5], Rasit Turan[5], Özlem Coşkun[5], Meriç Çalışkan Arslan[5], Çağrı Taha Delikanlı[5], Ece Çamkara[5]

[1] TNO Solar Energy, Petten, The Netherlands
[2] TNO Solar Technology and Applications, Eindhoven, The Netherlands
[3] SALD B.V., Eindhoven, The Netherlands
[4] Instituto de Energía Solar, Universidad Politécnica de Madrid, Spain
[5] Middle East Technical University Center for Solar Energy Research and Applications (ODTÜ-GÜNAM), Ankara, Türkiye
[6] Kalyon PV Solar Technologies Factory, Malıköy, Ankara, Türkiye

*Corresponding Author's E-mail: bart.geerligs@tno.nl

This presentation will introduce the TANDEM project that runs within the CETPartnership scheme, in a collaboration between 2 industrial partners and 3 research organizations. In the TANDEM project, monolithic (2-terminal) perovskite-silicon tandem PV technology is developed with emphasis on practical, industrially relevant, technology and emphasis on sustainability.

The solar cell technology in the project is based on using a TOPCon front junction on the silicon bottom cell. While in the TANDEM project the TOPCon stack is the emitter of a p-type PERC-like bifacial bottom cell, the subsequent perovskite cell processes will be more generally applicable to any other silicon cell with TOPCon front junction. PERC-like bottom cells can provide high performance because they can be based on high-lifetime Ga-doped wafers, front surface passivation by a TOPCon emitter, and rear side dielectric passivation with excellent opto-electronic properties. Therefore, this approach for bottom cell architecture warrants detailed investigation as we are performing in this project. Results of the bottom cell technology will also be presented in separate contributions to this conference.

The perovskite cell stack under development in the TANDEM project employs a thin two-layer indium-free recombination junction (RJ) processed by spatial ALD (sALD), using Al-doped zinc oxide (AZO) for contacting the TOPCon layer, and NiO as the basis for the hole transport layer. The perovskite absorber deposition is by slot-die (SD) coating technology, capable of full area coating across industrial size wafers. In the TANDEM project the bottom cell has a planarized front surface, but we have shown that the SD perovskite deposition is also suitable for silicon with submicron texture, and, in a hybrid process, for standard wafer texture. A particular advancement in the TANDEM project is the deposition of a high-quality perovskite absorber from a solution with 'green' solvents, meaning solvents that are not strongly restricted by European environmental and safety regulations, and which allow processing to take place in

ambient instead of in a closed glovebox-like compartment. The results of the sALD RJ development and the green solvent-based processing will be presented as well in separate contributions to this conference.

In terms of sustainability, the use of a PERC-like bottom cell (consuming hardly any silver for the rear side metallization), an indium-free RJ, and green solvents for the perovskite solution, already have significant positive impact. Additionally, in this project we investigate the application of screen-printed front side metallization with reduced or even zero silver consumption, and the possibilities for indium-reduction in the front transparent conductive oxide (TCO) layer. Results will be presented.

In the future, the TANDEM project will study the energy yield of small-size bifacial tandem modules made in the project, in Ankara and in the Netherlands. We will present some first results from a related prior R&D project, highlighting the use of bifaciality, and the possibilities for analysis that are enabled by digital twinning of module characteristics.

Acknowledgements

This research was funded by CETPartnership, the Clean Energy Transition Partnership under the 2023 joint call for research proposals, co-funded by the European Commission (GA N°101069750) and with the funding organizations detailed on https://cetpartnership.eu/funding-agencies-and-call-modules (Project CETP-FP-2023-00107). National support by the Netherlands Enterprise Agency (RVO) via its Horizon Europe Partnership (HEP) programme, call HEP 2024 (Project HEP24-03676625); by Scientific and Technological Research Council of Türkiye (TÜBİTAK) under grant number 224N162; in Spain by Agencia Estatal de Investigación, Proyectos de Cooperacion Internacional PCI2024-155050-2.

Keywords: tandem, perovskite, silicon, TOPCon, bifacial

SiLEAN – DEVELOPMENT OF SILICON HETEROJUNCTION SOLAR CELLS WITH LOW ENVIRONMENTAL FOOTPRINT AND ADVANCED INTERFACES

K. Bittkau[1,*], A. Zamchiy[1], G. Vescovi[2], V. Depauw[3], M. Mahajan[3], H. Javanbakht Lomeiri[3], Y. Zheng[4], E. Özkol[4], O. Isabella[4,5], M. R. Vogt[4], M. Zeman[5], T. Baumeler[6], D. Martineau[6], G. Giuliano[7], H. Nasser[8], and K. Ding[1]

[1] IMD-3 Photovoltaics, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany
[2] Nexwafe GmbH, Hans-Bunte-Straße 19, 79108 Freiburg im Breisgau, Germany
[3] Imec, imo-imomec, Genk, 8320, Belgium
[4] TU Delft, Stevinweg 1, 2628 CN Delft, the Netherlands
[5] PV Works B.V., Mekelweg 4, 2628 CD Delft, the Netherlands
[6] GraphEnergyTech, CH F1 496 (Bâtiment CH) Station 6, EPFL, 1015 Lausanne, Switzerland
[7] 3SUN S.R.L., Contrada Blocco Torrazze SNC, 95121 Catania, Italy
[8] Center for Solar Energy Research & Applications ODTU-GUNAM, 06800, Ankara, Türkiye

*k.bittkau@fz-juelich.de

Meeting the targets of the energy transition and the Paris Agreement requires photovoltaic (PV) electricity to play a central role in future energy supply. This demands PV technologies that combine very high efficiency, low cost, and a reduced carbon footprint. The current world-record efficiencies for crystalline silicon (c-Si) solar cells with front- and back-contact design rely on silicon heterojunction (SHJ) architectures. However, several barriers limit large-scale deployment, including the use of indium in contact layers, silver and bismuth in metallization and interconnection, and the reliance on energy-intensive Czochralski-grown wafers.

The Horizon Europe project “SiLEAN” aims to overcome these limitations and enable SHJ manufacturing at the terawatt scale through a lean, high-throughput process compatible with industrial wafer formats. The project focuses on developing a next-generation SHJ process chain based on (1) epitaxially grown wafers with reduced energy demand, (2) alternatives to highly absorptive hydrogenated amorphous silicon (a-Si:H) for surface passivation and carrier-selective contacts, (3) indium-free contact layers and silver-free metallization, and (4) bismuth-free interconnection strategies.

This presentation provides an overview of the SiLEAN concept, key technological approaches, and major achievements from the first two years of the project.

Acknowledgements

This work received funding from the European Commission through Horizon Europe project SiLEAN.

Keywords: silicon heterojunction, novel passivation, indium free, silver free, bismuth free

POLLUTION EFFECTS ON FLOATING PHOTOVOLTAIC SYSTEMS

Robert S. Balog*[1], Ibrahim Gunes[2]

[1] Texas A&M University, Electrical & Computer Engineering Department College Station Tx, USA
[2] Istanbul University Cerrahpasa ,Electrical Engineering Department, Istanbul, Turkiye

*Corresponding Author's E-mail: gunesi@iuc.edu.tr

Floating photovoltaic (FPV) systems have emerged as a promising renewable energy technology due to their enhanced cooling benefits, reduced land-use requirements, and improved power production over water surfaces. However, environmental pollution—manifesting as airborne particulate matter, organic material, chemical contaminants, and waterborne biological growth—introduces unique degradation pathways not typically observed in land-based PV installations. This paper provides a comprehensive analysis of pollutioninduced performance degradation mechanisms in FPV systems, focusing on soiling accumulation, corrosion of structural components, biofouling effects on buoyancy elements, and irradiance losses linked to water turbidity. A multi-dimensional overview of pollution characterization, environmental interactions, and energy-yield impacts is presented. Additionally, monitoring technologies, predictive computational tools, and mitigation strategies such as autonomous cleaning and antipollution coatings are evaluated. The study highlights critical gaps in standards and identifies future research directions for designing pollution-resilient FPV architectures. Findings underline the necessity of integrating environmental pollution modeling into FPV system planning and lifecycle assessment, particularly for high-risk water bodies suffering from industrial discharge, algal proliferation, or urban particulate emissions.

Floating photovoltaic (FPV) systems have gained significant global attention over the past decade as a viable alternative to traditional ground-mounted or rooftop PV installations. Their ability to utilize unused water surfaces such as reservoirs, industrial ponds, irrigation lakes, and hydropower dams makes them an attractive technology for regions facing land scarcity or ecological constraints. FPV modules generally benefit from lower operating temperatures due to the cooling effect of water, potentially enhancing energy yield by 5–15% compared to conventional PV systems. However, despite these advantages, FPV systems are exposed to complex environmental pollution conditions that differ substantially from land-based PV deployments[1-6]. Environmental pollution introduces multifaceted risks to FPV system performance, reliability, and long-term durability. These risks stem from both atmospheric and aquatic pollution sources. Airborne particulate matter generated by industrial zones, urban traffic, and agricultural activities can deposit on FPV module surfaces, leading to significant soiling losses. Unlike ground-mounted PV arrays, FPV panels are often located near water surfaces with high humidity levels, accelerating the adhesion of particulate matter and forming a more persistent pollutant layer. This combination of humidity and suspended solids can alter the optical characteristics of PV glazing, reduce transmittance, and affect maximum power output[7-11].

In this paper, we focused on Overview of Floating Photovoltaic (FPV) Technologies, Types of Environmental Pollution Affecting FPV Installations, Impact of Water Surface Contamination on PV Power Output, Airborne Particulate Matter Deposition on FPV Modules, Effects of Algal Bloom and Organic Pollution on FPV Efficiency, Influence of Water Turbidity on Reflected Irradiance and Energy Yield, Chemical Pollution and Corrosion of FPV Structural Components, Biofouling Effects on Buoyancy and System Stability, Thermal Performance Degradation Induced by Pollution Layers, Modeling Energy Losses Due to Pollution Accumulation, Experimental Assessment of Pollutant Adhesion on FPV Panels, Sensor-Based Monitoring Techniques for Pollution Detection, Cleaning Mechanisms and Maintenance Strategies for FPV Systems, Environmental Impact Analysis of Pollution on the Water Body[12-16].

Acknowledgements

Dr. Gunes acknowledges support of TUBITAK under grant (1059B192301551) which will support his continued research in this area and Dr. Gunes wishes to thank Texas A&M University and the Renewable Energy & Advanced Power Electronics Research (REAPER) Lab for hosting him as a Visiting Scholar, which made this paper possible.

Keywords: Floating photovoltaic FPV, Solar Energy, Environmental Effect, PV Panels, Pollution Effect.



Figure 1. Floating PV system

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Selective Patterning of BSG-Capped Poly-Si/SiOx Using a Screen-Printed Etch-Resist Mask

Eni Muka[1], Seda Kılıçkaya Ünver[1], Yiğit Mert Kaplan[1], Gökhan Altiner[1], Agageldi Muhammetgulyyev[2], Ayca Berfin Aydogdu[2], Hisham Nasser[1], Raşit Turan[1]
[1] ODTÜ-GÜNAM, Middle East Technical University, 06800, Ankara, Türkiye
[2]CW Energy Research and Development Center, Antalya, Türkiye
eni.muka@odtugunam.org

1. Introduction

Poly-Si/SiO_x stack enables excellent surface passivation and carrier selectivity, making it essential for achieving high efficiencies in both TOPCon and BC architectures. In conventional TOPCon designs, full-area poly-Si coverage on the front is limited by parasitic absorption, but patterned poly-Si/SiO_x fingers offer an effective solution, preserving passivation while minimizing optical losses [1]. In BC architectures, where both contacts are already located on the rear side, implementing poly-Si/SiO_x for the n- and p-type regions further suppresses interface recombination, significantly improving voltage values [2]. Despite these advantages, the fabrication of such structures is complex [3]. Conventional methods for patterning, such as laser or plasma etching, demand costly equipment and risk damaging the ultra-thin tunnel oxide [4]. To address these limitations, a wet-etching strategy is investigated as an alternative approach for the selective removal of doped poly-Si/SiOx stacks. An optimized etching process can selectively remove doped poly-Si/SiOx stack while keeping patterned structure defined by screen-printed etch-resist mask. This approach has the potential to simplify the fabrication of local poly-Si/SiOx stacks, reducing process complexity, equipment requirements, and overall costs, while maintaining the device performance. It provides a controllable, low-damage alternative for defining the charge carriers collecting layers on TOPCon and BC structures. As a first stage toward this goal, the present work focuses on establishing a wet-etching process for boron-doped poly-Si/SiO_x stacks, which must be optimized before proceeding to the n-type one due to the lower thermal budget of n-type poly-Si.

2. Experimental Method

The study was conceptualized on developing a wet-etching process for the selective removal of doped poly-Si/SiO_x stacks. Test samples, each measuring 3x3 cm2 were prepared on c-Si substrates coated with an ultra-thin SiO_x, a boron-doped poly-Si layer, a BSG cap and a screen-printed etch-resist mask. The mask defines the patterned regions of the BSG layer, while the BSG itself functions as a sacrificial barrier that protects the underlying poly-Si/SiO_x stack during the subsequent etching steps. To define the regions for selective poly-Si/SiOx etching, two different etch-resist pastes were evaluated. Both were screen-printed onto the wafer surface in patterned geometries to protect selected areas from the wet-etching treatments. Both pastes were evaluated in terms of their adhesion, edge definition, and resistance to alkaline solutions. Following mask preparation, the etching process begins with a selective glass-removal step that dissolves the exposed BSG, creating exposed regions of the underlying poly-Si/SiOx. The subsequent etching stage then removes the poly-Si/SiOx stack in these areas, while regions still covered by BSG remain protected. Process parameters such as solution concentration, temperature, surface additives were optimized to maintain stable etching behaviour, minimize lateral under-etching, and ensure a clear visual endpoint. The progress of etching was tracked visually through the surface color change, which served as

a simple endpoint indicator. After each step, optical inspection and sheet resistance (Rsh) measurements were performed to confirm complete removal of the poly-Si/SiOx stack in the openings and preservation of the masked regions. The experimental approach focused on evaluating etching effectiveness and process selectivity. Etching performance was monitored by sheet resistance (R_{sh}), where ~100 Ω/□ indicated full poly-Si/SiO_x removal and higher values (10^3–10^4 Ω/□) signified incomplete etching. Optical profilometry was used to quantify selectivity through height contrast between etched and masked regions, enabling optimization of a controlled and repeatable patterning process for back-contact solar cell fabrication.

3. Results

The experimental evaluation revealed clear dependencies between etching performance, process control, and the chemical parameters. Stable and uniform etching behaviour was achieved within a limited process window, where the alkaline solution remained sufficiently reactive to remove the exposed poly-Si/SiOx stack while preserving the BSG protection. The combined visual and optical profilometric confirm the uniformity and selectivity of the wet-etching process, as shown in Figure 1. a), b) respectively. The patterned wafer shown in Figure 1. a) displays well-defined features with clean edges and no evidence of mask lifting or lateral over-etching, demonstrating excellent stability and adhesion of the mask during processing. This is also supported by the profilometer data (Figure 1 b)), which reveal a consistent step height, corresponding to complete removal of the poly-Si/SiO_x stack. The clear height contrast between etched and masked regions further confirms strong etch selectivity and precise material removal with minimal surface damage.

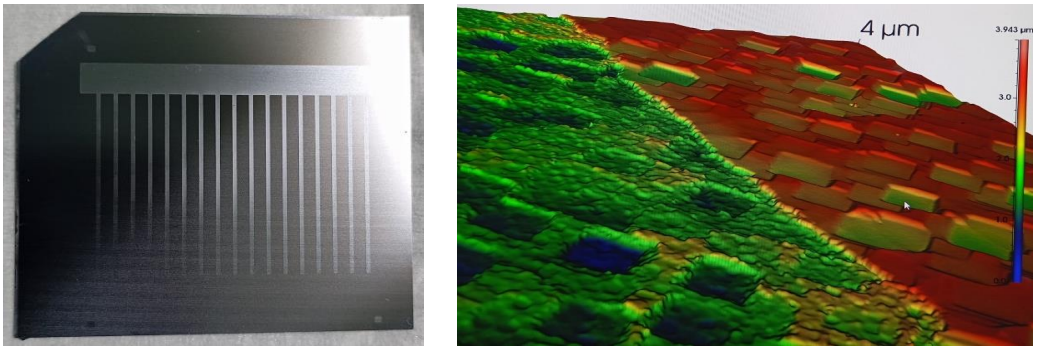


Figure 1. Optical and profilometric characterization of the selectively etched sample: a) patterned wafer showing well-defined etched lines; b) 3D optical profilometry revealing a step height between etched and masked regions

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Scalable Operation Window and Color Tunability in Hybrid-Processed Perovskite Solar Cells for BIPV

Elshan Asadi[1,2], Cem Maden[1], Mustafa Yaşa[1], Görkem Günbaş[1,2,3], and Selçuk Yerci[1,2,4*]

[1] Center for Solar Energy Research and Applications (ODTÜ-GÜNAM), Middle East Technical University, Ankara, Turkey.
[2] Department of Micro and Nanotechnology, Middle East Technical University, Ankara, Turkey.
[3] Department of Chemistry, Middle East Technical University, Ankara, Turkey.
[4] Department of Electrical-Electronics Engineering, Middle East Technical University, Ankara, Turkey.

* syerci@metu.edu.tr

Perovskite solar cells (PSCs), as a leading class of emerging photovoltaics (EmPV), are highly attractive for Building-Integrated Photovoltaics (BIPV) due to their high efficiency, low-temperature fabrication, and tunable optical properties[1]. However, practical implementation requires not only high performance but also fabrication robustness, scalability, and controlled visual appearance. Addressing these requirements demands a quantitative understanding of process tolerance and operation windows.

In this work, a comprehensive operation window is established for wide-bandgap (1.61 eV) p–i–n PSCs fabricated via a Hybrid Evaporation–Solution Method (HESM)[2]. This approach employs a thermally evaporated PbI_2 and CsBr template that is subsequently converted into a perovskite absorber using solution-deposited organic precursors. The processing space is systematically explored by varying PbI_2 thickness (50–300 nm) and precursor concentration across multiple values, enabling construction of a two-dimensional processing map. Device performance exhibits a clear dependence on both parameters, with a pronounced coupling between absorber thickness and solution concentration. Thin templates result in incomplete coverage and reduced current collection, while excessively thick layers introduce recombination and transport limitations, defining practical processing bounds. Optimal performance is achieved at 230 nm PbI_2 and 0.4 M precursor concentration, yielding a power conversion efficiency of 20%, V_{OC} of 1.08 V, J_{SC} of 22 mA cm^{-2}, and a fill factor of 85%. Profilometry confirms a consistent thickness scaling between the inorganic template and final perovskite layer, enabling reliable thickness control. Optical modeling based on transfer-matrix simulations, validated experimentally, demonstrates predictable thickness-dependent color tuning with angular stability, governed by interference effects within the device stack. This study defines a robust fabrication window that ensures reproducible device performance while enabling controlled color tuning and provides a practical framework for scalable PSC manufacturing and support the integration of high-performance, visually tunable devices in BIPV applications.

Acknowledgements

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Keywords: Perovskite solar cells (PSCs), Emerging photovoltaics (EmPV), Hybrid evaporation–solution processing, Building-integrated photovoltaics (BIPV)

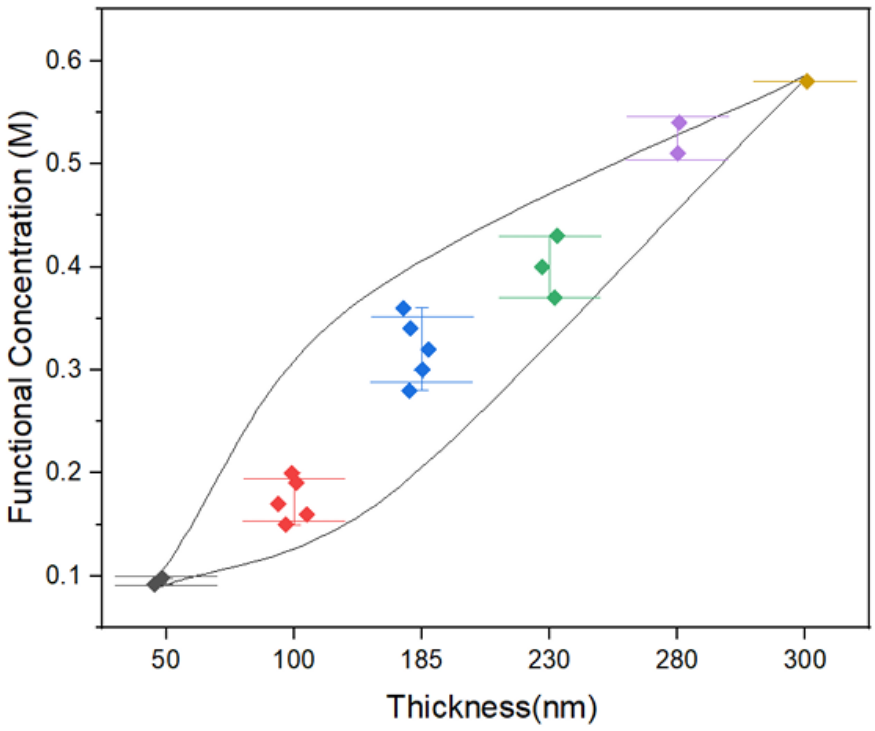


Figure 1. Operation window as a function of PbI_2 thickness.

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Optimizing Spatial ALD AlO_x for Silicon Solar Cell Edge Passivation

Furkan Eren Yılmaz*[1,2], Gökhan Altıner[1], Yiğit Mert Kaplan[1], Raşit Turan[1,2], Hisham Nasser[1]

[1]ODTÜ-GÜNAM, Center for Solar Energy Research and Applications, 06800 Ankara, Turkey
[2]Department of Physics, Middle East Technical University (METU), 06800 Ankara, Turkey
*furkan.yilmaz_06@metu.edu.tr

Edge recombination is a significant efficiency loss mechanism in silicon solar cells, arising from the highly defective surfaces created during wafer dicing or laser cutting. These cut edges expose a high density of unsatisfied silicon dangling bonds, crystal dislocations, and saw-induced damage, all of which act as very effective recombination centers. Unlike the front or rear cell surfaces, which benefit from well-established passivation schemes, the edge is geometrically challenging to coat uniformly and is often left untreated in standard cell processing, making it a disproportionately large source of recombination relative to its area [1]. In this work, we investigate edge passivation using aluminium oxide (AlO_x) deposited by a standard industrial spatial atomic layer deposition (ALD) tool, which was not purpose-built or optimized for edge coating, but rather represents the type of equipment already present in high-volume photovoltaic manufacturing lines.

To this end, we systematically evaluated the passivation efficiency of ALD AlO_x films deposited using trimethylaluminium (TMA) under high and low water (H_2O) co-reactant saturation levels, followed by thermal activation in either an inert N_2 furnace or a reactive, oxygen-rich ambient (hot plate). Industrial half-cut TOPCon solar cells were laser cut to approximately 1x10 cm^2 slices to facilitate the investigation of the edge passivation effects. Our results reveal critically divergent temperature dependencies dictated by the ALD precursor chemistry and the annealing environment. In an inert N_2 ambient, films deposited with high water content achieved optimal passivation at 425°C (Figure 1(b)) with a 0.57%$_{abs}$ increase in pseudo efficiency (Table 1). Conversely, pseudo efficiencies of the low-water-content films tend to decrease in N_2 ambient (Figure 1(d)). We attribute this decrease to the incomplete water saturation during deposition, which produces a less dense AlO_x matrix; this porous structure facilitates rapid, premature hydrogen effusion, leaving thermally broken interfacial bonds unpassivated [2]. However, subjecting these water-starved, less dense films to a reactive O_2 ambient (hot plate) fundamentally altered the passivation dynamics (Figure 1(a), (c)). While 425°C in O_2 yielded poor performance across both water regimes, elevating the temperature to 500°C successfully rescued the passivation quality of the low-water films. This recovery is driven by the active diffusion of ambient oxygen through the less dense AlO_x network. At 500°C, this external oxygen compensates for the lack of internal hydrogen by rapidly growing a protective, damage-consuming interfacial SiO_x layer and forming electronegative interstitials that maximize the negative fixed charge density (Q_f) for robust field-effect passivation [3]. Ultimately, this study demonstrates that effective edge passivation can be achieved using non-optimized industrial spatial ALD tools by deliberately pairing the precursor saturation levels with the corresponding thermodynamic activation environment.

An investigation of various AlO_x thicknesses in Figure 2 revealed that 20 nm yielded the optimal passivation in the as-deposited state. However, following thermal activation, all evaluated thicknesses exhibited a similarly severe degradation. Currently, this thickness analysis has only been conducted for the high-water-content regime under reactive O_2 annealing conditions. A comprehensive thickness study incorporating low-water-content precursors and N_2 annealing is actively underway and will be completed prior to the PVCON conference.

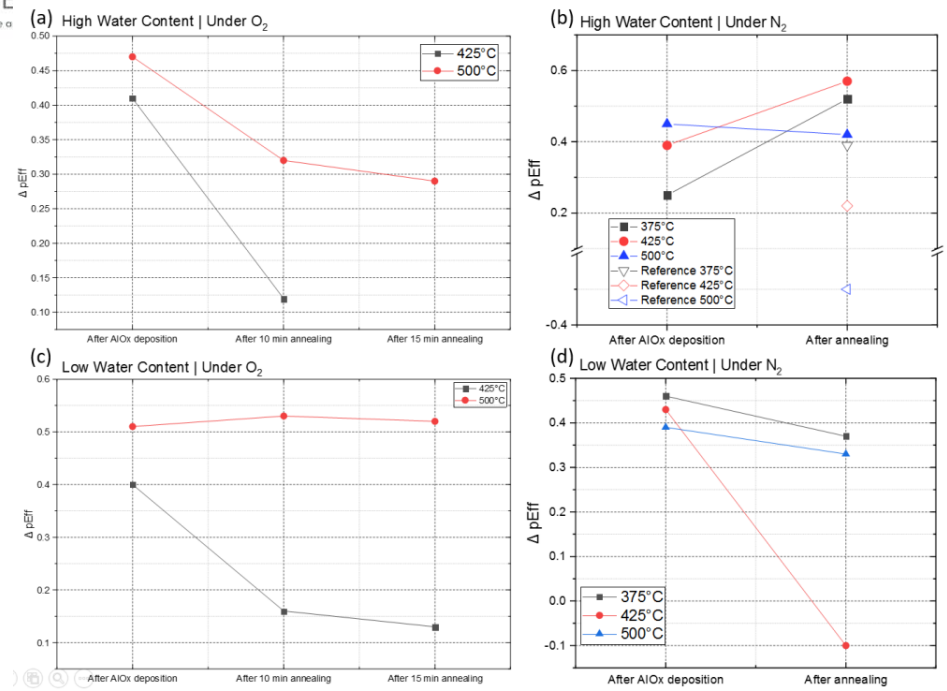


Figure 1. *Δ pseudo efficiency values for AlO_x deposited with high water content annealed under (a) O_2 and (b) N_2 ambient, and AlO_x with low water content annealed under (c) O_2 and (d) N_2 ambient. The reference samples were annealed without any prior deposition*

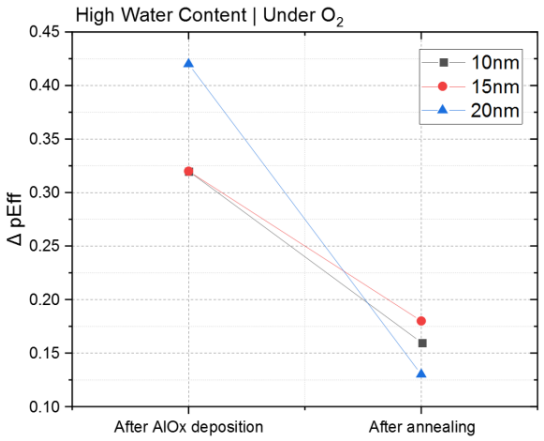


Figure 2. *Δ pseudo efficiency values for AlO_x for varying thicknesses deposited with high water content and annealed under O_2*

Table 1. *Best-performing cell (high water content, annealed under N_2) parameters (average of measurements from six different points)*

Samples	V_{oc}	pFF	pEff
Initial	713.00	77.92	22.22
After Deposition	715.17	79.02	22.61
After Annealing (425°C)	719.50	79.18	22.79

Keywords: Edge Passivation, Aluminum Oxide, Spatial Atomic Layer Deposition

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Analyzing Dynamics in Solar Energy Transition in Developing Economies Using Grounded Theory

Mert Güleç[1], Çağrı Topal[2], Yelda Erden Topal[3]

[1] METU/Business Administration, Ankara, Türkiye
[2] METU/Business Administration, Ankara, Türkiye
[3] METU/Business Administration, Ankara, Türkiye

*Corresponding Author's E-mail: mertg@metu.edu.tr

The transition from fossil fuel dependence to renewable energy systems is one of the most important global imperatives of the 21st century. This review examines the process of solar energy transition in developing economies including Nigeria, China, Iran, the Philippines, Bangladesh, Kenya, and Taiwan. Although transitions to solar energy are often evaluated through a technocratic lens, the existing literature shows that a successful energy transition is deeply embedded in social, psychological, and governance structures. The common methodological foundation of the examined studies is grounded theory, which helps reveal the reasons that accelerate or halt the adoption and diffusion of solar energy technologies.

Identifying and directing technological opportunities in the transition to solar energy is a critical first step. For example, patent analyses on dye-sensitized solar cells (DSSC) reveal high-value areas such as nanotube technology, enabling R&D strategies to be directed more effectively (Chiu et al., 2012). On the other hand, technical opportunities manifest themselves not only in hardware production but also in industrial application; as in the case of Iran, solar energy is positioned as a rational and economic survival mechanism in the face of rising energy costs in the poultry industry (Mohammadi et al., 2021). Similarly, the integration of solar panels, which were installed for lighting purposes in a rural region in Bangladesh but failed, into water treatment plants, which are the greatest need of the region, proves that idle technological components can be transformed into flexible assets in line with societal needs (Yi et al., 2024).

The financial dimension of the process often constitutes the biggest obstacle to the transition due to high initial costs. Studies conducted in the Philippines show that innovative, in-house financing models, such as the pay-as-you-go (PAYG) model instead of traditional bank loans, democratize the transition, especially for middle and low-income households (Co, 2024). At the macro level, the critical role of political systems in financial models stands out; China's model based on central coordination and direct subsidies and the United States' market-oriented structure based on tax deductions create different diffusion paths and structural challenges (Luo, 2023). Furthermore, as seen in the example of rural China, perceiving solar energy projects not only as an investment providing personal profit but also as a model increasing collective welfare significantly increases the willingness to adopt (Wang et al., 2023).

Energy transition is also an inherently political process and requires the reshaping of power dynamics. In developing economies where the state cannot provide basic public services, non-governmental organizations and informal platforms lead the way and develop hybrid governance models (Oates, 2021). However, experiences in Kenya proves that mere decentralization of energy does not automatically result in energy democracy; for equitable governance, women must be integrated into projects not only as users

but also as decision-makers (MacEwen and Evensen, 2021). On the other hand, governance barriers in Bangladesh and Iran clearly show that the influence of fossil fuel lobbies or powerful political leaders exploiting public projects for personal gain can easily collapse technological infrastructure (Yi et al., 2024; Pasandideh and Ezaan, 2025).

In addition to the concrete barriers of finance and politics, one of the most powerful obstacle that solar energy projects must overcome is psychological and cognitive barriers. Research on commercial buildings in Nigeria reveals that construction professionals approach polluting generators as both a threat and an indispensable savior in the face of an unreliable national grid, implying a kind of hostage syndrome (Unuigbe et al., 2023). In the context of rural China, passively observing neighbors using solar energy (peer effect) creates a much stronger persuasion on individuals in the process of adopting the system than active communication or abstract information received through the media (Wang et al., 2023). This psychological resistance can only be eliminated by increasing the number of visible pilot applications and implementing strategies that build social trust.

In summary, this literature review synthesizing ten different studies underlines that there is no one-size-fits-all transition model. Successful transition projects are only possible through the flexible adaptation of the established infrastructure to local conditions, the integration of components addressing vital needs into the project, and the alignment of political goals with social benefit. A sustainable and large-scale solar energy expansion can come to life through a holistic strategy that moves beyond technology-centric static views and considers psychological safety, social justice, and suitability to local conditions as much as photovoltaic efficiency.

Acknowledgements

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Keywords: Solar Energy Transition, Grounded Theory, Renewable Energy, Socio-Technical Systems, Local Adaptation

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Phenylethylammonium Iodide (PEAI)-Based Bulk Modification of CsFAMA Perovskites for High-Performance Indoor Photovoltaics

Ozer Ege Tankut[1,2], Yagmur Yaren Kurnaz[1,2], Bahri Eren Uzuner[2], Zeynep Gozukara Karabag[2], Gorkem Gunbas[1,2,3], Selcuk Yerci[2,4,5], Aliekber Karabag[*2]

[1] Department of Chemistry, Middle East Technical University (METU), 06800, Ankara, Turkiye
[2] Center for Solar Energy Research and Applications (ODTU-GUNAM), METU, 06800, Ankara, Turkiye
[3] Department of Polymer Science and Technology, METU, 06800, Ankara, Turkiye
[4] Micro and Nanotechnology Department, METU, 06800, Ankara, Turkiye
[5] Electrical Engineering Department, METU, 06800, Ankara, Turkiye

*Corresponding author: aliekber.karabag@odtugunam.org

The rapid growth of miniaturized electronics, wearable devices, wireless sensor networks, smart-home systems, and cloud-connected technologies has increased the demand for sustainable, maintenance-free, low-power energy sources. Indoor photovoltaics, particularly perovskite solar cells (PSCs), offer a promising solution due to their tunable bandgaps, strong visible-light absorption, solution processability, flexibility, and excellent low-light performance. Although record indoor PSC efficiencies exceed **45% under 1000 lux** and **42% under 200 lux**, average reported values generally remain below 40%, while long-term operational stability remains a major challenge.[1] Since efficiency and stability are closely linked, improving both requires reducing defects inside the perovskite layer, especially at grain boundaries, buried interfaces, and top surfaces. These defects cause recombination, ion migration, charge imbalance, and degradation. Therefore, incorporating **rationally designed functional materials** directly into the perovskite bulk is a promising strategy to passivate all these defects and enhance both efficiency and operational durability of indoor PSCs.

In this project, a structurally diverse library of phenylethylammonium iodide (**PEAI**)-based salts bearing hydrophobic substituents, including **F**, **Cl**, **Br**, **CF_3**, and **CH_3** was initially designed, synthesized, and characterized. For this purpose, a total of **16 target salts**, including 14 mono-ammonium salts (***x*-X-PEAI** (***x*** = *o*, *m*, *p*; **X** = F, Cl, Br), **F_2-PEAI**, **$(CF_3)_2$-PEAI**, **$(CH_3)_2$-PEAI**, **F_4-PEAI**, and **$(CH_3)_4$-PEAI**) and 2 di-ammonium salts (**$(CH_3)_2$-P(EAI)$_2$** and **$(CH_3)_4$-P(EAI)$_2$**, together with 32 intermediates, were successfully synthesized through a **practical 3-step route** involving CH_3NO_2-based ***Henry (Nitroaldol) Reaction (1)***, $LiAlH_4$-based ***Reduction Reaction (2)***, and HI (57wt. H_2O)-based ***Salt-Formation Reaction (3)***.[2] The molecular structures and purities of **all intermediates** (32 intermediate products in total) and **final target salts** (16 salts in total) were confirmed by comprehensive Nuclear Magnetic Resonance spectroscopy (**NMR**). In addition, the molecular masses of each salt were confirmed by High-Resolution Mass Spectrometry (**HRMS**) analyses. After completion of synthesis studies, all these 16 salts were incorporated in **CsFAMA** (**Cs**: Cesium; **FA**: formamidinium; **MA**: methylammonium)-based perovskite precursor as additives in **n-i-p type PSCs** with a cell architecture of Glass/ITO/SnO_2/**CsFAMA+additives**/PEAI/*Spiro*-OMeTAD/Au. Using the optimized additive concentration (0.75 mg/mL), the reference cell showed a champion **PCE of 36.40%** (**V_{OC} of 1.03 V**, **J_{SC} of 137.0 µA cm^{-2}**, and **FF of 77.32%**) under **1000 lux light emitting diodes (LED) illumination**. Among

the additives-treated PSCs, ***o*-Br-PEAI**- and **$(CH_3)_4$-PEAI**-based PSCs exhibited enhanced photovoltaic performance under identical indoor illumination conditions. Notably, ***o*-Br-PEAI** emerged as the most promising additive, achieving a highly encouraging **PCE of 38.74%**, approaching **39%**. These preliminary findings show that the photovoltaic effect of **PEAI**-based additives is strongly structure-dependent and highlight their potential for developing high-performance indoor PSCs.

Acknowledgements

This study was supported by Scientific and Technological Research Council of Türkiye (TUBITAK) under the Grant Number of **124F194**. The authors thank to TUBITAK for their supports. The authors also thank ODTU-GUNAM for access to synthesis, characterization, and cell fabrication facilities.

Keywords: Perovskite Solar Cells (PSCs), Additives, Phenylethylammonium Iodide (PEAI), Indoor Photovoltaics

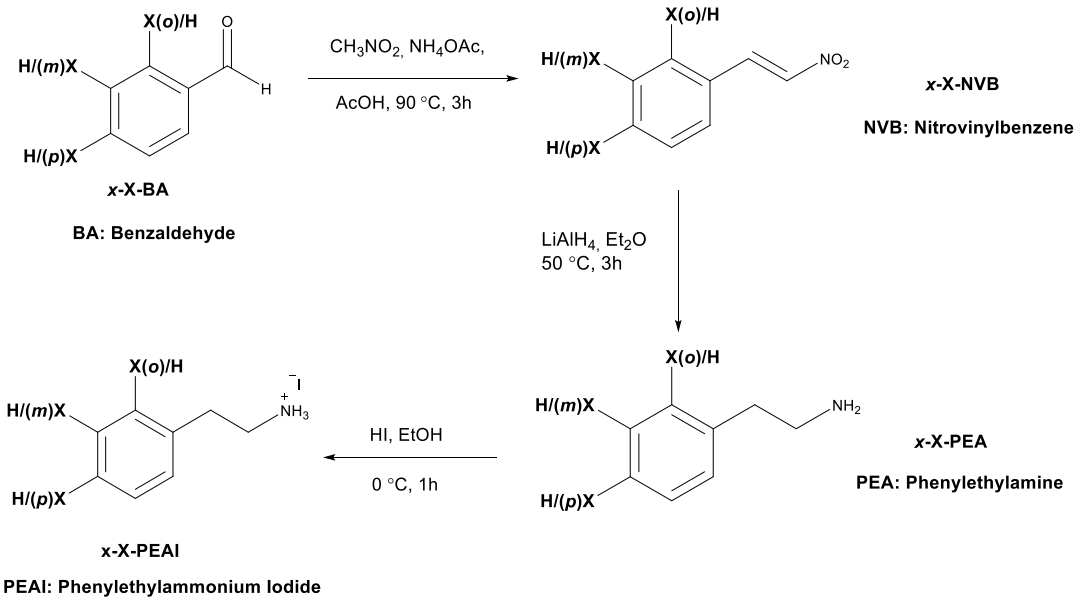


Figure 1. General synthesis pathway of ***x*-X-PEAI**-based salts from commercially sourced benzaldehyde derivatives.

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Dual-Functional Pyridine-Engineered Silver Nanowire Electrodes Enabling Efficient ITO-Free Thick-Film Organic Solar Cells

Parwaz Asif , Bruno Lucas, Remi Antony, Sylvain Vedraine*

University of Limoges, CNRS, XLIM, UMR-CNRS 7252, 87000 Limoges, France

*Corresponding author e-mail: sylvain.vedraine@unilim.fr

Contributing authors: parwaz.asif@unilim.fr; bruno.lucas@unilim.fr; remi.antony@unilim.fr

Abstract: Indium tin oxide (ITO)–free, solution-processed transparent electrodes are crucial for low-cost, scalable organic optoelectronic devices. Silver nanowire (AgNW) networks are promising ITO alternatives due to their high conductivity, transparency, flexibility, and roll-to-roll compatibility. Yet high-performance inverted organic photovoltaics (OPVs) with AgNW electrodes usually need complex electrode designs to ensure low roughness, proper energy-level alignment, and efficient charge extraction. Thus, creating fully solution-processed, carrier-selective contacts for large-area ITO-free OPVs remains a major challenge. Here, we report a simple and scalable strategy using a solution-processed pyridine interlayer as an electron-selective contact in ZnO/AgNW/ZnO (ZAZ) transparent electrodes. The pyridine interlayer, deposited on top of ZnO above the embedded AgNW network, enables precise tuning of interfacial electronic properties while preserving low-temperature, solution-based processing. Pyridine functionalization significantly improves both the optoelectronic performance and surface morphology of the ZAZ electrodes. The pyridine-modified ZAZ electrodes exhibit high optical transmittances of 88.27% and 88.50% at 550 nm, low sheet resistances of 13.24 and 17.30 Ω/sq, and high figures of merit of 21.69 and 17.00 $x10^{-3}$ Ω^{-1}, outperforming conventional ITO electrodes. Surface roughness is markedly reduced, facilitating uniform organic layer deposition. Importantly, this work provides the first detailed demonstration of surface potential evolution and work-function modulation in AgNW electrodes via pyridine functionalization, resulting in enhanced electron selectivity and extraction. Acting as dual-function transparent electrodes, they enable both efficient electron transport and collection. Fully solution-processed OPVs incorporating these electrodes achieve a power conversion efficiency of 10.93% and a fill factor of 65.22%, exceeding ITO-based reference devices. This work advances the development of high-performance, stable, and scalable ITO-free organic optoelectronic technologies.

Keywords: *AgNW transparent electrode, Pyridine coating, ITO-Free OSCs*

Harvesting Sunlight Without Blocking It: Fully Solution-Processed Semitransparent OSCs with Spray-Coated Ag Nanowire Electrodes for Agri-PV and BIPV

Parwaz Asif , Bruno Lucas, Remi Antony, Sylvain Vedraine*

University of Limoges, CNRS, XLIM, UMR-CNRS 7252, 87000 Limoges, France

*Corresponding author e-mail: sylvain.vedraine@unilim.fr

Contributing authors: parwaz.asif@unilim.fr; bruno.lucas@unilim.fr; remi.antony@unilim.fr

Semi-transparent organic solar cells (ST-OSCs) are promising for applications such as building-integrated photovoltaics, as they combine electricity generation with visible light transmission. Here, we report a fully solution-processed ST-OSC based on an inverted device architecture of ITO/ZnO/PM6:Y12/PEDOT:PSS/AgNW, in which all functional layers are deposited using low-temperature, scalable methods. The ZnO electron transport layer, PM6:Y12 bulk heterojunction active layer, and PEDOT:PSS hole transport layer are sequentially deposited by spin coating, while the transparent top electrode is formed by spray coating a silver nanowire (AgNW) network from an isopropyl alcohol dispersion, eliminating the need for vacuum-based metal deposition. Silver nanowires provide high optical transparency, good electrical conductivity, and compatibility with large-area fabrication, making them well suited for semi-transparent devices. The concentration of AgNWs is systematically optimized to balance transparency and charge collection by controlling the nanowire network density and sheet resistance. The optimized AgNW electrode exhibits uniform coverage with low optical haze, enabling efficient carrier extraction while preserving visible transmittance.

As a result, the optimized ST-OSC achieves a power conversion efficiency(PCE) of 8.77% and an average visible transmittance (AVT) of approximately 54% across the visible spectrum. The corresponding light utilization efficiency (LUE) reaches 4.73% for an active area of 0.300 cm^2, demonstrating an effective trade-off between efficiency and transparency. These results highlight spray-coated AgNW electrodes as a simple, low-cost, and scalable approach for high-performance semi-transparent organic solar cells suitable for transparent energy-harvesting applications.

Keywords: *Semi-transparent OSCs, AgNWs Electrode, Solution Processed OSCs*

High throughput roll-to-roll moisture barriers for perovskite solar cells using Spatial Atomic Layer Deposition

Hindrik de Vries[1*], Ivo Aretz[1], Jons Bolding[1], Floor Souren[1], Kaisa-Leena Väisänen[2], Thomas M. Kraft[2]

[1] SALD B.V., Eindhoven, The Netherlands
[2]VTT Technical research centre of Finland Ltd, Kaitoväylä 1, Oulu 90590, Finland
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*hindrik.devries@spatialald.com

SALD B.V. is a rapidly growing Dutch SME and original equipment manufacturer, leading the industrialization of Spatial Atomic Layer Deposition (s-ALD). At SALD B.V. we are committed to advancing a green and sustainable society by developing tools to enable large scale, robust and high performance functional layers for a.o. encapsulation of perovskite and organic solar cells.

Atomic Layer Deposition (ALD) is a well-known process from the semi-con industry and produces high quality conformal, pinhole free and dense coatings. A major disadvantage however is that the ALD process is operated in vacuum which seriously limits throughput and scalability to roll-to-roll (R2R) processing. Attempts to industrialize the R2R s-ALD process [**1**] have failed due to process criticality in the web handling and achieving insufficient throughput (5 m/min).

At SALD B.V. a novel R2R s-ALD concept has been developed that can maximize the throughput of s-ALD process achieving web speeds compatible with wet coating techniques (15-200 m/min). Aluminium oxide films have been deposited on PET and PEN foil and characterized on moisture permeance using a Technolox Deltaperm system. From these measurements a clear trend in moisture barrier performance with film thickness can be seen. In the first 10-20 ALD cycles no improvement of the barrier performance is observed which is attributed to either nucleation delay and a gradual closing of the inorganic layer on the low density polymer film **[2]**. Subsequently, a rapid decrease in the water vapour transmission rate (WVTR) is observed between 2 nm up to 20 nm coating thickness. The fast decrease of the WVTR with film thickness, following an exponential scaling relation, is attributed to percolation of randomly distributed defects. Further increase of the film thickness does not significantly improve the barrier performance reaching a plateau value of WVTR=2.10^{-3} g/m^2.d, see Figure 1. A solvent penetration test indicates that the WVTR plateau (>20nm) is most likely caused by the presence of defects or pinholes which results in unhindered transport of the moisture independent of barrier thickness **[3]**.

To further study the barrier performance in the plateau regime, aluminium oxide layers of 20 and 30 nm film thickness were deposited at 60 m/min web speed. The barrier samples were assessed through a calcium test and as barrier films of perovskite solar cells. In particular, the ALD films compared to commercial barrier films for perovskite layer encapsulation under standard weathering conditions (T, %RH, light).

Keywords: atmospheric, spatial-ALD, moisture barrier, roll-to-roll, perovskite solar cell

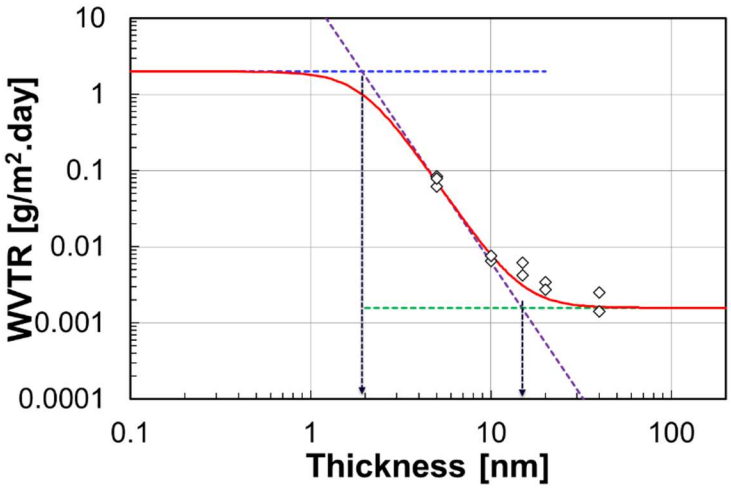


Figure 1. WVTR as a function of the film thickness

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Design of a PV/T Integrated Greenhouse Drying System

Hedil Karatekin[1,]

[1] Yildiz Technical University / Department of Electrical Engineering, Istanbul, Turkey

*hedilhamzeh@outlook.com

In order to reduce global warming and greenhouse gas emissions, renewable energy sources should be preferred. This study aims to design a system for drying products in a greenhouse integrated with Photovoltaic Thermal (PV/T) technology instead of the currently used natural gas-fired furnace drying method, thereby reducing environmental pollution and carbon emissions. Within this scope, a drying system has been designed for a cup holder product manufactured from 100% recycled paper pulp, using hot air and electrical energy obtained from solar energy. The fans used in the drying system are powered by the electrical energy generated from the PV/T panels, thus creating a new type of renewable energy-based system capable of producing its own energy. The system was modeled in ANSYS Fluent and analyzed in terms of drying performance, greenhouse internal hot air velocity distribution, and energy efficiency. Based on the obtained results, the designed system was compared with a natural gas-based drying system. According to the evaluation, it was determined that the greenhouse-type drying system integrated with PV/T panels reduces energy consumption and consequently energy costs, eliminates fossil fuel consumption, and decreases carbon emissions.

Acknowledgements

The author would like to express sincere gratitude to her advisor, Prof. Dr. Deniz Ulusarslan, for her valuable guidance and support throughout this study.

Keywords: Drying, Greenhouse-Type Drying, Photovoltaic Thermal System (PV/T), Renewable Energy, Solar Energy.

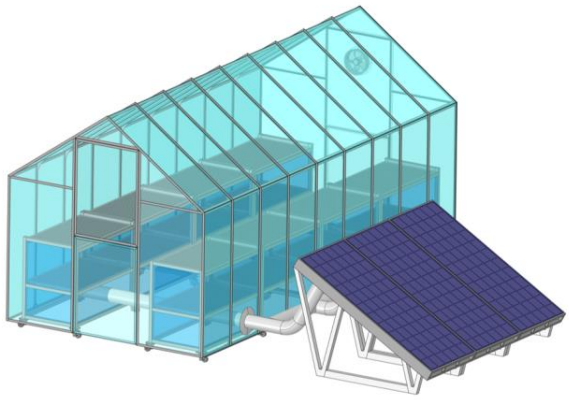


Figure 1. PV/T Integrated Greenhouse Drying System

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Surface-engineered Triphenylamine and Carbazole SAMs as efficient Hole-Selective Layers for Inverted Perovskite Solar Cells applications

Othmane El baz[1], Mohamed Ilsouk[1], Sarah Derbali[1]

[1] College of chemical science and engineering, Applied Chemistry & Engineering Research Centre of Excellence (ACER CoE), Mohammed VI Polytechnic University (UM6P), Benguerir, Morocco.

*sarah.derbali@um6p.ma

Self-assembled monolayers (SAMs) are emerging as highly promising hole-selective materials for next-generation inverted perovskite solar cells[1], [2]. In this work, we report the design and synthesis of carboxylic acid-anchored triphenylamine-based SAMs (T-SAMs) and carbazole-based SAMs (C-SAMs) for integration as hole-selective layers in CsFAMA-based inverted perovskite solar cells.

Uniform and low-defect T-SAM and C-SAM thin films were deposited onto indium tin oxide (ITO) substrates using a controlled chemical bath deposition method. The effects of immersion time, post-deposition treatments, and a co-solvent strategy to disassemble T-SAM and C-SAM micelles during processing were systematically investigated. The structural and surface properties of the resulting films were characterized using atomic force microscopy (AFM), energy-dispersive X-ray (EDX) mapping, and contact angle measurements, revealing well-organized monolayers with tunable wettability.

Importantly, the incorporation of T-SAMs and C-SAMs significantly influences perovskite crystallization and optoelectronic behavior. CsFAMA films grown on SAM-modified substrates exhibit enhanced crystallinity, optimized bandgap, more uniform surface coverage, and reduced defect density compared to films deposited on conventional PEDOT:PSS layers. These improvements are consistently confirmed by X-ray diffraction (XRD), scanning electron microscopy (SEM), photoluminescence (PL), and UV–Vis spectroscopy.

Finally, the developed T-SAMs and C-SAMs will be integrated into inverted perovskite solar cell devices to evaluate their impact on photovoltaic performance and operational stability in comparison with conventional hole-selective materials.

Overall, this study establishes clear structure-property relationships between SAM surface characteristics and perovskite film quality, demonstrating the strong potential of triphenylamine- and carbazole-based SAMs as efficient and tunable alternatives to conventional hole-selective layers in high-performance inverted perovskite solar cells.

Acknowledgements

Mohammed VI Polytechnic University (UM6P) and OCP collaborate as partners in advancing research and innovation through the OCP Chair of Waste Transformation and Power Efficiency (WTPE). This partnership, supported by OCP SBU Manufacturing, underscores a shared commitment to the successful realization of WTPE and all related projects.

Keywords: Triphenylamine-based SAMs, Carbazole-based SAMs, Inverted perovskite solar cells

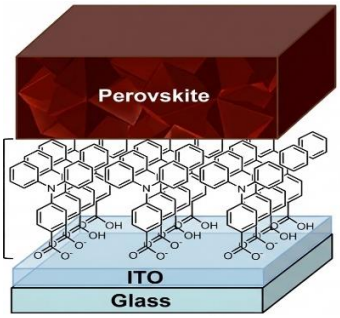


Figure 1. Schematic representation of a stacked structure showing SAM molecules on a substrate interfaced with a perovskite layer.

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Solar energy adoption and policy transformation in North Macedonia

Muratcan IŞILDAK , International Balkan University , Institute of Law, Department of Balkan Studies , Skopje

muratcanisildak@gmail.com, **ORCID:0000-0002-8156-4371,** +90 532 525 06 95

This paper explores the development and diffusion of solar photovoltaic (PV) energy in North Macedonia, focusing on its growing role within the country's energy transition and sustainability agenda. With abundant solar potential and increasing pressure to reduce dependence on lignite-based energy production, North Macedonia has accelerated its shift toward renewable energy sources in recent years. The study examines policy instruments and regulatory reforms such as feed-in tariffs, market premiums, and liberalization measures, that have facilitated investment in solar energy. It also analyzes the expansion of both utility-scale solar plants and decentralized rooftop systems among households and small enterprises. Despite this progress, the research identifies key structural challenges, including grid integration constraints, administrative complexities, limited financing mechanisms, and uneven public awareness. Using a qualitative methodology based on policy analysis, secondary data, and regional comparison, the paper situates North Macedonia within the broader Western Balkans energy transition context. The findings suggest that while solar adoption is increasing, achieving long-term sustainability requires a more coherent and integrated policy framework. Strengthening institutional capacity, enhancing grid infrastructure, and promoting decentralized energy solutions emerge as critical priorities. The paper concludes that solar energy can play a transformative role in North Macedonia's low-carbon transition, provided that regulatory clarity, investment conditions, and public engagement are effectively aligned.

Acknowledgements

This is the abstract template document for PVCON2026.

Keywords: North Macedonia , Energy, Solar Panels , Energy Emerge

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THE ROLE OF INTELLECTUAL PROPERTY IN SOLAR ENERGY TECHNOLOGIES

Şerife AKYILDIZ[1], Emre DEMİREZEN[1]

[1] Turkish Energy, Nuclear and Mineral Research Agency (TENMAK) - Industrial Relations and Contracts Department, Ankara, Türkiye

*serife.akyildiz@tenmak.gov.tr

Renewable energy technologies, such as solar and wind power, are key to reducing emissions in the electricity sector, which is currently one of the largest sources of CO_2 emissions. The imperative to achieve net-zero emissions globally by 2050 requires rapid progress in this endeavor. Government support and policies play a crucial role in accelerating the time required to bring new technological solutions to market and ensure their widespread adoption. This support includes fostering workforce development and employment priorities through appropriate educational models, funding research and development (R&D), establishing technology transfer networks for knowledge exchange, protecting intellectual property, enhancing companies' innovation capacity, promoting the widespread adoption of solar energy technology through public procurement, assisting industrial firms in developing innovations, investing in technical infrastructure, and establishing regulatory frameworks for markets. Intellectual property rights serve as a strategic guiding mechanism to promote innovation and commercialization in solar energy systems (SES). By granting exclusive rights to inventors, they encourage sustainable R&D investments and help recover the costs of innovation. Effective management of intellectual property strengthens collaboration among stakeholders, including scientists, technology developers, research institutions, and industry partners. In Türkiye, there are over 2,000[1] published patent applications in the SES sector, encompassing areas such as electricity generation, smart grids, industrial integration, energy storage, and digital energy management.

Keywords: Intellectual Property, Patent, Commercialization, Innovation, Solar Energy

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Industrial Solar Panel Investments and Sustainability Performance: Evidence from Emerging Economies

Özkan Özkara[1]

[1] Ministry of Inndustry and Technology/Department of Energy and Sustainability, Ankara, Türkiye

The growth of solar photovoltaic (PV) investments has become a main tool of the global green transition toward sustainability. Beyond clean electricity generation, solar investments produce larger environmental, economic and social benefits, especially for emerging economies dealing with energy security of supply, rising industrial costs and climate policy obligations. This paper examines the contribution of industrial solar panel investments to sustainability performance through a multi-dimensional framework covering carbon reduction, competitiveness, resilience and circularity. According to recent developments from international organizations and academic literature, the study outputs that solar PV is now one of the most competitive power technologies and is projected to dominate renewable capacity in coming years. For industrial users, on-site solar deployment can lower electricity expenditures, reduce energy costs, volatility and improve compliance with carbon-related trade measures and regulations. However, challenges in PVs remain in financing, grid integration, recycling infrastructure and supply-chain. The paper concludes that industrial solar investments should be treated not only as energy projects, but as strategic instruments for measurable sustainability transformation in emerging markets.

Keywords: Solar PV, Sustainability, Industrial Decarbonisation, Emerging Economies, Renewable Investments

Figure 1. Title / Description
(Please use your images, photos etc. in high resolution)

References

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A Physics-Based Digital Twin Framework with Deep Learning for PV Performance Monitoring and 10-Year Aging Prediction in Hot Semi-Arid Climates

Emna Akkari[1,2], Selma Hajri[1], Selma Aouida[1]

[1] Laboratoire de photovoltaïque (LPV), Centre de Recherches et desTechnologies de l'Energie (CRTEn) Borj Cedria B.P N°95 2050-Hammam Lif, Tunis, Tunisia
[2] Université de Carthage, Institut Supérieur des Technologies de l'Information et de la Communication, 1164, Ben Arous, Tunisie

*emna.akkari@istic.ucar.tn

The degradation of crystalline silicon photovoltaic modules installed in hot, semi-arid environments is accelerated by thermal cycling, dust deposition, and prolonged high irradiance, making physics-informed performance modelling and lifetime prediction essential for sustainable energy management. This work presents a physics-based Digital Twin framework that incorporates a Simscape one-diode equivalent circuit model, Long Short-Term Memory (LSTM) networks, and an LSTM autoencoder applied to a 36-cell, 50-W silicon module using a year's worth of real meteorological data at 10-minute resolution (52,560 measurement points).
The Simscape model generates complete I-V and P-V characteristic curves under dynamic conditions. Annual simulation over 4,009 sunshine hours and an irradiation of 2,050 kWh/m² yields a peak power of 59.29 W, a daytime average of 26.6 W, a mean fill factor of 0.784, and a total DC energy yield of 106.77 kWh. Seasonal analysis reveals a 4.5× energy ratio between summer (45 kWh, T_avg=33.7°C) and winter (10 kWh, T_avg=16.8°C), with a thermal amplitude of 49°C across the year. The LSTM achieves R^2=0.976 and RMSE=0.035. The LSTM autoencoder detects anomalous signatures with a global anomaly rate of ~11% of daytime points, peaking in March during khamsin dust storm activity.
According to a parametric 10-year ageing model, Pmax will decrease from 45.1 W to 40.0 W, which translates to an 11.1% cumulative loss at 1.11%/year. This is in line with reported rates for crystalline silicon in similar arid climates. The annual energy yield drops from 96.3 to 85.4 kWh before hitting the operational threshold of 80% at year 10. Anomalies are categorised into soiling, thermal stress, and structural degradation categories by a rule-based AI decision system, which then offers practical maintenance suggestions. Real-time parameter recalibration will be made possible by IoT-embedded sensors, which will complete the self-updating Digital Twin architecture.

Acknowledgements

Special thanks to enerMENA project for providing the meteorological datasets for the Tataouine site.

Keywords: Physics-based Digital Twin, LSTM Autoencoder, 10-Year Aging Prediction, Hot Semi-Arid Climate, Predictive Maintenance.

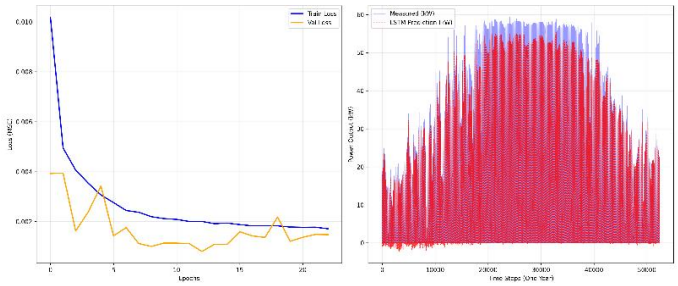


Figure 1. Model Training Convergence (Real MSE) and Annual Power Comparison (Tataouine)

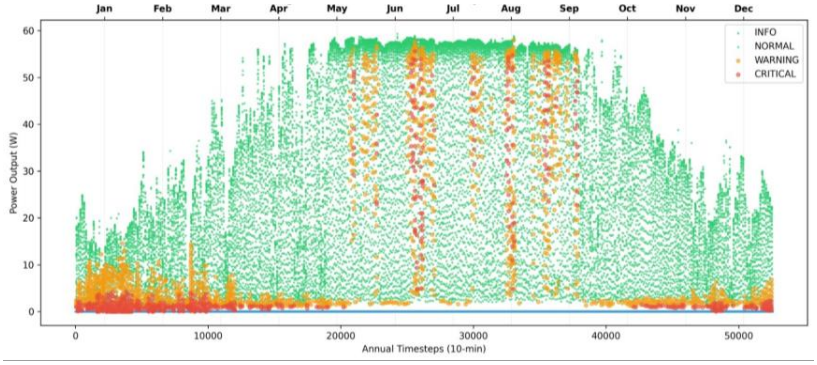


Figure 3. Annual AI Decision Map. NORMAL (green), WARNING (orange), CRITICAL (red), INFO/night (blue). Month labels on top axis.

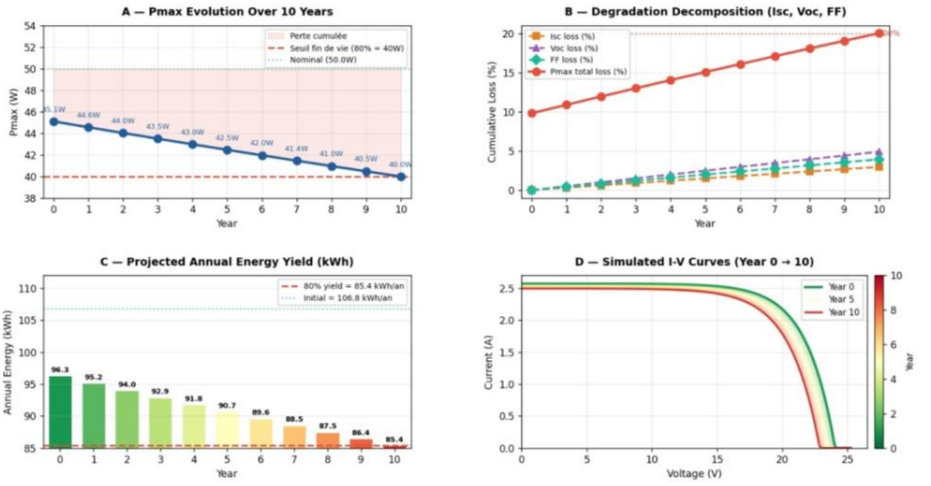


Figure 3. (Left) Pmax 10-year projection with 80% threshold. (Right) Simulated I-V curves Year 0 → 10 (green to red).

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BEYOND CONVENTIONAL TEXTURING: A NEW REGIME OF PLASMA-DRIVEN SHALLOW NANOTEXTURING IN SILICON

Ozan Aydın[1,2,*], Milad Ghasemi[2], Hisham Nasser[2], Raşit Turan[1,2,3]

[1] Micro and Nanotechnology, Graduate Program of Natural and Applied Sciences, Middle East Technical University, 06800 Ankara, Turkey
[2] ODTÜ-GÜNAM, Center for Solar Energy Research and Applications, 06800 Ankara, Turkey
[3] Department of Physics, Middle East Technical University, 06800 Ankara, Turkey

*ozan.aydin@odtugunam.org

Conventional surface texturing of crystalline silicon, particularly wet chemical methods, is widely used but faces limitations due to high chemical and water consumption as well as environmental concerns. As a result, there is increasing interest in alternative surface engineering approaches. Among these, plasma-based techniques have been extensively studied; however, they typically produce highly porous, high-aspect-ratio structures that are not always suitable for advanced device integration.

In this study, we demonstrate a new dry plasma etching regime enabling controllable shallow nanotexturing of crystalline silicon as an alternative to conventional wet chemical texturing methods, which are widely used but face limitations due to high chemical and water consumption as well as environmental concerns. Plasma-based techniques have been extensively investigated in this context; however, they typically produce highly porous, high-aspect-ratio structures that are not always suitable for advanced device integration. Using SF_6/O_2 inductively coupled plasma reactive ion etching (ICP-RIE), a distinct transition between smooth etching, controlled nanotexturing, and non-uniform regimes is identified by systematically varying chamber pressure. Within a narrow process window, shallow (~100–140 nm), rounded and pyramid-like surface features are reproducibly formed. The resulting surfaces exhibit reduced reflectance compared to flat and pyramid-textured silicon while maintaining a morphology suitable for subsequent passivation and device integration. These findings provide new insight into plasma–surface interactions and establish a controllable dry plasma approach for shallow silicon nanotexturing.

M2-size crystalline silicon (c-Si) wafers with a resistivity of 1.5–2 Ω·cm were used as substrates. Prior to plasma processing, only saw damage removal and standard ozone cleaning were applied. Nanotexturing was performed using an inductively coupled plasma reactive ion etching (ICP-RIE) system with an SF_6/O_2 gas mixture (3:2 ratio). The chamber pressure varied between 15 and 30 mTorr, while the ICP power was set to 600, 700, and 800 W with zero bias power. The substrate temperature was maintained at ~18 °C, and the etching time was fixed at 60 s. Optical properties were evaluated using a reflection spectrophotometer with measurements taken from five different points and weighted average reflection of the samples were measured as below as 5% (Fig. 1) while saw-damge etched (SDE) wafers typically exhibit reflectance values of ~35–45%, and conventionally pyramid-textured wafers with reflectance in the ~10–15% range [1,2]. Surface morphology of the samples was characterized by field emission scanning electron microscopy (FE-SEM) in cross-sectional mode. Representative SEM images (Fig. 2) reveal distinct morphological regimes. At lower pressure (15 mTorr), the surface remains relatively smooth. At 20 mTorr

and 600 W, a well-defined nanotextured morphology emerges, consisting of shallow, rounded, quasi-pyramidal features formed by a balance between chemical and ion-assisted etching. At higher pressure (30 mTorr) and 700 W, pyramid-like structures are observed. These results indicate the presence of a narrow process window for controlled nanotexturing. This morphology provides a balance between optical performance and surface quality, suggesting that shallow nanotexturing can enhance light trapping while avoiding the drawbacks of highly porous structures.

Acknowledgements

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Keywords: silicon nanotexturing, plasma etching, ICP-RIE, surface morphology, shallow nanostructures

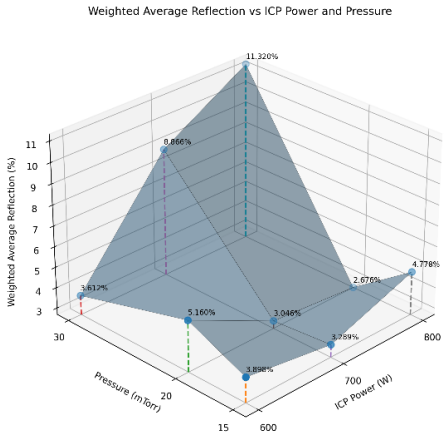


Figure 1. Reflection values according to ICP power and room pressure variation.

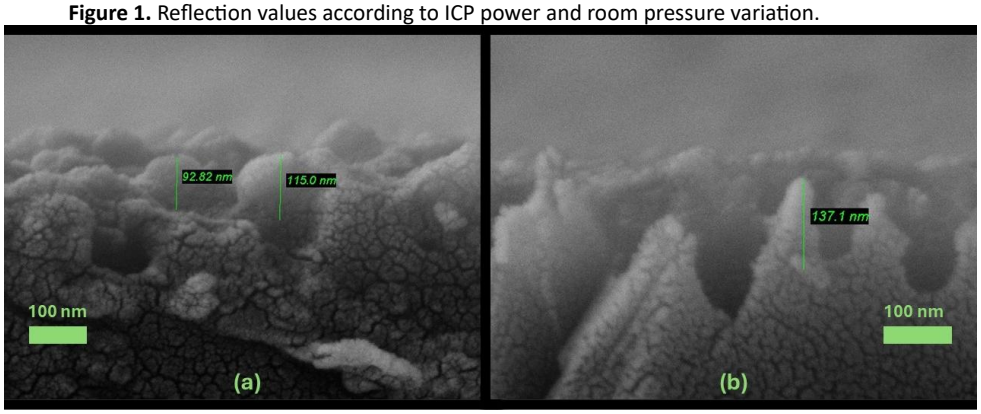


Figure 2. SEM images of (a) rounded structures formed under 600 W, 15 mTorr texturing, (b) nano-quasi-pyramid shaped 700 W, 30 mTorr structures.

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Optimizing Ag Growth in IZO/Ag/IZO Electrodes via Seed Layers for High-Efficiency SHJ Solar Cells

Khushi Muhammad Khan[1,2], Andrea Lo Mastro[1,2], Antonio Terrasi[1,2]

1. Dipartimento di Fisica e Astronomia "Ettore Majorana", Università di Catania, Via S. Sofia 64, 95123 Catania, Italy
2. CNR-IMM, Via S. Sofia 64, 95123 Catania, Italy

*Corresponding Author's E-mail: kkhan@unisa.it

To improve carrier transport and reduce resistive losses in transparent conductive electrodes for silicon heterojunction (SHJ) solar cells, IZO/Ag/IZO multilayer structures incorporating ultrathin seed layers (Cu, Ti, and Sn) were investigated. The introduction of a metallic Ag interlayer significantly enhances electrical conductivity, while the seed layer controls its growth behavior and film continuity. The structural, optical, and electrical properties of the multilayer films were systematically analyzed. All samples exhibit high optical transmittance in the visible region, while electrical performance strongly depends on the seed layer. The seed-free film shows a sheet resistance of 14.78 Ω/sq, whereas the Cu-seeded sample demonstrates improved stability after annealing with a reduced sheet resistance of 15.1 Ω/sq and increased carrier concentration of 1.24×10^{17} cm^{-3}. In contrast, the Sn-seeded film shows degraded performance, with sheet resistance increasing to 110 Ω/sq after annealing. When applied as front transparent electrodes in SHJ solar cells, the Cu-seeded IZO/Cu/Ag/IZO structure exhibits a more uniform spectral response, with external quantum efficiency approaching ~98% in the visible region, indicating enhanced light harvesting and carrier collection. These results demonstrate that seed layer engineering effectively optimizes Ag growth and improves the optoelectronic performance of multilayer electrodes. The proposed structure provides a promising route toward high-performance and cost-effective transparent electrodes for next-generation SHJ solar cells.

Keywords: Transparent conductive oxide (TCO), IZO/Ag/IZO multilayer, Seed layer engineering, Silicon heterojunction (SHJ) solar cells

The Earth poles; renewable energy with wind and sun

D. Kılınçoğlu, B. G. Akinoglu, C. Baykal, H. C. Avci and A. B. Karaveli

The climate of the Earth poles is quite similar except the obliqueness of Earth. Depending on the latitude, the day time and night time varies annually. The wind is blowing within the climatological variations while the sun is shining little above the horizon. Use of the wind turbines and efficient solar cells can be used effectively [1,2].

Two models and the structures to be used in poles are explained. The findings show that -10-20 kW of turbines and solar cells of 100 m2, 35% efficiency are enough to produce the useful energy of a 200 m2 size research facility. It should be noted that Li ion batteries are to be used. The design structures and the protection details are clearly given [2]. The settlement of Türkiye in Horse the shoe island of Antarctic [2, 3] and possible research on mainly the latitudes in Arctic [3] are obtained in detail.

Another important issue is the warranted of different countries on Antarctic and Arctic. There are 5 countries on Antarctic and 8 on Arctic. The problems on sharing (partaking) issues for these countries and also for all the other countries is another point of discussions [4]. The details are given in this work and rather “peaceful” actions to be taken are clearly explained. The related international political issues are clarified. This is, of course, also related to the use of useful energy in pole research works and also for the future prospects.

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Impact of Geometric Design Parameters on Energy Yield and Under-Panel Light Availability in Fixed Agrivoltaic Systems: A Comparative Study of Ankara and Palermo

Ecem ÖNEN[1*], Vincenzo DI DIO[2], Talat ÖZDEN[3]

[1] University of Salerno / Department of Information and Electrical Engineering and Applied Mathematics, Salerno, Italy
[2] University of Palermo/ Department of Engineering, Palermo, Italy
[3] Middle East Technical University / Center for Solar Energy Research and Applications(GÜNAM), Ankara, Türkiye
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*eonen@unisa.it

This research aimed to comparatively analyze the effects of pitch, mounting height, and tilt angle variation on both photovoltaic energy production and agricultural light availability under the panels in a fixed, south-facing, row-based agrivoltaic system for Ankara and Palermo. In the study, the system type, module structure, and basic placement approach were kept constant; only the geometric design variables were changed, and their effects were assessed through simulation. Meteorological and radiation data were obtained from the Photovoltaic Geographical Information System at an hourly resolution for both locations, and simulations were carried out in the pvlib environment, using the same photovoltaic module and calculation approach. Since photosynthetically active radiation is not a native output of pvlib, it was derived from the simulated broadband solar radiation by applying a standard conversion coefficient. In the analysis, the pitch value was defined in the range of 5.0–10.0 m with 0.5 m increments, the mounting height in the range of 2.5–5.0 m, and the tilt angle at 20°, 25°, and 30°. For each scenario, incident radiation, annual energy production, and changes due to shading were quantified computationally. In the agricultural dimension of the study, light access under the panels was interpreted through photosynthetically active radiation. The aim is not to directly predict yield for individual plant species, but to comparatively evaluate the obtained light conditions in terms of plant groups with different light requirements. The results show that the most significant effect on the photosynthetically active radiation under the panel is due to the pitch variable, the effect of the tilt angle is more limited, and the mounting height plays a secondary role in this respect. Thus, the study reveals how the same agrivoltaic design variables behave in two different climatic contexts and offers a simple and repeatable evaluation framework for determining more balanced design ranges between energy production and agricultural light access.

Acknowledgements

Keywords: agrivoltaics, comparative analysis, energy yield, light availability, system geometry

Mounting Height as a Design Variable in Bifacial Tracked Agrivoltaic Systems: A Simulation Study under Palermo Conditions

Ecem ÖNEN[1*], Vincenzo DI DIO[2], Talat ÖZDEN[3]

[1] University of Salerno / Department of Information and Electrical Engineering and Applied Mathematics, Salerno, Italy
[2] University of Palermo/ Department of Engineering, Palermo, Italy
[3] Middle East Technical University / Center for Solar Energy Research and Applications(GÜNAM), Ankara, Türkiye
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* eonen@unisa.it

This study investigates the effect of mounting height on an east-west bifacial tracked agrivoltaic system under Palermo conditions. System type, orientation, and row spacing were kept constant; thus, the effect of mounting height was assessed through simulation. Meteorological and radiation data for Palermo were obtained from the Photovoltaic Geographical Information System at hourly resolution, and simulations were carried out using a pvlib-based modeling approach. Since photosynthetically active radiation is not a native output of pvlib, it was derived from the simulated broadband solar radiation by applying a standard conversion coefficient. The analysis evaluated annual photovoltaic energy output, cell temperature behavior, and under-panel photosynthetically active radiation distribution across the different mounting height configurations. The findings show that mounting height provides only a limited increase in energy production, while contributing to a slight decrease in cell temperature. In terms of under-panel photosynthetically active radiation, higher mounting did not create a significant and consistent improvement across configurations, but produced limited yet regular differences in light levels throughout the year. In this context, mounting height stands out not so much as a primary parameter determining energy efficiency or under-panel lighting conditions alone, but rather as a design variable that influences the geometric spacing and shading distribution of the system.

Acknowledgements

Keywords: agrivoltaics, bifacial photovoltaics, height, light availability, mediterranean climate

From Architectural Intent to Manufacturable Module: Design-to-Order Digital Workflows as Enablers of BIPV Value Chain Scale-Up

Demirtaş[1], Ahmet Rasim, Karahançer[2], Enes Berk

[12] Electravis Teknoloji A.Ş. (SolarVis), Ankara, Türkiye

*ardemirtas@solarvis.co

Building-Integrated Photovoltaics (BIPV) is among the largest untapped solar surfaces in the European Union. The global BIPV market is projected to grow from USD 13.45 billion in 2025 to USD 47.02 billion by 2031 at a 23.06% compound annual growth rate [1], with regulatory pressure further accelerating this trajectory. Under Article 10 of the recast Energy Performance of Buildings Directive (EU) 2024/1275, all new public and non-residential buildings above 250 m² must be solar-ready by the end of 2026, with phased obligations extending to existing non-residential buildings from 2027 and to new residential buildings by the end of 2029 [2]. Yet, despite both market pull and regulatory push, BIPV diffusion remains structurally slower than its potential. Peer-reviewed evidence attributes this gap not primarily to module technology, but to design-stage friction — high product complexity, low architect awareness of BIPV, and the scarcity of turn-key offerings have all been identified as central adoption barriers [3] — and the multidisciplinary nature of BIPV (architectural, electrical, mechanical, regulatory) turns each project into a bespoke engineering exercise. This contribution argues that closing the BIPV adoption gap is, before anything else, a value-chain digitalisation problem, consistent with IEA PVPS Task 15's stated need for new digital approaches that can ease the BIPV design process and coordinate the broader BIPV value chain [4]. We outline what a design-to-order digital workflow must do to be useful at scale: ingest architectural geometry from BIM/CAD environments without re-modelling; encode manufacturing constraints (active area, string topology, electrical limits, lamination feasibility) as enforceable rules at the point of design rather than as post-hoc validation; and produce a manufacturable, quotable specification an architect, integrator, or SME installer can act on without specialist PV-engineering support. The premise is illustrated using operational evidence from a B2B solar-design platform that has supported more than 55,000 feasibility studies and 25,000 delivered projects across 16 countries, where the design-to-quote bottleneck observed in standard PV is directly informative for the customisation-heavy reality of BIPV. We conclude by mapping implications for architects, BIPV manufacturers, and standardisation bodies, positioning design-to-order digitalisation not as a productivity convenience but as a precondition for BIPV deployment at the scale that EU climate targets demand.

Acknowledgements

The author thank ODTÜ-GÜNAM for the kind invitation to contribute an oral presentation to PVCon 2026.

Keywords: Building-Integrated Photovoltaics (BIPV), Design-to-order configurator, Architecture-to-manufacturing integration, BIM/CAD interoperability, PV value chain digitalization



Figure 1: Schematic of a design-to-order digital workflow for BIPV. Architectural design intent originating from the architect or integrator (left) is ingested directly from BIM/CAD environments; manufacturing, electrical, and code constraints are enforced as rules at the point of design rather than as post-hoc validation; the workflow then exports an order-ready specification with a validated quote (right) that the BIPV manufacturer can produce against — replacing the bespoke engineering loop that currently sits between architectural intent and manufacturable BIPV.

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A Multi-Level Design Methodology for Matrix-Shingled Vehicle-Integrated Photovoltaics: From Cell Metallization to Platform-Specific Electrical, Thermal and Energy-Yield Assessment

Parisa Sharif[1], Arian Goodarzi[1], Melisa Korkmaz Arslan[1], Hisham Nasser[1], Veysel Unsur[1,2], Talat Ozden[1]

[1] The Center for Solar Energy Research and Applications (ODTÜ-GÜNAM), Ankara, Türkiye
[2] Necmettin Erbakan University / Department of Fundamental Sciences in Engineering, Konya, Türkiye

*parisa.sharif@odtugunam.org

Vehicle-integrated photovoltaics (VIPV) require a multi-scale design methodology in which photovoltaic device architecture, module interconnection, vehicle surface constraints, power-electronic compatibility, and environmental operating conditions are considered as coupled design variables. Unlike stationary PV systems, VIPV generators are constrained by limited and non-planar installation areas, heterogeneous irradiance exposure, strict mass and safety requirements, electrical interface limitations, and the need for seamless aesthetic integration into the vehicle body. Therefore, the development of high-performance VIPV systems requires a systematic transition from cell-level optimisation to vehicle-level architectural design and simulation-based validation.

In this work, a requirement-driven design framework is developed for matrix-shingled TOPCon-based VIPV modules intended for urban electric mobility platforms. At the device level, metallization and segmentation studies are performed to define application-specific shingled cell geometries. A stripe-based TOPCon configuration is considered for larger integration areas, while compact rectangular shingled cell concepts are evaluated for geometrically constrained surfaces. These cell-level designs are translated into module-level matrix-shingled layouts to enable high active-area utilization, reduced visible metallization, current–voltage tunability, and improved adaptability to irregular vehicle geometries. The matrix-shingled approach also allows the electrical layout to be tailored according to surface-specific boundary conditions while maintaining compatibility with modular power-electronic interfaces.

At the system level, vehicle surface mapping and boundary-condition analysis are used to identify feasible integration zones by considering geometric envelope, curvature, mass limitations, service accessibility, safety restrictions, and regulatory constraints. Based on these constraints, surface-specific series–parallel configurations are defined to obtain electrically compatible PV sub-generators for distributed maximum power point tracking. The resulting VIPV architecture is then assessed through a multi-domain simulation workflow, including electrical converter simulations, steady-state thermal analysis, and location-dependent energy-yield estimation. Electrical simulations confirm the dynamic feasibility of the selected converter-control approach, while thermal simulations indicate stable module operation under high-irradiance conditions without critical overheating. Energy-yield simulations further show that the proposed multi-surface design strategy can support distributed solar energy harvesting under realistic urban mobility conditions.

The proposed methodology demonstrates that VIPV design should be treated as an integrated optimisation problem rather than a post-integration exercise in which conventional PV modules are simply placed on available vehicle surfaces. By linking cell geometry, shingled interconnection, vehicle boundary conditions, converter compatibility, thermal behaviour, and energy-yield prediction, this study establishes a scientifically traceable design route for the development and validation of next-generation VIPV systems.

Acknowledgements

This work was supported by the European Union's Horizon Europe research and innovation programme through the SUN-TRANS project, Solar Urban e-Mobility Transition, under Grant Agreement No. 101236202.

Keywords: Vehicle-Integrated Photovoltaics, Matrix-Shingled Modules, TOPCon Solar Cells, Cell Metallization, Electrical Architecture, Energy-Yield Simulation

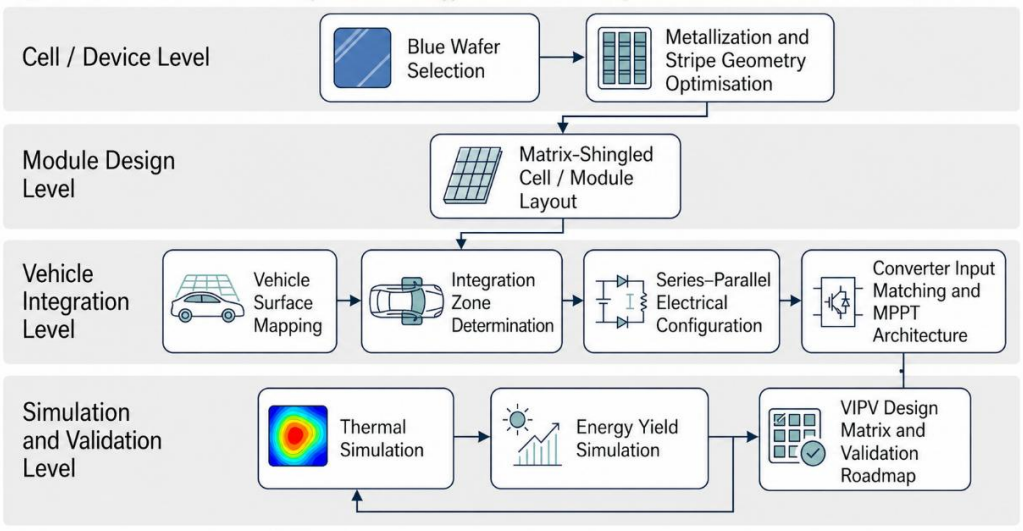


Figure 1. Multi-level VIPV design methodology from cell-level optimization to vehicle-level validation

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Rapid Prototyping Workflow for a PV Inverter FPGA-Based Model Predictive Control (MPC)

Poornima Gulur Chakrapani [1], Gustavo Cerda-Villafana [2], Robert S. Balog [1]

[1] Texas A&M University / Electrical and Computer Engineering, College Station, Tx USA
[2] University of Guanajuato / Department of Electronics Engineering, MEXICO

*Corresponding Author's E-mail: rbalog@tamu.edu

Finite Control Set Model Predictive Control (FCS-MPC) is a powerful control strategy for photovoltaic inverters due to its ability to handle multiple control objectives such as maximum power point tracking (MPPT) and volt/var control simultaneously while optimizing system performance in real time [1]. However, implementing MPC in hardware has long held a stigma of not being practical do to its high computational demand in real-time applications [2]. The Field Programmable Gate Array (FPGA) is a good choice for realizing FCS-MPC controllers as it offers highly parallel, low latency, deterministic timing behavior, which give it perforemnce and cost advantages over sequential-instruction processor-based implementation. However, FPGA development traditioanlyl involves extensive manual HDL coding, synthesis, and debugging processes that are time-consuming and error-prone. To address these challenges, rapid prototyping tools such as MATLAB/Simulink HDL Coder [4] and hardware-in-the-loop (HIL) simulators like Typhoon HIL can be leveraged to automate and accelerate the development cycle. This integration allows for seamless migration from simulation-based control design to FPGA hardware deployment while maintaining design fidelity. In this work, we present a workflow that bridges MATLAB/Simulink, Quartus, and Typhoon HIL to realize an FPGA-based MPC controller for a converter system. The workflow, illustrated in Fig1, begins with controller design and validation in MATLAB/Simulink, followed by HDL code generation and FPGA synthesis in Quartus. The complete system is verified using Typhoon HIL, enabling real-time performance testing and signal validation through FPGA-hardware interaction. This paper details each stage of the workflow, highlighting its suitability for prototyping advanced control algorithms..

Keywords: model predictive control (MPC), rapid prototype, PHIL, FPGA, PV inverter

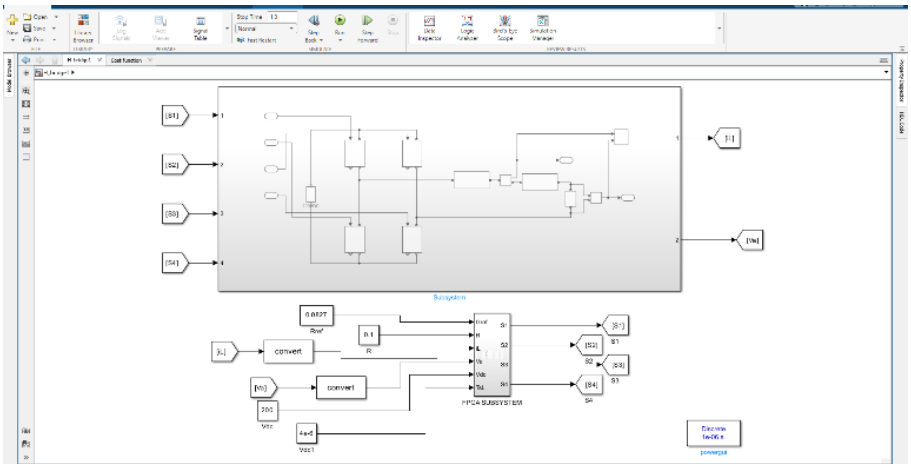


Figure 1. MATLAB model of the H-bridge PV inverter (top) and MPC (bot) Title / Description

Industrial Solar Panel Investments and Sustainability Performance: Evidence from Global Trends and Emerging Economies

Özkan ÖZKARA[1]

[1] Ministry of Industry and Technology/Ankara, Türkiye

Solar photovoltaic (PV) investments have led as one of the most substantial drivers of the global green transition in terms of sustainability aspects. Their importance covers far beyond clean power generation, contributing industrial competitiveness, energy market security, carbon mitigation and circular economy. Despite the rapid growth of solar capacity worldwide, the broader sustainability meaning of PV investments—for emerging economies undergoing industrial transformation particularly—continue inadequately integrated in the literature. This study provides as a precursor study, including a multidimensional analytical framework to evaluate solar panel investments across six sustainability dimensions: environmental impact, economic performance, resilience, social value, circularity, and governance readiness. Drawing on recent evidence and comparative policy views, this study looks into how solar investments contribute to lifecycle emission reductions, lower industrial energy costs, improved energy independence, and compliance with carbon-related trade measures. The findings suggest that the long-term sustainability of PV investments depends not only on installations , but also on regulatory frameworks, grid structures, end-of-life recycling systems, critical mineral security, and digital optimization tools. The study further argues that emerging economies such as Türkiye can leverage industrial solar installations as a strategic instrument for export competitiveness and low-carbon economy transition. Therefore, solar PV investments should be treated not merely as renewable energy projects, but as multidimensional sustainability assets.

Keywords: Circular Economy, Emerging Economies, Industrial Decarbonisation, Solar PV, Sustainability, ,

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Sun-Position-Based Shadow Calculation for Photosynthetically Active Radiation Control in Agrivoltaic Systems

Mohammad Derogarian Miandoab [1,2], Talat Özden [1]

[1] ODTÜ-GÜNAM The Center for Solar Energy Research and Applications/IntegratedPV Division, Ankara, Türkiye
[2] Middle East Technical University/ Electrical and Electronics Engineering, Ankara, Türkiye

* mohammad.miandoab@odtugunam.org

Agrivoltaic systems have emerged as a promising approach for the simultaneous production of renewable energy and agricultural yield on the same land, helping to reduce the land-use conflict between photovoltaic electricity generation and crop production. Their successful implementation depends on maintaining appropriate photosynthetically active radiation (PAR) at crop level, since excessive shading can suppress plant growth while insufficient shading may reduce the protective benefits of the photovoltaic structure. A major challenge in this context is that panel-induced shadow behavior is highly dynamic and nonlinear, varying with solar position, panel orientation, time of day, day of year, and season. Therefore, accurate shadow calculation is a prerequisite for reliable sunlight-sharing operation in agrivoltaic farms. This study proposes a sun-position-based framework for shadow calculation and PAR-oriented control in an agricultural photovoltaic system. A three-dimensional geometric representation of the farm and photovoltaic rows is established, and the instantaneous shadow of each panel is determined by projecting its vertices onto the farm plane along the solar direction. The analysis is then extended to farm scale, enabling the computation of the shadowed region, union shadow area, and shadow coverage ratio over the cultivated field. Building on this shadow-calculation engine, a control algorithm is incorporated to regulate panel rotation angle according to crop light requirements. In this way, the proposed framework establishes a direct link between solar geometry, panel shadow projection, farm-scale shadow quantification, and adaptive panel-angle control. The methodology provides a computational basis for shadow-aware agrivoltaic operation and supports the future development of intelligent decision-support and sunlight-sharing tools for agricultural photovoltaic systems.

Keywords: Agrivoltaic Systems, Crop Light Management, Photosynthetically Active Radiation, Shadow Analysis

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A Fuzzy-Logic-Based Decision-Making Framework for Crop-Environment Management in Agrivoltaic Systems

Mohammad Derogarian Miandoab [1,2], **Talat Özden** [1]

[1] ODTÜ-GÜNAM The Center for Solar Energy Research and Applications/IntegratedPV Division, Ankara, Türkiye
[2] Middle East Technical University/ Electrical and Electronics Engineering, Ankara, Türkiye

* mohammad.miandoab@odtugunam.org

Agrivoltaic systems require decision-making strategies that can balance photovoltaic energy production with crop-related requirements under continuously varying solar and seasonal conditions. In this study, a fuzzy-logic-based framework is proposed for regulating the rotation angle of photovoltaic panels with a primary focus on photosynthetically active radiation (PAR), while remaining extendable to other crop-environment variables in future developments. The framework employs normalized radiation-related and shadow-related inputs, enabling the decision process to account for the nonlinear and time-dependent nature of sunlight availability and shading potential in agrivoltaic environments. This normalization is necessary because both achievable crop-light regulation and available shadow range vary significantly with hour, day, and season, making direct rule-based angle selection difficult. Based on a set of linguistically defined fuzzy rules, the framework generates a normalized shadow command as its output. This output is then translated into a target shadow area, and a search-based optimization step is used to determine the nearest feasible panel rotation angle through the pre-established shadow–angle relationship of the agrivoltaic geometry. In this way, the proposed method combines the interpretability and flexibility of fuzzy logic with geometric shadow calculation and angle selection to support intelligent sunlight-sharing operation in agrivoltaic systems. The framework provides a practical basis for crop-aware panel operation and for the future integration of additional environmental variables into agrivoltaic decision-making.

Keywords: Agrivoltaic Systems, Crop-Environment Management, Decision Making, Fuzzy Logic, Sunlight Sharing

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Over 33%-efficient 4 cm² perovskite-silicon tandem solar cells with optimized screen-printed metallization

Kerem Artuk[1], Michele De Bastiani[1], Jun Zhao[1], Lisa Champault[1], Antoine Descoeudres[1], Julien Hurni[2], Jonas Geissbühler[1], Laurie-Lou Senaud[1], Nicolas Badel[1] Jean-David Decoppet[1], Adrien Theytaz[1], Vanessa Gainche[1], Thibault Schaller[2], Florent Sahli[1], Christian M. Wolff[2], Tonio Buonassisi[1], Christophe Ballif[1, 2], Bertrand Paviet-Salomon[1], and Quentin Jeangros[1]

[1] Centre Suisse d'Electronique et de Microtechnique (CSEM), Rue Jaquet-Droz 1, 2000, Neuchâtel, Switzerland

[2] École Polytechnique Fédérale de Lausanne (EPFL), Institute of Electrical and Microengineering (IEM), Photovoltaics and Thin-Film Electronics Laboratory (PV-Lab), Rue de la Maladière 71b, 2000, Neuchâtel, Switzerland

* kerem.artuk@csem.ch

Perovskite–silicon tandem solar cells have reached 35% efficiency on small-area (~1 cm²) laboratory devices on 1-inch substrates. However, these records rely on an evaporated metallization front grid, limiting scalability. Bridging this gap requires industry-compatible approaches such as screen-printed metallization under the temperature constraints imposed by the perovskite top cell.

Here, we demonstrate perovskite–silicon tandem solar cells fabricated on full 4-inch wafers (**Fig. 1a–b**) using optimized screen-printed metallization. By systematically varying paste composition, curing conditions, and TCOs, we identify a low-temperature (<130 °C) process window compatible with perovskite integration. Devices employing an optimized pure-Ag paste achieve a reverse-scan efficiency of 33.4% (**Fig. 1c**) and a stabilized efficiency of 33.3% (**Fig. 1d**) on a 4 cm² area. The external quantum efficiency of a sister device (**Fig. 1e**) reveals a current mismatch of 1.4 mA cm^{-2}, consistent with high fill factors enabled by a bottom-cell pseudo-fill factor of 86%.

Furthermore, reducing silver consumption while maintaining performance is critical for lowering costs and improving sustainability, motivating Ag–Cu-based pastes as alternatives to pure-Ag. Comparative electrical measurements of pure-Ag versus Ag–Cu (35% Ag) pastes (**Fig. 1f**) show lower contact resistivity at the ITO/metal interface with pure-Ag paste, while the bulk resistivity remains comparable between the two pastes. These results indicate that Ag–Cu pastes are already showing reasonable electrical performance, and further improvements in paste formulations are expected to bridge the remaining gap. Device efficiency and reliability results comparing pure-Ag and Ag–Cu pastes will be shown at the conference, highlighting this approach as a pathway toward cost-effective, scalable, and more sustainable tandem technologies.

Keywords: perovskite-silicon tandems, screen-printing

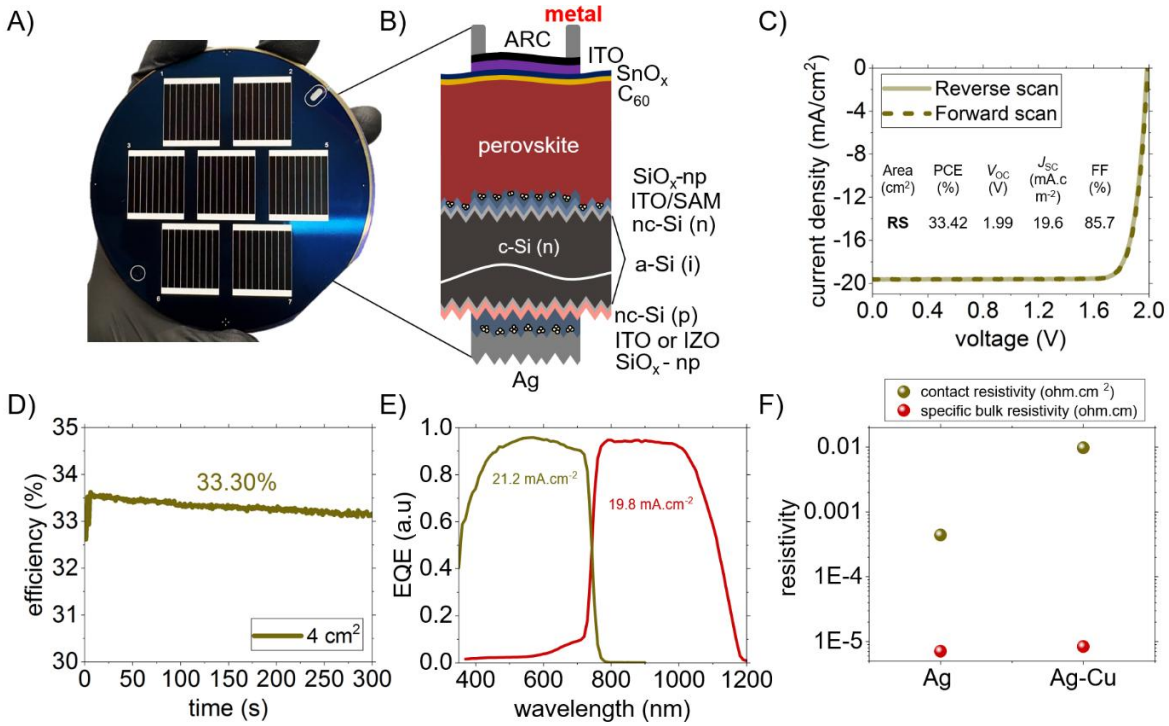


Figure 1. A) Optical image of the cell design (7 pixels of 4 cm^2) on a 4-inch wafer, and B) device schematics. C) Champion 4 cm^2 reverse and forward JV curves. D) Maximum power tracking of the 4 cm^2 champion device and the steady-state power conversion efficiency. E) External quantum efficiency of a sister device. F) Contact resistivity of different pastes to ITO and specific bulk resistivity.

INSIGHTS INTO INTERFACIAL MECHANISMS OF N-I-P AND P-I-N PEROVSKITE SOLAR CELLS THROUGH ELECTROCHEMICAL IMPEDANCE SPECTROSCOPY

Mohammad Aamir[1], Sandra Winnie Angelo[1], Rajni Rohilla[2], Anubhav Raghav[2], Tabish Rasheed[1*]

[1] Department of Applied Sciences, School of Engineering and Technology, BML Munjal University, Gurugram, India
[2] Department of Applied Sciences, The NorthCap University, Gurugram, India
[3] Name of Institution/Department, City, Country
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*Corresponding Author's E-mail: tabish_rasheed_physics@yahoo.co.in

Lead halide perovskite solar cells (PSCs) have emerged as a leading photovoltaic technology [1] over the past decade due to their exceptional optoelectronic properties and ease of fabrication. Power conversion efficiencies (PCEs) exceeding 25% have been achieved for single-junction devices [2]. However, stability remains the primary challenge hindering large-scale commercialization. Recently, the choice of device architecture has become a topic of active debate. While the conventional n–i–p configuration offers higher efficiencies, it often suffers from poor long-term stability. Conversely, p–i–n devices have demonstrated improved stability, and their efficiencies have now become comparable to those of n–i–p counterparts.

In this work, we fabricated both n–i–p and p–i–n perovskite solar cells and performed bias-dependent electrochemical impedance spectroscopy (EIS) measurements [3] to gain insights into their interfacial charge transport and kinetic processes. Our results indicate that, although n–i–p devices exhibit higher efficiency, p–i–n structures show significantly reduced ionic conduction, minimizing electrochemical reactions at the interfaces. We have quantified electronic-ionic parameters such as interfacial capacitance, ionic conductivity and recombination resistances. Overall, this study provides mechanistic insights into interfacial phenomena governing device performance and stability, shedding light on pathways to design more durable perovskite solar cells.

Keywords: perovskite solar cell, electrochemical impedance spectroscopy, n–i–p, p–i–n

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TEMPERATURE STABILITY AND RADIATION HARDNESS OF GaP/Si HETEROJUNCTIONS GROWN BY PE-ALD

Alexander Gudovskikh [1,2], Alexander Uvarov[1], Artem Baranov [1], Vyacheslav Pozdeev[1,2], Alina Maksimova[1,2], Ekaterina Vyacheslavova[1], Oleg Mikhailov[1], Ernst Yarchuk[1,2]

[1] St. Petersburg Alferov University, St. Petersburg, Russia
[2] St. Petersburg Electrotechnical University "LETI", St. Petersburg, Russia

*gudovskikh@spbau.ru

GaP/Si heterojunctions are of interest for photovoltaic application as the bottom junction of multijunction solar cells grown on Si substrates, as well as single-junction Si-based solar cells. GaP is an indirect wide-bandgap (2.26 eV) semiconductor that is lattice-matched to Si. Therefore, GaP is a promising candidate for direct epitaxial growth on Si to form a wide-bandgap window with low interface defect density [1]. Recently, epitaxial growth of a thin GaP layer on Si was achieved by plasma deposition at 380 °C, which provides the capability for low-cost, high-throughput mass production of GaP/Si solar cells [2]. The significant valence band offset (0.6-0.8 eV) and relatively low conduction band offset (0.3-0.4 eV) at the GaP/Si interface make GaP an effective electron-selective contact to Si [3]. In this case, an anisotype n-GaP/p-Si heterojunction is more preferable configuration. On the other hand, solar cells based on p-type Si wafers are of interest for low-Earth orbit space application due to their higher radiation hardness compare to n-type Si. However, the temperature stability of the GaP/Si interface fabricated by plasma at low temperature is the key point for its integration into multijunction devices, while radiation hardness is essential for space application. In this work, the influence of thermal annealing and electron irradiation on n-GaP/p-Si heterojunctions fabricated by PE-ALD are studied. The n-GaP/p-Si heterojunctions and test solar cells with Al BSF and Ag/Au contact grid were annealed in the range of 500-700°C and irradiated with 1 MeV electron fluences of $5 \cdot 10^{14}$ and 10^{15} cm^{-2}. Interface properties were studied by Hall measurements of the n-GaP and the inversion layer formed in Si near the GaP/Si interface due to band discontinuities. Additionally, EQE, dark and illuminated I-V curves and their temperature dependence, as well as capacitance spectroscopy, were used for interface characterization of the test solar cells. High temperature stability and radiation hardness of the n-GaP/p-Si interface was observed. The observed degradation of solar cell performance after electron irradiation is due to defects generated in the Si bulk and is not related to GaP/Si interface degradation.

Acknowledgements

This work was supported by the Russian Science Foundation under grant number 24-19-00150.

Keywords: heterojunction solar cell, GaP, PE-ALD, GaP/Si interface

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A DIGITAL VOUCHER SYSTEM FOR RENEWABLE ENERGY COMMUNITIES: APPLICABILITY ANALYSIS ACROSS AGRI-FOOD SME TYPOLOGIES IN TÜRKIYE

Fırat Salmanoğlu [1], Harun Gümüş[1], Gökhan Devekıran[1], Mete Çubukçu[1]

[1] Ege University/Solar Energy Institute, İzmir, Türkiye

* mete.cubukcu@ege.edu.tr

Agri-food SMEs in Türkiye face a structural energy cost problem intensified by an 87% rise in industrial electricity prices between 2020 and 2023. Renewable Energy Communities (RECs) offer a collective solution, yet their governance models rarely account for the heterogeneous energy profiles and operational rhythms of different SME types — a mismatch that contributes to low participation and cooperative fragility. This paper proposes a Digital Voucher System (DVS) as a governance and settlement framework for agri-food RECs, and evaluates its applicability across three representative SME typologies in Türkiye: a cold storage facility, a dairy processing plant, and an irrigation cooperative. Each typology presents a distinct energy consumption profile, seasonality pattern, and input procurement structure. The DVS converts each member's share of collectively generated renewable energy into digital vouchers redeemable against agricultural inputs — feed, fertiliser, fuel, seeds — through supplier exchange agreements, embedding a transparent, verifiable settlement layer into REC operations. Analysis shows that the DVS offers the strongest fit for continuous, high-baseload consumers such as cold storage and dairy facilities, where predictable energy flows enable stable voucher generation and redemption cycles. Irrigation cooperatives present greater seasonal variability, requiring adaptive allocation rules but offering high potential for input cost reduction during peak agricultural periods. Across all three typologies, the DVS addresses the primary reported cause of cooperative breakdown in Türkiye: the perceived unfairness of opaque benefit distribution among members. The paper concludes that settlement transparency, rather than capital access alone, is the critical design variable for durable agri-food RECs.

Acknowledgements

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Keywords: Renewable Energy Communities, Digital Voucher System, agri-food SMEs, cooperative governance

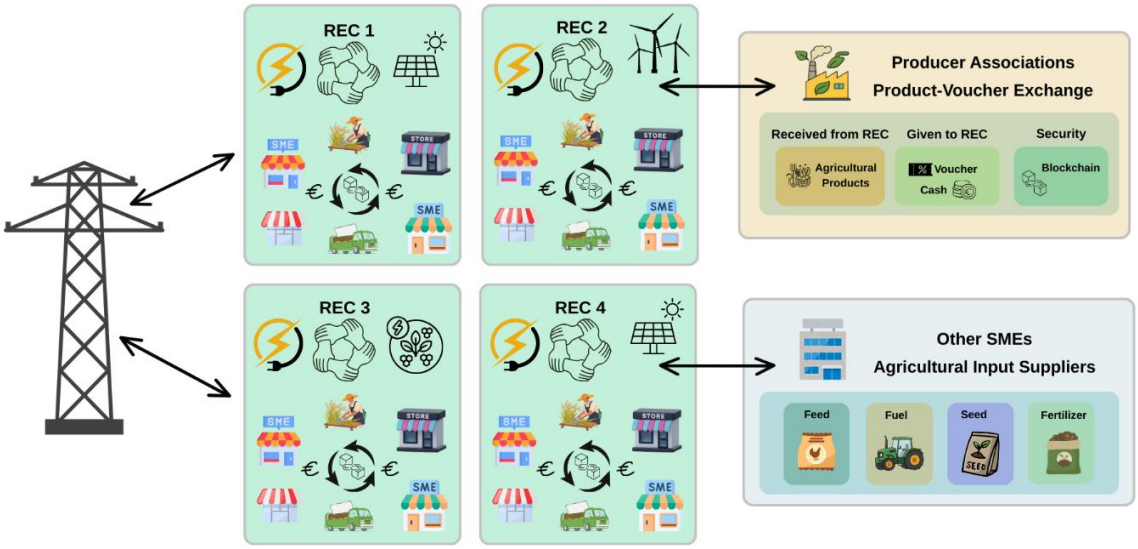


Figure 1. Ecosystem Architecture of the Digital Voucher System within Agri-Food Renewable Energy Communities

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INTEGRATED AGRIVOLTAIC DESIGN APPROACHES IN TÜRKİYE: FROM TRANSMISSIVE PV SYSTEMS TO SPECTRAL OPTIMIZATION USING GCC PANELS

Duygu Kuzyaka[1], Ömer Yalçın[1], Talat Özden[1]

[1] The Center for Solar Energy Research and Applications (GÜNAM), Middle East Technical University (METU), Ankara 06531, Türkiye

*Corresponding Author's E-mail: duygu.kuzyaka@odtugunam.org

Agrivoltaic (AgriPV) systems offer a promising pathway to reconcile land-use competition between food and energy production under increasing climate variability. In Türkiye, where diverse climatic zones and crop patterns impose distinct design constraints, the development of AgriPV systems demands location-specific optimization of light distribution, spectral composition, and system geometry [1–3]. This study presents integrated design, characterization, and early monitoring results from two complementary projects — the national S-ATP project and the EU Horizon project PV4Plants (Grant No. 101096409) — co-deployed on a shared single-axis East–West tracking structure at TAT Gıda's research field in Mustafakemalpaşa, Bursa. The installation comprises three sub-systems totalling ~68 kWp DC across 1,288 m² of AgriPV area, each paired with an open-field reference plot, sharing a 23% ground coverage ratio and a 5 m minimum clearance height. Within the S-ATP framework, bifacial PERC module configurations with optimized coverage ratios and elevation strategies were developed, supported by photosynthetic photon flux density (PPFD) based light-distribution modelling for pea and processing tomato cultivation. AgriPV configurations are projected to reduce peak-hour radiation stress while offering required PPFD values specific to crops. The PV4Plants component introduces panels with luminescent glass color converter re-emitting absorbed blue–green light as red light. The combined findings demonstrate that AgriPV performance in Türkiye is strongly dependent on multi-parameter optimization spanning panel transparency, spectral engineering, layout geometry, and crop-specific light thresholds. Ongoing first-season monitoring at the Bursa site, encompassing energy yield metrics and agronomic assessment of crops, is expected to provide quantitative validation of the projected benefits.

Acknowledgements

This work has been supported by the Horizon Europe project "AgriPV system with climate, water and light spectrum control for safe, healthier and improved crops production" (acronym: PV4Plants), Grant Agreement No: 101096409, and the TÜBİTAK 1004 project "Türkiye Tarimsal Üretiminde Küresel İklim Değişikliğine Uyumlu Sürdürülebilir Tarim Teknolojileri Platformu" (acronym: S-ATP), Project No: 23AG020, and is presented as the scientific outputs of these projects.

Keywords: Agrivoltaics, Transmissive PV, GCC Panels, Spectral Engineering, PPFD, Crop Yield Optimization



Figure 1. Photograph of the agrivoltaic system setup.

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Full-Process Development of Large-Area Rigid and Flexible Perovskite Modules Using Scalable Slot-Die Coating and Drying Technologies

Katsumi Araki[1]

[1] Alpha Precision Systems Inc / International Business, Texas, USA

*karaki@alphaps.co

Introduction

Perovskite solar cells are widely recognized as a promising next-generation photovoltaic technology due to their high efficiency potential and low-temperature processability. However, the transition from laboratory-scale devices to large-area, manufacturable modules remains a major challenge. In particular, achieving uniform film formation, process reproducibility, and stable device performance on large rigid and flexible substrates requires manufacturing-oriented process development rather than laboratory-scale optimization.

This work presents a full-process development approach for large-area perovskite modules, focusing on scalable coating, drying, and integration technologies suitable for industrial manufacturing environments. Instead of pursuing record efficiencies at small scale, the objective is to establish a reproducible and scalable process platform that supports rigid and flexible module fabrication using the same core manufacturing concepts.

Approach

All core process tools, including slot-die coating systems, vacuum drying units, and thermal drying equipment, were developed in-house to enable precise control over coating uniformity, solvent removal, and crystallization behavior. This integrated process platform allows continuous scalability from small-area devices to large-area modules without fundamental changes in process architecture.

Two in-house pilot lines were established with substrate formats of 300 × 300 mm² and 1200 × 600 mm². The 300 × 300 mm² line was used for rapid process optimization, device structure development, and material screening, while the 1200 × 600 mm² line was dedicated to scale-up validation, uniformity control, and large-area manufacturability assessment on both rigid and flexible substrates.

Material development was conducted in parallel with process development through collaborations with academic partners, with a strong emphasis on manufacturability, slot-die coating compatibility, and robustness against process fluctuations. In addition, simplified device architectures were explored through a comparative study of conventional C60-based electron transport layers and C60-free device structures, aiming to reduce process complexity and improve large-area manufacturing compatibility.

Results

Using the 300 × 300 mm² rigid substrate pilot line, stable power conversion efficiencies of approximately 22% were achieved, demonstrating a reproducible baseline process suitable for scale-up.

On the 1200 × 600 mm² pilot line, both rigid and flexible perovskite modules were successfully fabricated. The rigid modules demonstrated efficiencies exceeding 20%, while flexible modules of the

same format exhibited comparable performance, confirming the scalability of the developed processes across different substrate types.

Comparative studies between C60-based and C60-free architectures showed that C60-free devices achieved competitive efficiencies while enabling a simplified process flow. Preliminary stability trends indicate that C60-free structures exhibit promising behavior under operational conditions, supporting their potential suitability for manufacturing-oriented device architectures.

Uniform and stable coating was achieved across the entire 1200 × 600 mm² area using slot-die coating, with no critical thickness variations or coating-induced defects observed. This confirms that the developed equipment design and process control strategy are suitable for large-area perovskite module manufacturing.

Conclusion

This study demonstrates a scalable full-process development platform for large-area rigid and flexible perovskite modules based on slot-die coating and scalable drying technologies. By integrating equipment development, process optimization, and material design, a reproducible manufacturing-oriented process was established that supports smooth scale-up from 300 × 300 mm² devices to 1200 × 600 mm² modules.

The successful fabrication of high-efficiency rigid and flexible large-area modules, together with simplified C60-free device architectures and demonstrated coating uniformity, indicates that the developed process platform provides a practical pathway toward industrial-scale manufacturing of perovskite photovoltaics.

Keywords: Perovskite, Slot-die, Vaccum dry, Flexible, Rigid, C60-free, PiN, Large-scale

Figure 1. Process flow and module structure (300 × 300 mm² and 1200 × 600 mm²).

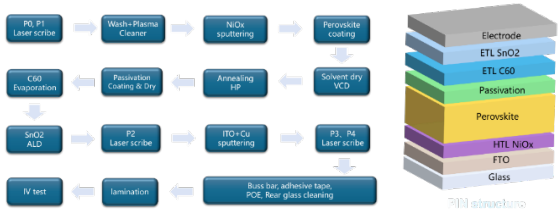


Figure 2. Photographs of representative 1200 × 600 mm² rigid and flexible perovskite modules.

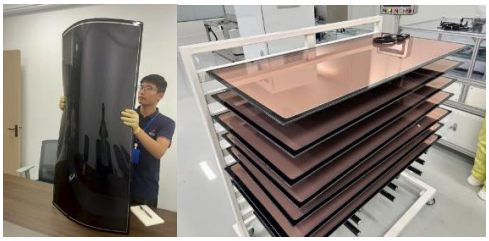
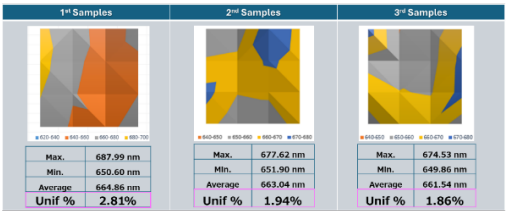


Figure 3. summarizes the efficiency data of C60-based and C60-free devices.

Panel Data with Tinfab ETL

Pmax/W	Isc/A	Voc/V	Voc/V	Ipm/A	Vpm/V	FF	Rs/Ω	Eff	Jsc(mA/cm²)
15.058	0.435	47.062	1.148	0.389	38.700	0.736	10.148	22.243	25.710

Figure 4. Coating uniformity and performance distribution across 1200 × 600 mm² glass substrates.



Indoor Photovoltaic Performance of GaAsNP Solar Cells: Impact of Bandgap Engineering and Antireflection Coatings Compared with AlGaAs and InGaP

Volkan KIZILOĞLU[1]

[1] Erzurum Technical University/Department of Electrical and Electronics Engineering, Erzurum, Türkiye

*volkan.kiziloglu@erzurum.edu.tr

Indoor photovoltaic technologies have gained significant attention as a sustainable power source for Internet-of-Things (IoT) devices operating at ultra-low power levels. Unlike outdoor solar irradiation, indoor illumination is characterized by low intensities (100–1000 lx) and a narrow spectral distribution primarily in the visible range, leading to different optimization requirements for photovoltaic devices. Under indoor illumination, wide-bandgap materials (~1.8–2.0 eV) can achieve higher conversion efficiencies by reducing thermalization losses [1].

Recent studies have shown that GaAsPN alloys offer a tunable bandgap of ~1.4–1.9 eV and strong optical absorption coefficients exceeding 10^4 cm^{-1}, making them highly suitable for photovoltaic applications [2], [3]. In this study, the performance of GaAsNP-based solar cells is numerically investigated for indoor energy harvesting applications using a drift–diffusion model coupled with optical simulations. The device behavior is analyzed under multiple indoor light sources, including 2700 K, 4000K, 6500K LED and 4000K fluorescent illumination.

The results are compared with AlGaAs and GaInP solar cells, which are wide-bandgap materials proposed for indoor photovoltaics [4]. The results indicate that GaAsNP provides competitive performance under indoor illumination, with improved spectral matching capability compared to conventional materials. Furthermore, the implementation of anti-reflection coating (ARC) significantly enhances device efficiency under low-intensity conditions.

Overall, this study demonstrates that due to its tunable bandgap and strong absorption, GaAsNP is a promising candidate for indoor photovoltaic applications and offers a flexible platform for self-powered IoT systems.

Keywords: Indoor Photovoltaics, GaAsNP, Bandgap Engineering, Antireflection Coating, IoT Energy Harvesting

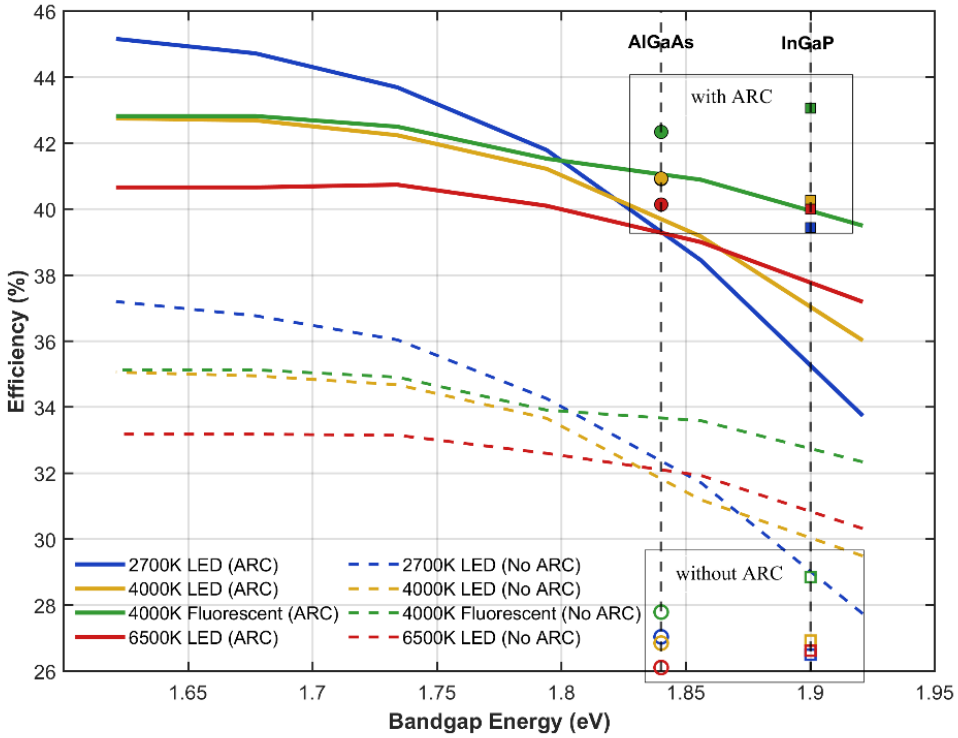


Figure 1. Figure 1. Simulated power conversion efficiency as a function of absorber bandgap energy for different indoor illumination sources. Solid lines represent devices with anti-reflection coating (ARC), while dashed lines indicate the performance without ARC. The considered spectra include 2700 K LED, 4000 K LED, 4000 K fluorescent, and 6500 K LED. Vertical dashed lines denote the bandgap energies of AlGaAs (~1.84 eV) and InGaP (~1.90 eV). Markers indicate the corresponding efficiency values of these benchmark materials under each illumination condition, both with and without ARC.

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Additive Engineering of PEAI-based Additives for High-Efficiency Indoor Perovskite Photovoltaics

Yagmur Yaren Kurnaz[1,2], Ozer Ege Tankut[1,2], Bahri Eren Uzuner[2], Zeynep Gozukara Karabag[2], Gorkem Gunbas[1,2,3,4] , Selcuk Yerci[2,4,5], Aliekber Karabag[*2]

[1]Department of Chemistry, Middle East Technical University (METU), 06800, Ankara, Turkiye
[2]Center for Solar Energy Research and Applications (ODTU-GUNAM), METU, 06800, Ankara, Turkiye
[3]Department of Polymer Science and Technology, METU, 06800 Ankara, Turkiye
[4]Micro and Nanotechnology Department, METU, 06800, Ankara, Turkiye
[5]Electrical Engineering Department, METU, 06800, Ankara, Turkiye

*Corresponding author: aliekber.karabag@odtugunam.org

The rapid expansion of the Internet of Things (IoT) ecosystem has increased the demand for sustainable, self-powered microelectronics, including wireless sensors and wearable devices, which typically operate at microwatt-to-milliwatt power levels. However, powering a large number of IoT devices remains a practical challenge, since frequent battery replacement or wired power supply is costly, inconvenient, and unsustainable. Harvesting ambient indoor light using photovoltaic cells offers a promising route to extend device lifetime and enable self-powered operation. Unlike outdoor solar cells, indoor photovoltaics must harvest the energy from low intensity artificial power sources, such as light emitting diodes (LEDs) and fluorescent lamps, which requires the absorber materials with suitable bandgaps and tunable optoelectronic properties. Thus, perovskite photovoltaics (PVK-PVs) are well suited for indoor purposes, because of their tunable bandgap, high absorption coefficients, long carrier diffusion lengths and high defect tolerances.[1] Owing to these properties, indoor PVK-PVs have progressed rapidly, with recent reports demonstrating power conversion efficiencies (PCEs) exceeding 40% under artificial illumination. Among the strategies used to improve indoor PVK-PV performance, additive engineering of the perovskite precursor solution is a promising route, since it provides precise control over film crystallization and grain boundary passivation. PEAI salt and their derivatives are known by their ability to form low-dimensional perovskite phases at grain boundaries and effectively passivating defects.[2] However, the relationship between the molecular structure of PEAI-derived salts and their effectiveness as bulk precursor additives in different cell architectrues in PVK-PV remains unsufficently understood.

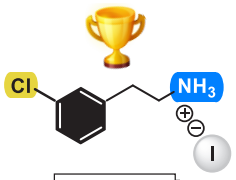
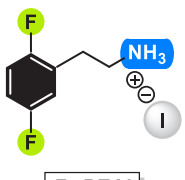
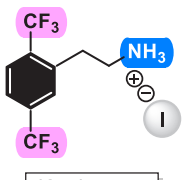
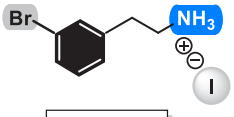
In this study, a molecularly engineered sixteen PEAI-based ammonium salts, was systematically evaluated as precursor additives in the perovskite layer of p–i–n type indoor PVK-PVs. An initial concentration optimization at 0.50, 0.75, and 1.00 mg mL^{-1} identified 0.75 mg mL^{-1} as the optimal additive loading. This concentration was therefore adopted for the systematic evaluation of the full library of 16 PEAI-based additives. As summarized in **Table 1** and **Figure 1**, the **reference cell** showed a champion **PCE of 30.12% under 1000 lux LED illumination**, with an open circuit voltage (V_{OC}) of **0.83 V**, short-circuit current density (J_{SC}) of **123.5 µA cm^{-2}**, and a fill factor (**FF**) of **83.12%**. Among the screened additives, ***m*-Cl-PEAI**, ***m*-Br-PEAI**, **F_2-PEAI** and **$(CF_3)_2$-PEAI** emerged as the most substantial improvements in cell performances. Notably, ***m*-Cl-PEAI** achieved an enhanced **V_{OC} of 0.88 V**, a **J_{SC} of 129.2 µA cm^{-2}**, and a **FF of 84.93%,** yielding a champion **PCE of 33.20%**. Overall, these results highlight the potential of chemically tailored PEAI-based additives to advance the efficiency of indoor PVK-PVs.

Acknowledgements

This study was supported by Scientific and Technological Research Council of Türkiye (TUBITAK) under the Grant Number of **124F194**. The authors thank to TUBITAK for their supports. The authors also thank ODTU-GUNAM for access to synthesis, characterization, and cell fabrication facilities.

Keywords: Additive engineering, Indoor photovoltaics, PEAI-based additives, Perovskite solar cells

Table 1. Chemical structures of the best-performing PEAI-derived additives in p–i–n type PSCs: **F_2-PEAI**, **$(CF_3)_2$-PEAI**, ***m*-Cl-PEAI**, and ***m*-Br-PEAI**.

Moleculars structure of best-performing additives (bp-ADDs), incorporated in p-i-n type PSCs	 ***m*-Cl-PEAI**	 **F_2-PEAI**	 **$(CF_3)_2$-PEAI**	 ***m*-Br-PEAI**
PCE (%) of bp-ADDs-integrated PSCs	**33.20%**	**32.46%**	**32.14%**	**31.88%**
PCE (%) of reference cell	**30.12%**			
p-i-n type PSCs architecture	Glass/ITO/NiO_x/**CsFAMA+bp-ADDs**/LiF/C_{60}/BCP/Cu			

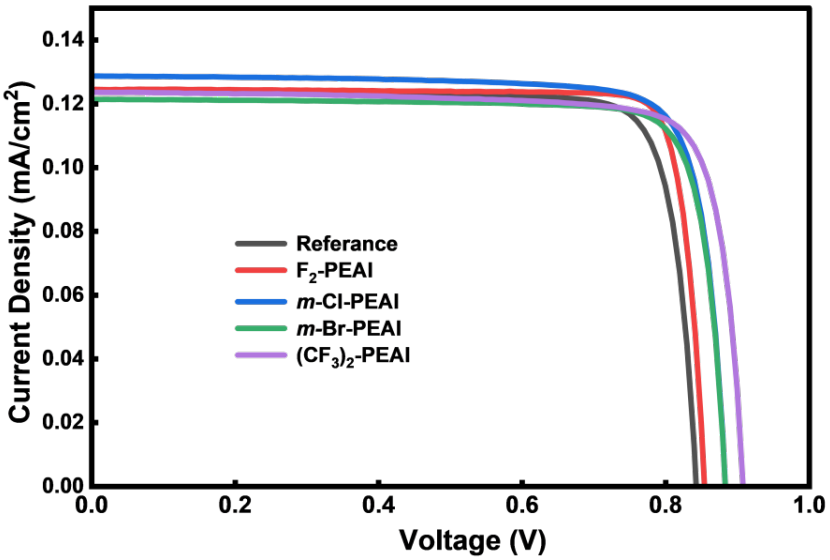


Figure 1. *I–V* curves of the best-performing PEAI-derived additives in p–i–n type PSCs under 1000 lux indoor illumination.

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An Improved PSO MPPT Using Reduced Error Pruning Model Tree for Partially Shaded PV Systems

Ahmed Bouhouta [1], Hanane Hadjab [2]

[1] Research Laboratory of Electrical Engineering & Automatic, LREA, University of Medea, Algeria

[2] University of Science and Technology Mohamed Boudiaf Oran, Algeria

Corresponding Author's E-mail: bouhouta.ahmed@gmail.com

Maximum power point tracking (MPPT) techniques based on bio-inspired algorithms such as particle swarm optimization (PSO) often face challenges due to their slow convergence, oscillatory behavior near the global optimum, resulting in power loss and a large search space that can increase tracking time, especially under conditions of rapid change irradiance or partial shading. To address these limitations, this paper introduces an intelligent regression approach that integrates the global search capabilities of the PSO algorithm with the fast and accurate decision-making of the reduced error pruning (REP) model tree. The proposed PSO-REPTree technique first uses PSO for global exploration under partial shading and then leverages a REPTree to learn and replicate its optimal decision-making process. This learned model is translated into a compact set of if-else rules, eliminating iterative calculations and enabling fast and accurate tracking time of the true global maximum power point (GMPP). Through extensive simulation and FPGA-in-the-loop (FIL) experiments conducted on an Altera board, the proposed MPPT exhibits superior performance compared to both conventional PSO and existing hybrid PSO variants, attaining an exceptionally rapid tracking time of 0.05 seconds without oscillations. Furthermore, it demonstrates remarkable robustness, sustaining a near-optimal MPPT efficiency of 99.84% even under complex partial shading.

Keywords: Global maximum power point tracking, Reduced error pruning decision tree, Particle swarm optimization, Photovoltaic system, Partial shading.

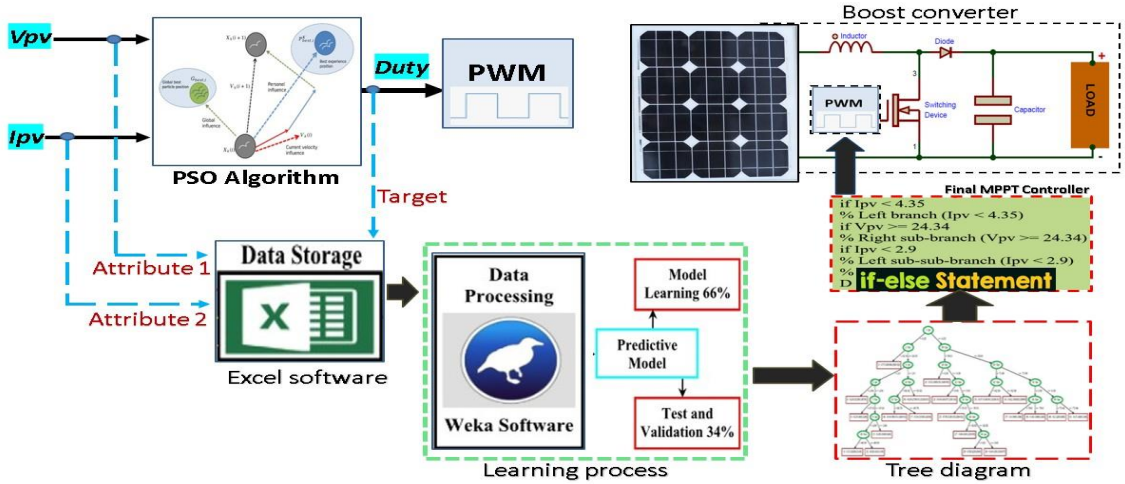


Figure 1. Chain scheme of the proposed algorithm

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Hybrid Co-Evaporation of Perovskite Solar Cells Under Open Air Conditions Using Automated Spin Coating: Optimization of PbI_2 to Perovskite Conversion

Cem Maden[1],Mohammad Dehnavi[1], Eren Uzuner[1], Selçuk Yerci*[1,2]

[1] *ODTU GUNAM, Middle East Technical University, Çankaya, Ankara 06800, Türkiye*
[2] *Department of Electrical Electronics Engineering, Middle East Technical University, Cankaya, Ankara 06800, Türkiye*
*syerci@metu.edu.tr

Perovskite solar cells have emerged as a leading candidate for next generation photovoltaics, yet scalable and industrially viable fabrication remains a critical challenge. In this work, we present our efforts toward open air perovskite layer fabrication using a hybrid co-evaporation approach, where PbI_2 is deposited via physical vapor deposition (PVD) and subsequently converted to $CsBrFAPbI_3$ perovskite through an automated spin coating process utilizing the SCIPRIOS Spinbot system. This transition from nitrogen filled glovebox processing to ambient conditions introduces significant challenges, particularly regarding uncontrolled rapid crystallization, which can compromise film homogeneity and device performance.

To address these challenges, we systematically optimizing the conversion recipe through a multi characterization approach aimed at understanding the conversion mechanism rather than solely targeting device performance. Optical imaging confirms the visual transformation from the yellow PbI_2 layer to the dark perovskite film, while photoluminescence imaging provides spatial insight into crystallization homogeneity across the film surface (Figure 1). X-ray diffraction analysis reveals the evolution of phase composition, capturing the suppression of residual PbI_2 and the emergence of a well defined perovskite diffraction peak as key indicators of conversion quality (Figure 2A). Current density–voltage characteristics serve as a functional validation of the conversion process at this early stage of development, reflecting the direct impact of film quality on charge transport and collection (Figure 2B). Together, these characterization tools form the foundation for a systematic optimization strategy toward a reproducible, ambient compatible fabrication route suitable for industrial upscaling.

Keywords: hybrid co-evaporation, Perovskite Conversion, Automated Spic Coating, Ambient fabrication, Photoluminescence, XRD

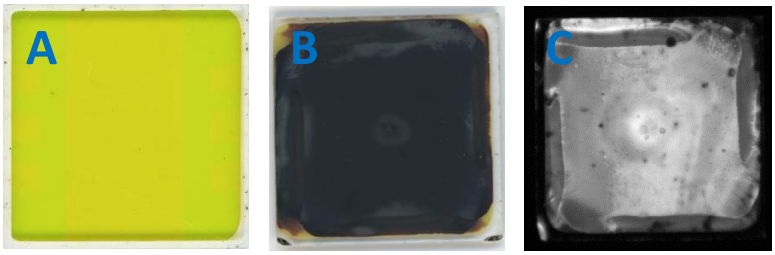


Figure 1. A) Optical images of the evaporated PbI_2 layer, B) the converted perovskite film, illustrating the visual transformation upon conversion under open air conditions. C) Photoluminescence image of the perovskite layer provides spatial insight into crystallization homogeneity across the film surface.

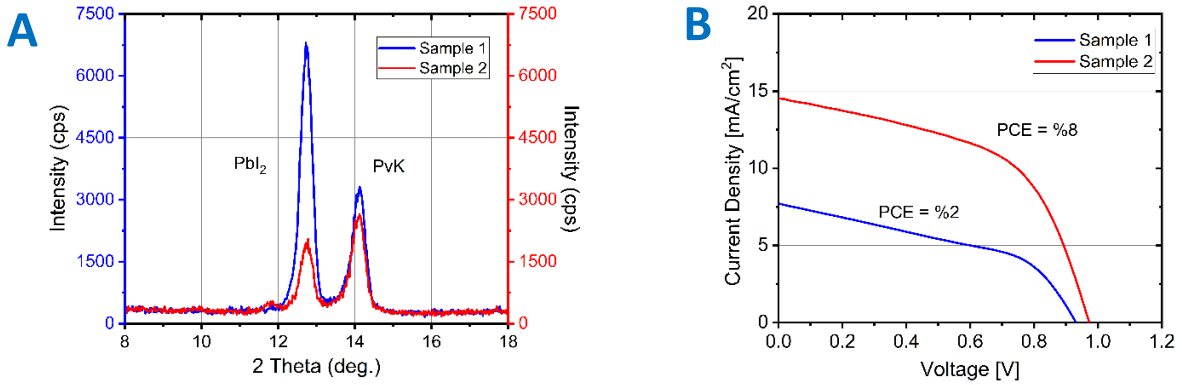


Figure 2. A) XRD patterns of two representative samples showing the evolution of phase composition: the suppression of the residual PbI_2 peak and the emergence of the perovskite diffraction peak serve as key indicators of conversion quality. (B) Current density–voltage characteristics of the corresponding samples, used as functional validation of the conversion process at this early stage of development.

Investigation of Al-Si Rear Contact Formation for iTOPCon Solar Cells

Melisa K. Arslan[1*], Seda K. Ünver, Aysel B. Uluşan[1], Raşit Turan[1,2], Veysel Ünsür [3]

[1] ODTU-GUNAM, Middle East Technical University, 06800 Ankara, Türkiye
[2] Department of Physics, Middle East Technical University, 06800 Ankara, Türkiye
[3] Department of Electrical and Electronics Engineering, Necmettin Erbakan University, 42090 Konya, Türkiye
*melisa.arslan@odtugunam.org

The rapid transition from PERC to iTOPCon solar cell technology has significantly increased the consumption of silver (Ag) in metallization, creating a major cost and sustainability challenge for large-scale photovoltaic manufacturing. TOPCon has already surpassed PERC in market share and is projected to dominate future production due to its high efficiency potential (>27%) [1,2]. This study investigates the feasibility of Al-Si-based screen-printable pastes as a low-cost alternative to conventional Ag rear contacts in commercial n-type TOPCon solar cells.

M10 iTOPCon cells were processed using laser contact openings (LCO) followed by screen-printing of two Al-Si pastes with different Si contents (~15% and ~40%) and a reference Ag paste. Co-firing was performed in the temperature range of 660-820 °C to evaluate the impact of thermal budget on contact formation. Electrical characterization was carried out using the Transfer Length Method (TLM), while interfacial morphology was analyzed via scanning electron microscopy (SEM).

The Ag reference exhibited stable contact resistivity values of ~0.68-0.78 mΩ·cm² at 780-800 °C, consistent with industrial firing conditions [3]. In contrast, Al-Si pastes required lower optimal firing temperatures for effective contact formation. Al-Si (15% Si) achieved a minimum contact resistivity of ~0.53 mΩ·cm² at 720 °C, outperforming the Ag reference under optimized conditions. However, both insufficient and excessive firing led to degraded electrical performance, highlighting a narrow process window. The higher Si-content paste showed delayed contact formation and higher resistivity (~1.4 mΩ·cm² at 740 °C), consistent with previously reported challenges in Al-based contacts on n-type silicon [6,7]. Line resistivity measurements further confirmed the competitive performance of Al-Si contacts, with ~0.1 Ω·cm for low-Si paste compared to ~1 Ω·cm for Ag counterparts. SEM analysis revealed that contact formation is governed by Al penetration into the n^+ poly-Si layer, which increases with firing temperature and directly impacts electrical behavior.

These results demonstrate that Al-Si pastes can form stable ohmic contacts on n-type TOPCon structures when properly optimized. The findings highlight the strong potential of Al-based metallization for reducing Ag consumption while maintaining electrical performance, supporting ongoing efforts toward Ag-reduced or Ag-free photovoltaic technologies [4,5].

Acknowledgements

This work was supported by TÜBİTAK (The Scientific and Technological Research Council of Türkiye) under the 1004 - Excellent Research Infrastructure Program (Project No: 20AG010 & 124C196).

Keywords: Al-Si Metallization, Silver Reduction, Fast Firing, Laser Contact Opening (LCO), TOPCon

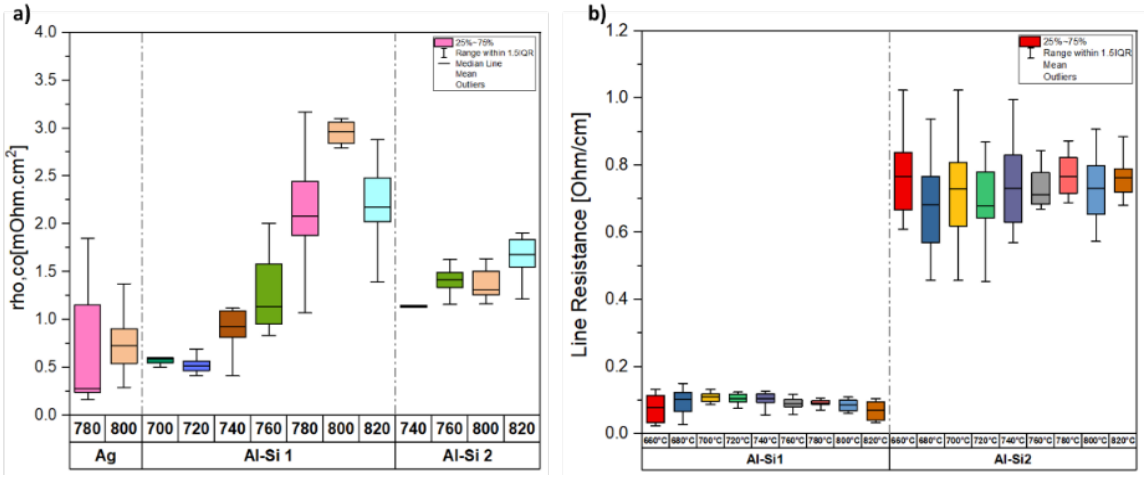


Figure 1. a) Contact resistivity for different peak T for Ag, Al-Si, and Al-Si 2, and b) line resistivity for the Al-Si contacts.

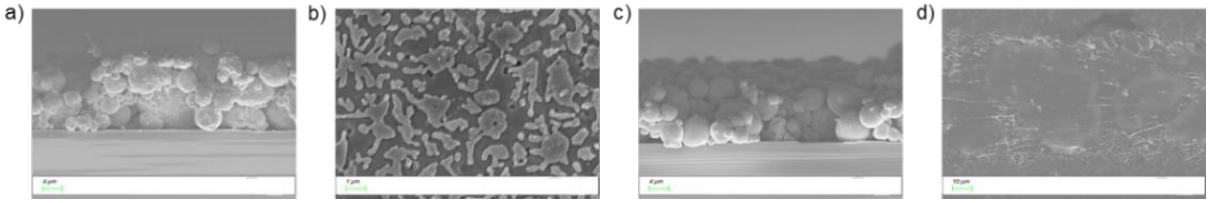


Figure 2. SEM micrographs of Al-Si 1 contacts: (a) cross-sectional view before etching at 660 °C, (b) corresponding etched surface revealing the Al-Si/poly-Si interface, (c) cross-sectional view before etching at 800 °C, and (d) etched surface after firing at 800 °C.

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Redefining TCO Design Rules for Perovskite Solar Cells in Indoor Environments

M. Mustafa ÇODUR[1,2], Mustafa YAŞA[1], Görkem GÜNBAŞ[1,2,3]*, Selçuk YERCİ[1,2,4]*

[1] ODTU-GÜNAM, Middle East Technical University, Ankara 06830, Türkiye
[2] Department of Micro and Nanotechnology, Middle East Technical University, Ankara 06830, Türkiye
[3] Department of Chemistry, Middle East Technical University, 06800 Ankara, Türkiye
[4] Department of Electrical-Electronics Engineering, Middle East Technical University, Ankara 06830, Türkiye

*ggunbas@metu.edu.tr;syerci@metu.edu.tr

The rapid expansion of the Internet of Things (IoT) ecosystem—projected to reach nearly 29.7 billion connected devices by 2027—has created a growing demand for reliable, efficient, and sustainable power sources for indoor electronic systems [1]. Indoor photovoltaics (IPVs) have emerged as a promising solution, enabling energy harvesting under artificial lighting conditions. However, achieving high device performance under indoor illumination requires photovoltaic architectures specifically adapted to low-light operation. Under such conditions, the generated current density is reduced by more than two orders of magnitude compared to standard AM1.5G illumination, fundamentally altering the relative importance of electrical loss mechanisms. In conventional solar cell design, series resistance—dominated in part by the sheet resistance of the transparent conductive oxide (TCO)—plays a critical role in limiting performance, necessitating relatively thick TCO layers (e.g., >150 nm for Indium Tin Oxide). In contrast, under indoor illumination, the significantly reduced current diminishes the impact of series resistance, while recombination and shunt-related losses become more prominent. Despite this shift in operational regime, the implications for TCO design in perovskite-based IPVs remain largely unexplored.

In this work, we investigate the effect of TCO thickness on the performance of perovskite solar cells under indoor lighting conditions. Using a combination of Transfer Matrix Method (TMM) and a single-diode electrical model, we perform a comprehensive optoelectrical analysis to evaluate device behavior across a wide range of TCO thicknesses. Our results reveal that, under indoor illumination, the power conversion efficiency remains nearly unaffected even when the TCO thickness is reduced to only a few nanometers. In stark contrast, under AM1.5G illumination, device performance rapidly deteriorates with decreasing TCO thickness, approaching zero efficiency in the ultrathin limit. These findings establish a new design paradigm for perovskite-based indoor photovoltaics, demonstrating that TCO layers can be significantly thinned without compromising device performance. This not only enables reduced material consumption and cost but also opens pathways toward alternative TCO materials with lower conductivity requirements, offering important implications for scalable and sustainable IPV technologies.

Keywords: Indoor photovoltaics, Perovskite solar cells, Thickness optimization, Transparent conductive oxide

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Meteorological sensitivity and production stability of rooftop and floating photovoltaic systems: a comparative machine learning analysis

Hilal Çapkan[1], Bilge Sıla Çevik[1], Ceyda Aksoy Tırmıkçı[1]

[1] Sakarya University/Electrical and Electronics Engineering, Sakarya, Türkiye

bilge.cevik@ogr.sakarya.edu.tr

This study investigates the impact of meteorological conditions on solar energy generation by comparing rooftop and floating photovoltaic (PV) systems under identical environmental conditions. The rooftop PV system, located on the M6 building of Sakarya University, was analyzed using real production data obtained from panels with different orientations (east, west, south, and flat/horizontal). In contrast, the floating PV system, modeled for Reisler Okçular Pond, was evaluated using simulation data generated through PVsyst/PVsis. For the rooftop PV system, Random Forest and Extreme Gradient Boosting regression models were applied to analyze the relationship between meteorological parameters and power generation. In contrast, the floating PV system was analyzed based solely on simulation data, without the use of machine learning methods. The results show that rooftop PV systems are highly sensitive to panel orientation and short-term meteorological variations. The flat/horizontal panel configuration achieved the highest specific yield, reaching 97.50 kWh/kWp in May 2025, which is approximately 136–146% higher than the south-, east-, and west-oriented panels. On the other hand, the floating PV system achieved a specific yield of 160.24 kWh/kWp during the same period and maintained a stable production profile despite approximately 32.5% cloud cover. This stability is attributed to the microclimatic effects of the water surface, including natural cooling and additional irradiance from reflected radiation. Overall, the findings indicate that rooftop PV systems require careful orientation optimization due to their high sensitivity to environmental conditions, whereas floating PV systems offer more stable and reliable performance due to their inherent environmental advantages.

Acknowledgements

We would like to express our sincere gratitude to Assoc. Prof. Ceyda Aksoy Tirmikci for her valuable guidance, insightful comments, and continuous support throughout this research.

Keywords: Floating PV, Rooftop PV, photovoltaic systems, meteorological parameters, machine learning, Random Forest, XGBoost.

INTEGRATED ENERGY PLATFORM: A PRINTABLE NANO-PASTE MULTILAYER SYSTEM FOR GENERATION, STORAGE AND THERMAL MANAGEMENT

K. Tosun[1] and B. G. Akinoglu[2]

1 METU, Earth System Science, Ankara, Türkiye and Suniversal Ltd.

2 METU, Dept. of Physics and Earth System Science, Ankara, Türkiye

*Corresponding Author's E-mail: info@suniversal.com.tr

Abstract

Conventional energy infrastructures address electricity generation, storage, and thermal management through separate, fragmented systems, leading to high costs, complexity, and inefficiencies, particularly in cold and low-light conditions [1]. Non-conventional energy systems such as solar cells and wind energy (including floating structures on water lands) are the main sources to attain less effects on global warming [2,3,4].

This work presents a next-generation integrated energy platform that unifies these three functions within a single printable panel architecture. The technological foundation is a printed nano-paste platform consisting of four functional layers: a solar active layer, an energy storage (battery) layer, a thermal management layer, and a conductive integration layer. Unlike conventional cell-based manufacturing, this layer-by-layer printing architecture eliminates external cabling, separate battery units, and additional heating systems.

Results demonstrate that the integrated panel generates electricity, stores energy within the same surface, actively prevents snow and ice accumulation, and maintains production under diffuse light conditions. This architecture reduces external battery dependency, lowers installation costs, enhances system safety, and ensures year-round energy continuity.

In conclusion, this innovative approach transforms energy generation from a passive surface into an active, self-sufficient module. This platform represents not merely a product innovation but a fundamental reconfiguration of energy infrastructure towards an integrated, scalable, and intelligent ecosystem suitable for residential, commercial, and industrial applications.

Keywords: Integrated energy platform, printable nano-paste, energy storage, thermal management, low-light performance, cold climate resilience.

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Satellite screen shots and next generation solar cells

E. Akyumuk[1], S. Ener Ruşen[2], İ. Turan[3] B. G. Akinoglu[4]

[1] METU Dept. of Physics and TENMAK, Ankara, Türkiye

[2] Karamanoğlu Mehmet Bey University, Energy Systems Engineering, Konya, Ankara, Türkiye

[3] METU Dept. of Physics, METU Ankara, Türkiye

[4] METU Dept. of Physics and Earth System Science, METU Ankara, Türkiye

The satellite images of the Earth surface can be used to estimate the solar irradiation all over the World [1]. Therefore, it is rather straightforward to give an estimate of how the use of conventional energy sources can be reduced, in rather long term; using renewables. Solar cells are the main device to attain this reduction so that to reduce the global warming.

High-resolution color satellite imagery is available through NASA and ESA. Polar imagery and all-satellite color images on the Earth surface play a critical role in investigating energy issues, ocean temperatures and their correlation with global warming. The colored satellite images can be used to resolve better the solar irradiation as it would be better than black-and-white images, which was studied before [1].

The useful energy produced by renewables has intermittency thus the production directly depends on seasonal (climatic) variations levels and though the latitude of the location. Therefore, colorized satellite images can be used to identify the intermittency of the useful energy output of the photovoltaic panels. Thus, this clarifies the effect of the climate variability on the solar cells to be used and photovoltaic panel structures. Therefore, study on the colored satellite images will give information on the levelized cost of energy (LCOE), levelized profit of energy (LPOE) and levelized revenue of energy (LROE) should be considered to obtain the payback for economic viability [2]. This wil thoughl help economic viability of the renewables [2].

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Preparation and Characterization of $MAPbI_3$ Thin Films Using Spin Coating Method

Merhan Kılıç, Teoman Özdal, Hamide Kavak
Çukurova University, Department of Physics, Adana, 01330, Turkey

*merhankilic@gmail.com

The $CH_3NH_3PbI_3$ ($MAPbI_3$) hybrid perovskite structure has emerged as a promising photoactive layer in the thin-film photovoltaic field due to its exceptional semiconductor properties. Furthermore, it is being investigated because of its strong visible light absorption and favorable optoelectronic properties thanks to its suitable optical band gap. However, its susceptibility to atmospheric conditions and rapid decomposition (PbI_2) continue to restrict and limit low-cost production methods. In this study, $MAPbI_3$ thin films were prepared under completely open-air conditions using a one-step spin coating process. To improve structural and optoelectronic properties, the parameters of temperature, solvent components, coating rate and time, and annealing temperature were investigated in solution preparation. It was observed that the produced $MAPbI_3$ thin films have a crystal structure in the (*110*) orientation and have stable optical absorption in the visible region.

Acknowledgements

This work was supported by the Research Fund of Çukurova University (Grant No FBA-2022-14410, FBA-2025-17549).

Keywords: Perovskites, $MAPbI_3$, Spin Coating, Thin Film.

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DETERMINANTS OF SOLAR HEAT FOR INDUSTRIAL PROCESSES ADOPTION IN TÜRKİYE

Fatma Ece Demirer[1], Gulsah Karakaya[1], Yelda Erden Topal[1]

[1] Middle East Technical University/Department of Business Administration, Ankara, Türkiye
*eced@metu.edu.tr

Industrial decarbonization is one of the central pillars of the energy transition. While renewable electricity has made substantial progress, industrial heat still relies heavily on fossil fuels. Given that process heat accounts for nearly two-thirds of total industrial energy consumption, decarbonizing industrial heat remains a significant challenge (IEA SHC, 2024). In this context, solar heat for industrial processes (SHIP) offers a promising solution, especially for low- and medium-temperature industrial applications. Türkiye possesses favorable conditions for SHIP adoption due to its abundant solar resources and substantial industrial energy demand. However, current SHIP adoption remains limited, indicating a pronounced gap between technical potential and actual adoption. Accordingly, this paper presents a literature-based assessment of the criteria shaping SHIP adoption from both government and industry perspectives, supported by preliminary findings from stakeholder interviews. Existing studies suggest that SHIP adoption is influenced by multiple and interrelated technical, economic, climatic, spatial, institutional, regulatory, and social factors. Preliminary interview findings, based on more than 10 interviews conducted over the past six months, are largely consistent with this structure. The literature further indicates that the adoption of SHIP and similar renewable energy technologies has often been examined through multi-criteria decision making methods. In this sense, the present study provides an initial basis for a future multi-criteria framework for decision makers by identifying the potential objectives and main criteria emerging from both the literature and the preliminary stakeholder findings. Thereby, the study contributes to ongoing discussions on solar energy policy design, social acceptance, and the broader socio-technical determinants of SHIP adoption in industrial contexts.

Acknowledgements

This study is supported by Scientific and Technological Research Council of Turkey (TUBITAK) under Grant Number 125K081.

Keywords: Solar industrial process heat, Solar heat, Solar thermal, Renewable energy, Multi-criteria decision making

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DEVELOPMENT OF A PHOTOVOLTAIC ENABLER INDEX (PVEI) AND ITS EFFECT ON PV ADOPTION IN TÜRKIYE

Furkan TÜZÜN[1], Pınar DERİN GÜRE[2], Erkan ERDİL[2]

[1]Social Sciences University of Ankara, Dept. of Economics, Ankara, Türkiye
[2]Middle East Technical University, Dept. of Economics, Ankara, Türkiye

*furkan.tuzun@asbu.edu.tr

Building upon the findings of Tüzün et al. (2025), this study examines the effect of previously identified factors on the installed capacity of license-exempt solar PV in Türkiye. The first step of the study consists of constructing the PV Enabler Index (PVEI) based on the drivers and challenges identified in Tüzün et al. (2025). The second step involves applications of panel regression with fixed-effects specifications to understand the effect of PVEI on the installed capacity of license-exempt electricity generation facilities. The results indicate a significantly positive association between the PVEI and the installed capacity of license-exempt electricity generation facilities in Türkiye. This means that the drivers and challenges of PV adoption revealed in a series of interviews with industrial stakeholders by Tüzün et al. (2025) do not suffer from sample selection bias by statistical evidence, and generalizable to the entire country. Thus, the PVEI can serve as a useful tool for public authorities in developing renewable energy policies that can be implementable in Türkiye, especially within the scope of license-exempt electricity generation by industrial sectors. By grounding econometric analyses directly on the results of the previously conducted qualitative study, this study provides new statistical insights into theorising firm decision-making in PV adoption/investment.

Keywords: Photovoltaics, License-exempt, Index, PV Adoption, Türkiye
JEL Codes: Q42, Q48, D22, C23

Figure 1. Correlation matrix for index components and installed capacity



Figure 2. Correlation matrix for PVEI variants and installed capacity

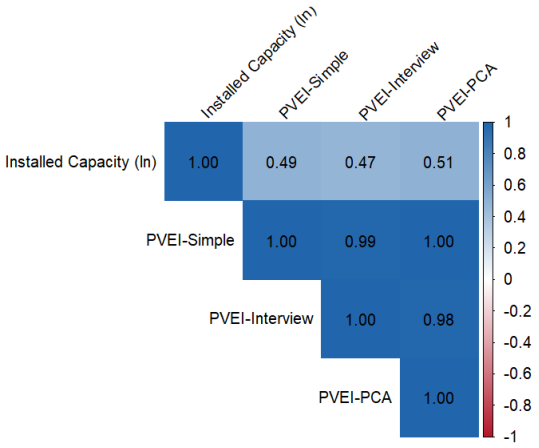


Table 1. Fixed-effects panel regression results

Dependent Variable: "Installed Capacity"

Independent Variable	Model Specification	Coeff.	R^2	Hausman P-Value
PVEI-Simple	Province FE	1.8689***	0.5593	0.0126
PVEI-Interview	Province FE	1.7701***	0.5309	0.0204
PVEI-PCA	Province FE	1.8708***	0.5828	0.0142

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Synthesis of Low Band Gap Energy Subporphyrazine Dye Materials and Their Potential Use in Photovoltaic Solar Cells

Serap Tere[a], Uğursoy Olgun[a,b], İlkay Şişman[a], Mustafa Gülfen[a,b]

[a]*Department of Chemistry, Sakarya University, 54187, Sakarya, Turkey*

[b]*Polimer Malzeme ve Teknolojileri Araştırma Uygulama Merkezi (Polimer Tekmer), Araştırma-Geliştirme Uygulama ve Araştırma Merkezi (Sargem), Sakarya University, 54187, Sakarya, Turkey*

The organic photovoltaic solar cells (OPVs) are promising due to their simple fabrication procedure, low material cost and flexibility. In recent studies, the semiconductive conjugated organic materials as the electron donor materials blended with [6,6]-phenyl-C_{71}-butyric acid methyl ester ($PC_{71}BM$) have been investigated extensively using a single bulk heterojunction (BHJ) device structure [1-3]. The semiconductivity and solar cell material properties of many phthalocyanine and subphthalocyanine dyes have been also investigated previously [4,5]. In the present work, the synthesis, characterization and photovoltaic properties of new conjugated Al subporphyrazine dye (Al-subPz) were investigated. The Al-subPz dye shown in Figure 1 is a red color dye material with a band gap energy of 1.77 eV. Currently, we are exploring the potential technological applications of this red light emissive Al-subPz dye in different optic and electronic devices. As a result, the new Al subporphyrazine structure with imidazole rings can be considered as a promising organic solar cell dye material.

Keywords: Subporphyrazine, Dye, Photovoltaic, Solar cell, Band gap, Solar energy

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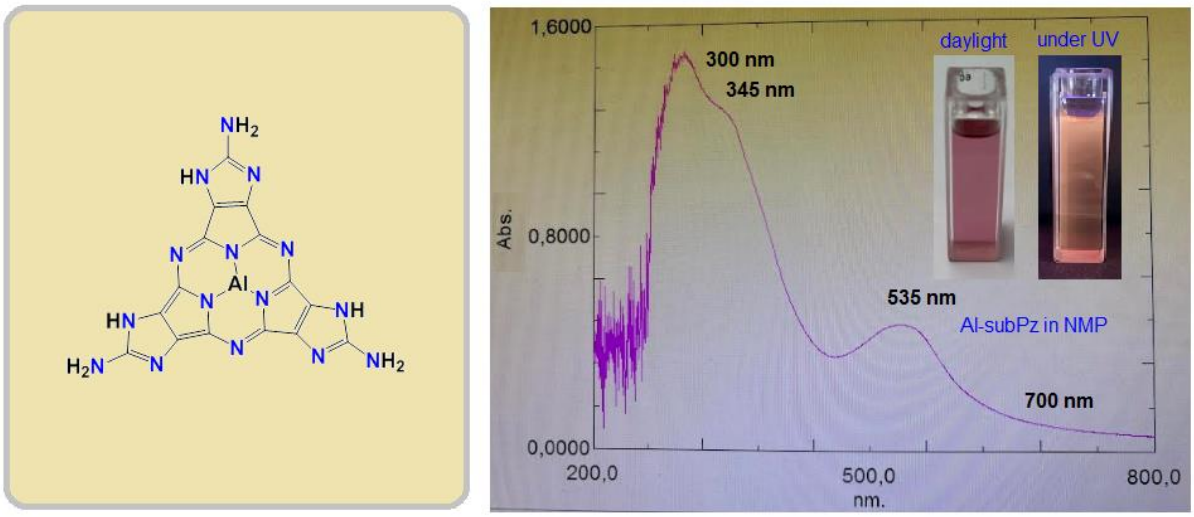


Figure 1. Flourescence Al-SubPz dye molecule and its UV-vis spectrum in NMP with flourescence emission under UV light.

Metal Oxide Nanoparticle-Based Photonic Glass Coatings for Structural Coloration of BIPVs

Parisa Sharif[1], Eda Cevik[2], Ilknur Ozbayrak[2], Sahin Coskun[3], Husnu Emrah Unalan[2,4], Alpan Bek[1,5], Talat Ozden[1]

[1] The Center for Solar Energy Research and Applications (ODTÜ-GÜNAM), Ankara, Türkiye
[2] Department of Metallurgical and Materials Engineering, METU, Ankara, Türkiye
[3] Department of Metallurgical and Materials Engineering, ESOGU, Eskişehir, Türkiye
[4] Energy Storage Materials and Devices Research Center (ENDAM), METU, Ankara, Türkiye
[5] Department of Physics, METU, Ankara, Türkiye

*ilknur.ozbayrak@metu.edu.tr

The widespread implementation of building-integrated photovoltaics (BIPVs) requires photovoltaic (PV) modules that can offer visual adaptability while maintaining high energy conversion efficiency. Addressing this need, this study investigates an inorganic photonic glass concept in which coloration is achieved through light scattering by synthesis-controlled metal oxide nanospheres. This approach enables coloration without relying on pigments or multilayer stacks, thereby avoiding their shortcomings such as short lifetime, absorptive temperature rise and directional color perception. Molybdenum trioxide (MoO_3) and vanadium pentoxide (V_2O_5) nanoparticles are prepared via a solution-phase synthesis route, where reaction parameters and precursor composition are systematically tunes to control nucleation and growth dynamics. This approach enables the production of nearly monodisperse nanospheres with well-controlled size distributions and near-stoichiometric compositions, while recognizing that slight minor oxygen deviations may influence optical absorption. The synthesized particles are subsequently assembled into coatings on glass substrates using ultrasonic spray deposition, a scalable technique suitable for large-area applications. The resulting films form disordered photonic structures in which multiple scattering events give rise to angle-independent coloration governed by Mie scattering. Structural and morphological properties are characterized using X-ray diffraction (XRD) and scanning electron microscopy (SEM). After optical and colorimetric assessment, the coated glasses are incorporated into 15 cm × 15 cm crystalline silicon (c-Si) mini-modules through lamination processes, followed by current–voltage (I–V) measurements to evaluate device performance. The electrical results indicate that the primary impact of the coatings is a reduction in photocurrent, whereas open-circuit voltage and fill factor remain largely unchanged. In this context, V_2O_5-based coatings preserve more than 90% of the initial efficiency relative to the reference (uncoated) device, while MoO_3-based coatings show more pronounced losses, retaining roughly 60%, consistent with differences in scattering and absorption behavior linked to synthesis-dependent material properties. In summary, the study shows that precise control of nanoparticle synthesis governs the trade-off between optical appearance and photovoltaic performance, positioning metal oxide photonic glass coatings as a viable and scalable route for color-integrated BIPV technologies.

Acknowledgements

This work was financially supported by the Scientific and Technological Research Council of Türkiye (TÜBİTAK) under Grant No 123F372.

Keywords: BIPV, colored solar panel, metal oxide, nanospheres, photonic glass, aesthetic impact

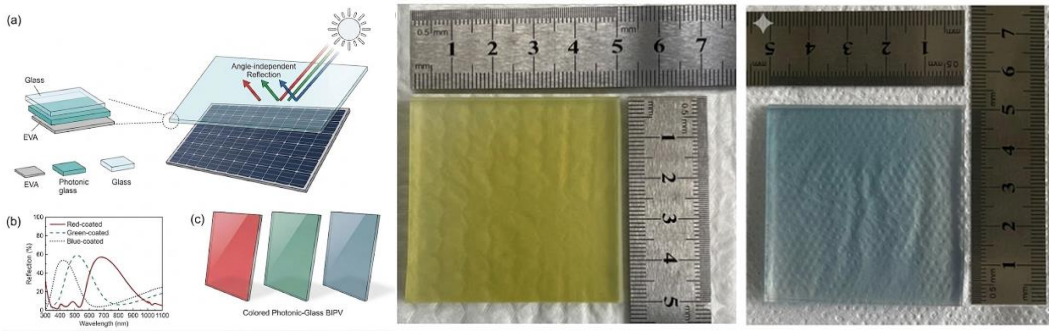


Figure 1. Photonic glass approach and fabricated V_2O_5 and MoO_3 coated colored glass samples for BIPV applications.

$Mo_3C_2T_x$ MXene Engineered SnO_2 for Tunable Wettability, Conductivity, and Work Function toward High Performance Perovskite Solar Cells

Hameed Ullah[1], Sajid Sajid[2], Gabriel Dias Trevisan[1], Sherdil Khan[2], Carlos F. O. Graeff[1]

[1] Department of Physics and Meteorology, School of Sciences, Sao Paulo State University (UNESP), Bauru, Sao Paulo, 17033-360, Brazil.

[2] Laboratory of Nanomaterials for Renewable Energy and Artificial Photosynthesis. Universidade Federal Do Rio Grande Do Sul, Porto Alegre, Brazil.

* Hameed Ullah (hameedktk331@gmail.com) and Carlos F.O. Graeff (carlos.graeff@unesp.br)

Abstract

The performance of planar perovskite solar cells (PSCs) is often constrained by the limitations of pristine SnO_2 electron transport layers (ETLs), such as poor crystallinity, suboptimal energy-level alignment, low wettability, and limited electrical conductivity. In this study, conductive $Mo_3C_2T_x$ MXene nanoflakes with tunable surface terminations and strong interfacial compatibility are incorporated into SnO_2 to overcome these challenges. The inclusion of MXene enhances the structural and electronic properties of SnO_2 by improving its crystallinity and charge transport while enabling precise tuning of its work function and surface wettability. These improvements promote the formation of high-quality perovskite films with better interfacial contact and reduced defect density. Furthermore, improved energy-level alignment and increased conductivity facilitate more efficient charge extraction and transport, as confirmed by steady-state photoluminescence, electrochemical impedance spectroscopy, and dark J–V measurements. As a result, PSCs based on MXene-modified SnO_2 achieve a power conversion efficiency (PCE) of 20.16%, outperforming devices based on pristine SnO_2 (18%), while also demonstrating enhanced stability by retaining 95.1% of their initial efficiency after 42 days at 25 °C under 40–60% relative humidity. Overall, this work establishes MXene incorporation into ETLs as an effective strategy for improving both the efficiency and long-term stability of perovskite solar cells

Acknowledgements

I acknowledge FAPESP for financial support under grant numbers 2024/02264-0 and 2024/13743-6.

Keywords: MXene; $Mo_3C_2T_x$; Perovskite Solar Cell; Efficiency; Stability

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Multi-Objective Analysis of Semi-Transparent Photovoltaic Façades: Balancing Energy Generation and Indoor Visual Comfort in a Mediterranean Climate

Amirhossein Karimizadeh[1], **Ercan Hoskara**[1]

[1] Department of Architecture, Faculty of Architecture, Eastern Mediterranean University, North Cyprus via Mersin 10, Gazimağusa 99628, Türkiye ; ercan.hoskara@emu.edu.tr

*Corresponding Author's E-mail: amirhossein.karimizadeh@emu.edu.tr

Photovoltaic (PV) façades represent a promising approach to transform building envelopes into on-site renewable energy generators while influencing indoor environmental quality. Beyond energy performance, design parameters significantly influence the indoor environment, including daylight availability and glare risk, which are critical for occupant visual comfort. While PV technologies are commonly optimized at the module scale, their performance in building-integrated applications remains insufficiently explored, especially regarding the trade-offs between energy generation and occupant comfort. This study investigates how variations in Visible Transmittance (VT) of semi-transparent PV modules and tilt angles affect both energy generation and indoor visual conditions on a South-facing façade. A mid-rise building in Northern Cyprus, representing a Mediterranean climate with high solar radiation potential, is considered as a case study. A parametric simulation-based approach is adopted, utilizing Ladybug, Radiance, and PVsyst to evaluate multiple PV façade configurations. Performance indicators include annual energy yield (kWh), spatial Daylight Autonomy (sDA), and Daylight Glare Probability (DGP). By analyzing the impact of VT levels and tilt angles, the study explores design strategies that maximize energy generation while optimizing occupant visual comfort. This research addresses a critical gap between architectural and engineering perspectives, contributing to the performance-driven integration of PV systems within the built environment.

Acknowledgements

This is the abstract template document for PVCON2026.

Keywords: PV façades, Semi-transparent PV, Tilt angle, Energy generation, Visual comfort, Mediterranean climate

ABSTRACT TITLE

Somayyeh Rahimi[1], Murat Göl[1]

[1] Middle East Technical University / Electric and Electronics, Ankara, Turkey

*somayyeh.rahimi@metu.edu.tr

Increasing penetration of solar photovoltaic (PV) generation introduces additional uncertainty into power system operation and energy management, thereby increasing the need for accurate short-term PV power forecasting. However, rapid variations in solar irradiance and meteorological conditions continue to limit forecasting performance.
This study focuses on comparing standalone deep learning models, such as long short-term memory (LSTM), one-dimensional convolutional neural network (CNN-1D), and gated recurrent unit (GRU) models, with hybrid models that integrate LSTM with Gradient Boosting, XGBoost, LightGBM, and CatBoost. The effects of meteorological variables, historical PV generation, forecasting architecture, and input window size on prediction accuracy are tested across all models. All models are implemented in Python and evaluated using RMSE, nRMSE, and R^2. The experimental results on the ODTU campus show that the hybrid models generally outperform their standalone deep learning counterparts. XGBoost-LSTM with RMSE of 0.0038 and 9.07% reduction in RMSE compared with LSTM, achieved the best result among the evaluated techniques. This result indicates that integrating ensemble learning with standalone models such as LSTM can improve forecasting accuracy. The improvement is mainly due to the combined model's ability to capture nonlinear variations in PV generation more effectively.

Keywords: Deep learning, energy management systems, short-term forecasting, solar power forecasting, time-series prediction, weather feature selection

CIRCULAR PHOTOVOLTAICS: LOW-TEMPERATURE DELAMINATION FOR GLASS SUBSTRATE REUSE

Doguscan Donmez[1,2], Figen Varlioglu Yaylali[2], Tayfun Hiz[2], Selcuk Yerci[3,4], Gorkem Gunbas[1,2]

[1] Middle East Technical University/Chemistry, Ankara, Turkiye
[2] ODTU-GUNAM/Division of Materials Development and Recycling, Ankara, Turkiye
[3] ODTU-GUNAM/Division of Emerging Photovoltaics, Ankara, Turkiye
[4] Middle East Technical University/Electrical-Electronics Engineering, Ankara, Turkiye

*doguscan.donmez@odtugunam.org

Legacy photovoltaic (PV) modules were not originally designed with recyclability in mind, making the recovery of raw materials challenging and often limiting them to lower-value applications. To address these limitations, a transition toward sustainable, next-generation PV designs is crucial. Such designs can facilitate the efficient valorization of secondary resources and significantly reduce the environmental impact of the rapidly expanding solar industry.

In this study, an innovative approach has been adopted to ensure PV glass is recovered undamaged during the process. In this way, unlike traditional methods such as destructive recycling or downgrading, the obtained glass is made ready for the next PV module production. For this purpose, a sacrificial layer was introduced between the PV glass and the POE encapsulant. After scanning various materials, the most suitable material for this purpose was identified, and solution-based coating processes have been initiated.

After the prototype production, solvent-based tests were conducted on the delamination processes. Using a basic solution, the glasses were successfully separated without damaging the device stack. Following the successful results, a second stage involved designing a 50 cm x 50 cm module. Then, the damp heat test was conducted by keeping fabricated modules in climate chambers at 85°C temperature and 85% relative humidity (RH). It was determined that the structure maintained its original condition for 200 hours.

This study demonstrates that the proposed method has strong potential to contribute to future PV design standards and to support the development of more effective circular-economy approaches.

Acknowledgements

This work was supported by the APOLLO project, which has received funding from the European Commission (HORIZON EUROPE) under the grant agreement No. 101122277.

Keywords: sustainability, end-of-life management, design for recycling, material recovery, delamination

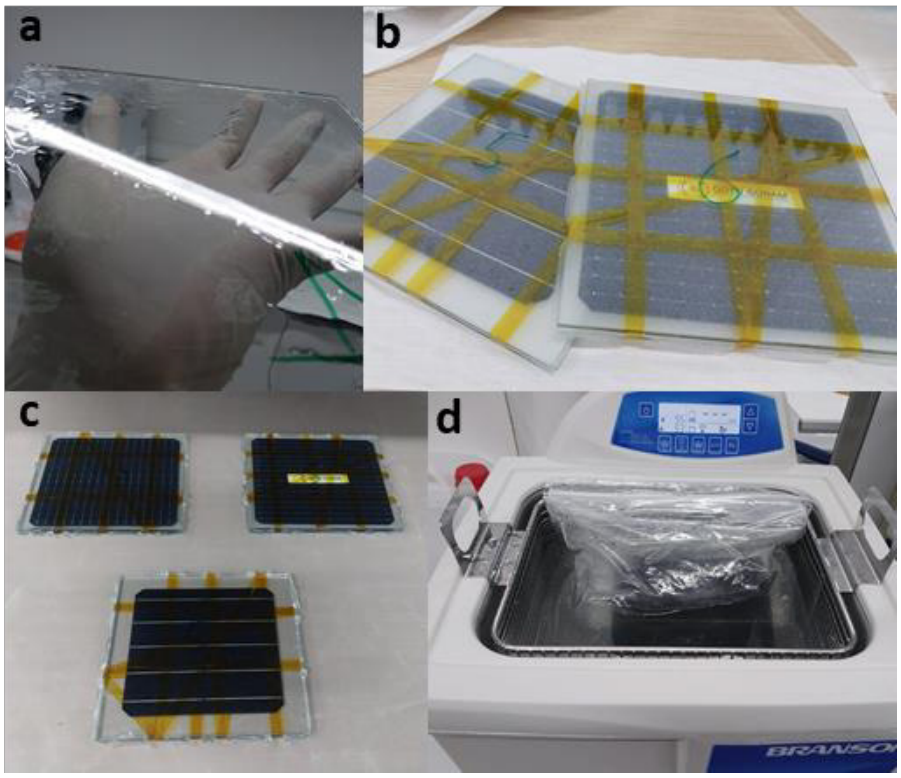


Figure 1. Title / Description

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CONTACT OPTIMIZATION OF TOPCON SOLAR CELL USING HALOGEN LAMP AND REVERSE CURRENT

Tunçer Deniz Kurttekin*[1,3], Bülent Arıkan[1], Hande K. Cankul[1], Agageldi Muhammetgulyyev[4], Raşit Turan[1,2]

[1] Center for Solar Energy Research and Applications (ODTÜ-GÜNAM), Ankara, Türkiye
[2] Department of Physics, Middle East Technical University (METU), Ankara, Türkiye
[3] Department of Micro and Nanotechnology, Middle East Technical University (METU), Ankara, Türkiye
[4] CW Enerji, Antalya, Türkiye
***deniz.kurttekin@metu.edu.tr**

Tunnel oxide passivated contact (TOPCon) solar cells have become one of the leading industrial crystalline silicon photovoltaic technologies due to their high efficiency potential and compatibility with large-scale manufacturing. However, the contact between screen-printed Ag/Al metallization and the front-side boron emitter can still introduce high contact resistivity and metallization-induced recombination losses, limiting device performance. Laser-Enhanced Contact Optimization (LECO) is commonly used to improve this metal-semiconductor interface by combining localized laser heating with electrical bias [1],[2]. In this study, a simpler non-laser contact optimization approach was investigated for n-type TOPCon solar cells by using halogen lamp illumination under electrical bias.

Industrial n-type TOPCon solar cell samples without prior LECO treatment were cut into 9.2cmx2.2cm strips from full-size M10R, 16-busbar cells. Contact optimization was performed using halogen lamp illumination at approximately 3.5suns under a constant bias of 19 V. The treatment was applied for different durations between 2 and 5 minutes, with reverse bias used for the front-side treatment and forward bias used for the rear-side treatment. The impact of the treatment was evaluated through electroluminescence imaging and current–voltage measurements before and after processing.

The results show that halogen lamp-assisted bias treatment significantly improved the contact quality of the TOPCon strips. Before treatment, the samples exhibited very weak or dark electroluminescence response, indicating poor contact formation. After treatment, the EL images became visibly brighter and more uniform, confirming improved carrier transport and reduced contact-related losses. Electrical measurements also supported this improvement. No measurable I-V response was observed before the treatment, whereas treated samples showed clear photovoltaic response after processing. Among the tested conditions, the best performance was obtained for the 5-minute treated strip, reaching a Voc of 0.736 V, a Jsc of 41.0 mA/cm², a 75.03% FF and 22.94% efficiency.

These preliminary results demonstrate that halogen lamp illumination under electrical bias can improve the contact quality of n-type TOPCon solar cells without using a conventional laser-based LECO process. Although further optimization and validation on full-size cells are required, this approach shows promise as a simpler, more accessible, and potentially lower-cost alternative for contact optimization in industrial TOPCon solar cell manufacturing.

Keywords: Solar Cell, TOPCon, Metallization, Contact Optimization, LECO

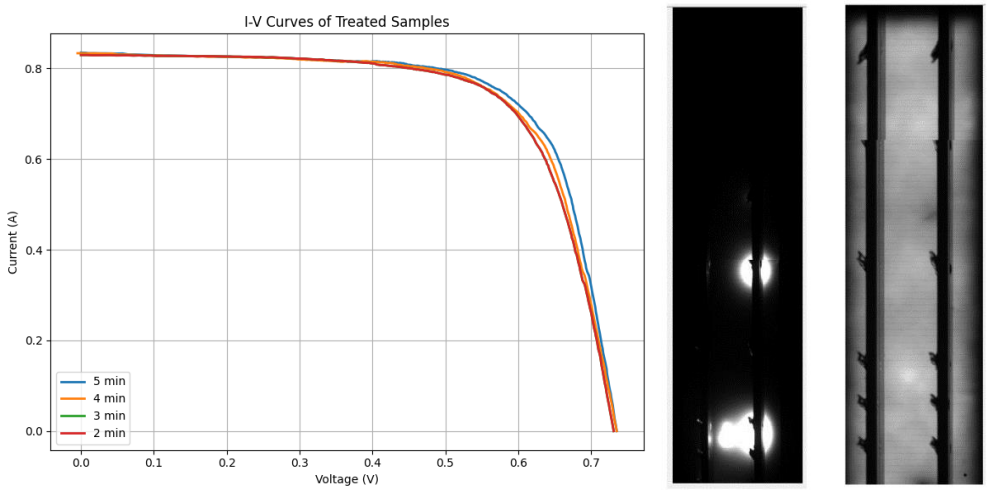


Figure 1. (A)I-V curves of treated samples. **(B)** Before and after images of a 5min-treated sample
(Please use your images, photos etc. in high resolution)

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Thermal-Budget Compatibility of CIGS Processing with Silicon Bottom Cells for Alternative Thin-Film/Si Tandem Photovoltaics

Mustafa Büyükgüzel[1], Büşra Altınsoy[1], Seda Kılıçkaya Ünver[1], Bahri Eren Uzuner[1], Yiğit Mert Kaplan[1], Gökhan Altıner[1], Selçuk Yerci[1,2], Raşit Turan[1,2] Veysel Ünsür[1,3]

[1] ODTU-GUNAM, Middle East Technical University, 06800, Ankara, Turkiye
[2] Middle East Technical University, 06800, Ankara, Turkiye
[3] Necmettin Erbakan University, 42090, Konya, Turkiye

*mustafa.buyukguzel@odtugunam.org

Tandem photovoltaic architectures offer a promising route for surpassing the practical efficiency limits of single-junction crystalline silicon solar cells by combining absorber materials with complementary spectral responses. While current tandem research is largely dominated by perovskite–Si devices, $Cu(In,Ga)Se_2$ (CIGS) remains an attractive alternative thin-film top-cell candidate due to its tunable bandgap, mature processing routes, long-term stability, and suitability for monolithic tandem integration [1-4]. However, the elevated temperatures commonly associated with CIGS absorber growth and post-deposition treatments raise important compatibility questions for the temperature-sensitive passivation, carrier-selective, and transparent conductive oxide (TCO) layers of the silicon bottom cell [5,6].

In this work, representative IBC silicon bottom-cell structures (**Figure 1, a-c**) with a 100 nm front-side indium tin oxide (ITO) interlayer were investigated under CIGS-relevant thermal exposrue simulated by N_2 annealing for 30 minutes at selected temperatures. The results show that ITO sputtering reduced the iV_{OC} of the phosphorus-diffused emitter by approximately 23 mV, indicating passivation degradation due to sputtering-induced interfacial damage, whereas the n^+ poly-Si passivating contact maintained a high iV_{OC}, suggesting greater tolerance to ITO deposition (**Figure 1, d**). Sheet resistance measurements further reveal that ITO deposited on highly doped phosphorus-diffused and n^+ poly-Si regions exhibit much lower effective sheet resistance than ITO deposited on bare silicon, with values of approximately 40–50 Ω/sq, 60–70 Ω/sq, and 400–500 Ω/sq, respectively. This indicates that the measured response corresponds to an electrically coupled multilayer stack, rather than the isolated ITO (**Figure 2**). Although sheet resistance increases after exposure to higher temperatures, particularly in the 500–600 °C range relevant to CIGS processing, the doped-layer/ITO stacks retain relatively low effective sheet resistance which is encouraging from the perspective of lateral charge transport and tandem interconnection. These findings suggest that CIGS–Si tandem integration may be feasible if the boron emitter retains sufficient electrical and passivation stability under CIGS-relevant thermal exposure. Ongoing boron-emitter and ITO/contact-stack analyses will further define the compatible process window before the conference.

Acknowledgements

This work is supported by TÜBİTAK under the grant of 125N269.

Keywords: Tandem solar cells, crystalline silicon solar cells, IBC, CIGS

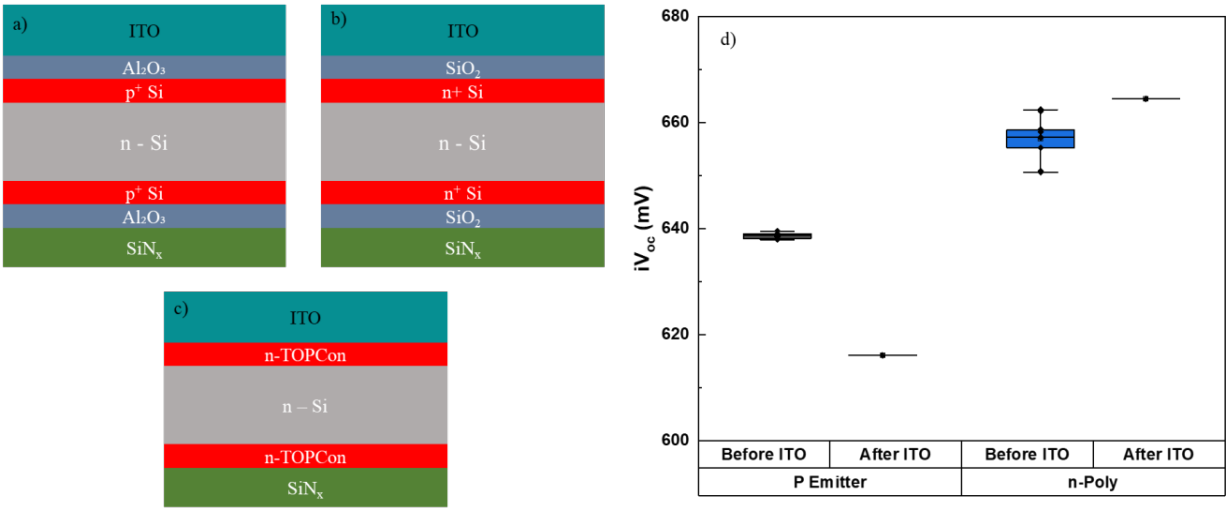


Figure 1. Schematic description of ITO-sputtered structures emulating: a) B-emitter, b) P-emitter, c) n+ Poly-Si structures studied in this work and d) iV_{OC} measurements of P emitter and n^+-poly samples before and after ITO deposition.

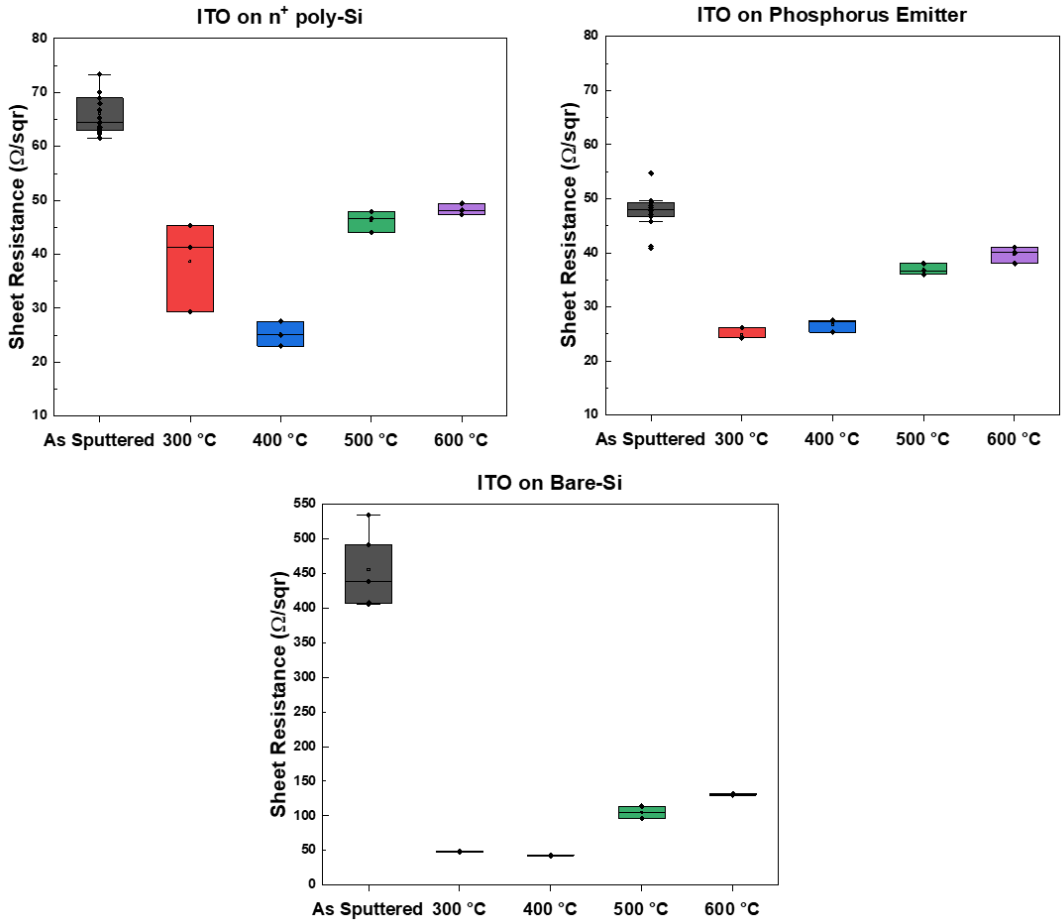


Figure 2. Sheet resistance measurements for ITO deposited on n^+ poly-Si, Phosphorus emitter, and bare silicon.

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Novel PACz-Derived Self-Assembled Monolayers for Interfacial Engineering and Organic Solar Cell Applications

Shayan Sajedi[1], Pelin Oral[1], Aliekber Karabag[2], Gorkem Gunbas[1,2,3,4], Selcuk Yerci[2,4,5], Gonul Hizalan Ozsoy[2]*

[1] Department of Polymer Science and Technology, Middle East Technical University (METU), 06800, Ankara, Turkiye
[2] Center for Solar Energy Research and Applications (ODTU-GUNAM), METU, 06800, Ankara, Turkiye
[3] Department of Chemistry, METU, 06800, Ankara, Turkiye
[4] Micro and Nanotechnology Department, METU, 06800, Ankara, Turkiye
[5] Electrical Engineering Department, METU, 06800, Ankara, Turkiye

*Corresponding author: gonul.ozsoy@odtugunam.org

The growing global energy demand and climate concerns have accelerated the development of renewable energy technologies, with solar energy emerging as a key solution. Photovoltaic (PV) technologies convert sunlight into electricity, playing a central role in clean energy systems. While silicon-based solar cells achieve high efficiencies, they suffer from limitations such as high cost, rigidity, and complex processing.

Organic photovoltaics (OPVs) offer a promising alternative due to their lightweight, flexibility, semitransparency, and low-cost solution processability. However, their performance is still limited by interfacial energy losses, inefficient charge extraction, and recombination. Interfacial engineering is therefore critical, as it directly affects energy-level alignment, charge transport, and device stability.

Self-assembled monolayers (SAMs), particularly carbazole-based PACz derivatives, are effective interfacial modifiers. Deposited on indium tin oxide (ITO), they tune work function, improve energy alignment, and enhance selective charge extraction, reducing recombination losses.

In this study, four novel dialkyl amine-containing PACz-derived SAMs (**SAM1–4**) were designed and synthesized via optimized three-step routes with >95% purity. Structural variations in the carbazole core were introduced to investigate structure–property relationships. The compounds were characterized using Nuclear Magnetic Resonance (**NMR**: ^{1}H NMR and/or ^{13}C NMR), High-Resolution Mass Spectrometry (**HRMS**), Cyclic Voltammetry (**CV**) and Ultra Violet (**UV**) techniques.

OPVs with the cell architecture of ITO/**SAMX (X: 1–4)**/active layer/cathode interlayer/Ag were fabricated. In the active layer PM6:Y6 polymer, non-fullerene acceptor mixture was used. Work function of the ITO electrodes functionalized with SAMs were determined with UPS. The results demonstrate that molecular design significantly affects interfacial energetics and work-function modulation. Among the **SAM1-4** series, the novel **SAM4**-incorporated OPVs exhibited the superior performance, with the champion cell achieving a **PCE of 6.22%**, a V_{OC} **of 0.53 V**, a J_{SC} **of 18.84 mA cm^{-2}**, and an **FF of 61.98%**. By employing a mixture of **SAM4** and commercially sourced **2PACz**, the **PCE** was further enhanced to **6.90%** (with V_{OC} **of 0.59 V**, J_{SC} **of 19.18 mA cm^{-2}** and **FF of 61.21%**), which is attributed to improved surface coverage and optimized interfacial contact.

Acknowledgments

This study was supported by Scientific and Technological Research Council of Türkiye (TUBITAK) under the Grant Number of **122F307**. The authors thank to TUBITAK for their supports.

Keywords: Semi-transparent Organic Photovoltaics (OPVs), Self-Assembled Monolayers (SAMs), 2PACz, Emerging Photovoltaics (EmPV)

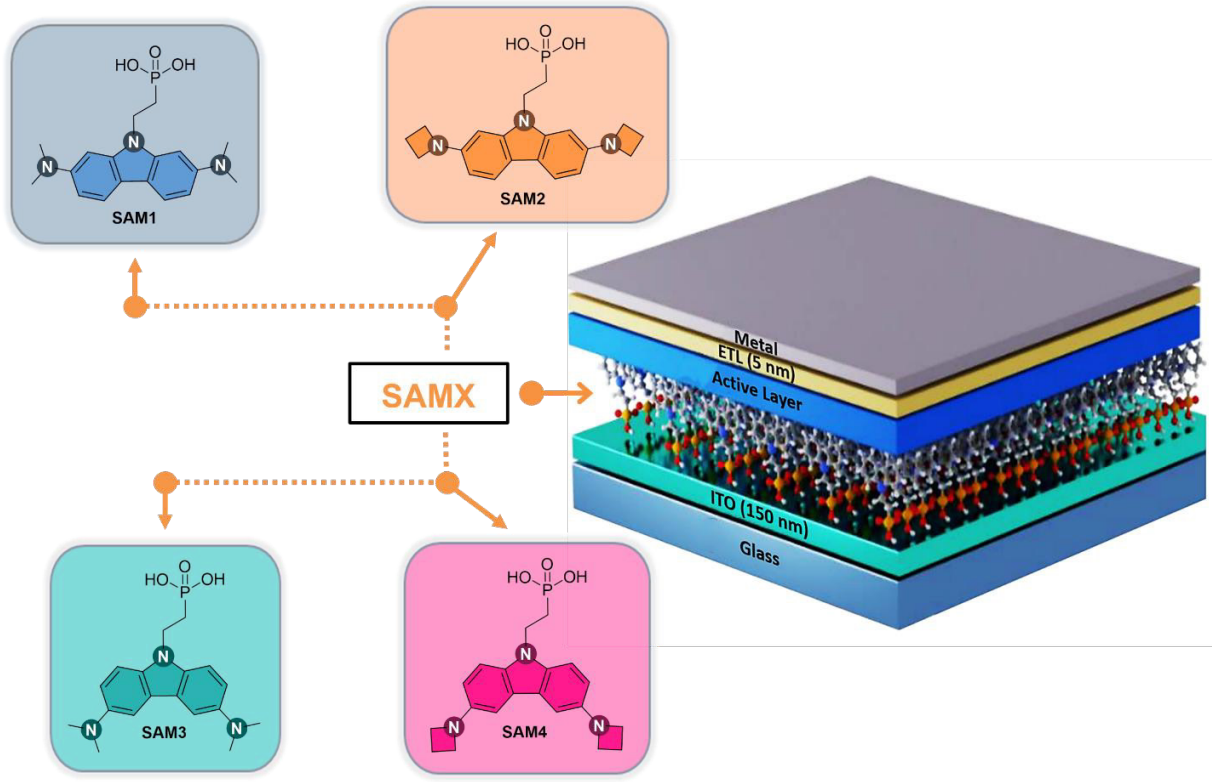


Figure 1. Representation of novel **SAM1-4**-integrated OPV architecture

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Pushing the Efficiency Limits of Inverted Perovskite Solar Cells through Organic Salt Passivation

Gül Simge Özdemir[1,2,5], Sude Çebi[2,3,5], Figen Varlıoğlu Yaylalı[2], Mustafa Yaşa[2], Selçuk Yerci[1,2,4], Görkem Günbaş[1,2,3]

[1] Middle East Technical University/Department of Micro and Nanotechnology, Ankara, Türkiye
[2] ODTU-GUNAM/ Division of Materials Development and Recycling, Ankara, Türkiye
[3] Middle East Technical University/Department of Chemistry, Ankara, Türkiye
[4] Middle East Technical University/Department of Electrical and Electronics Engineering, Ankara, Türkiye
[5]Equally contributed

*gul.ozdemir@metu.edu.tr

Inverted (p-i-n) perovskite solar cells (PSCs) require sophisticated interfacial engineering to suppress non-radiative recombination and ensure robust operational stability.[1] While methoxy-substituted phenylethylammonium iodide (PEAI) derivatives have been previously reported to enhance device performance through Lewis base passivation, the impact of chalcophilic substitutions remains less explored.[1,2] In this study, we systematically investigate the impact of substituent types, methoxy (-OMe) and thiomethyl (-SMe), and their positions (*ortho* vs. *para*) on the PEAI backbone, as illustrated in **Figure 1**. The target organic salts were successfully synthesized via a systematic three-step sequence starting from corresponding benzaldehyde precursors, as detailed in **Figure 2**.

Our experimental findings reveal that dual-position thiomethyl substitution significantly outperforms its counterparts by providing superior coverage and multi-site coordination at the interface. Specifically, ***o,p*-SMe-PEA$^+$** treatments yielded power conversion efficiency (PCE) of **18.34%**, with Fill Factor (FF) reaching **80.54%**, as shown in the J-V curves in **Figure 3**. The exceptional performance of the thiomethyl-based devices is uniquely rooted in the **chalcophilic nature** of sulfur. The -SMe groups facilitate strong coordination with Pb^{2+} and Ni^{2+} sites, acting as a molecular anchor that promotes efficient charge extraction and boosts the short-circuit current density (J_{SC}).

Crucially, this dual-functionalized interface serves as a robust stability enhancer by forming a dense hydrophobic barrier against moisture ingress and ion migration. By optimizing the molecular design of the organic salt structure, we demonstrate that the *o,p*-SMe-PEA$^+$ derivative provides a reliable pathway to achieve high-performance and stable inverted PSCs, surpassing the baseline performance of standard reference devices.

Acknowledgements

This study was supported by Scientific and Technological Research Council of Turkey (TUBITAK) under the Grant Number 123F373. The authors thank to TUBITAK for their supports.

Keywords: perovskite solar cells, passivation, phenylethylammonium salts, power conversion efficiency, stability.

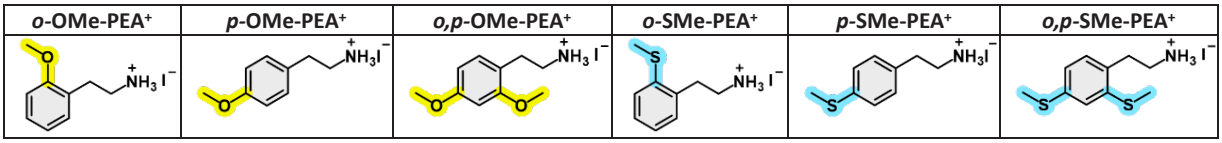


Figure 1. Structure of the synthesized PEAI derivatives.

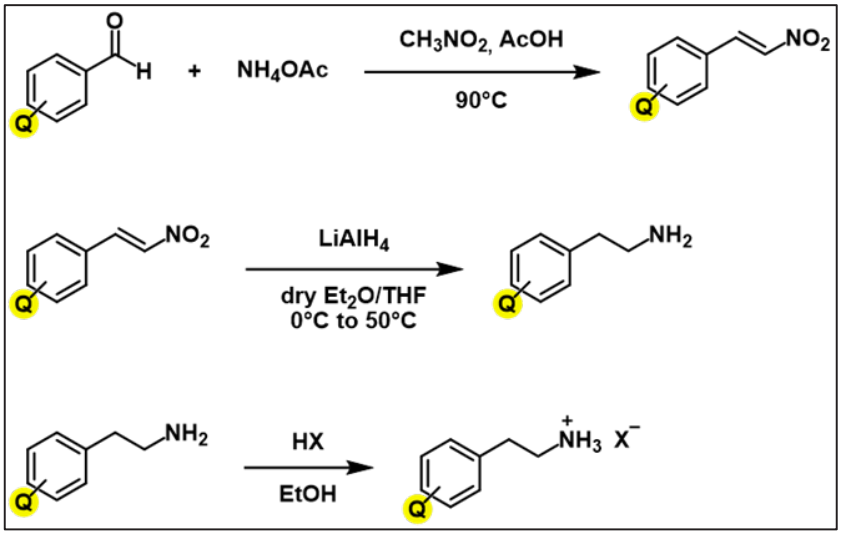


Figure 2. Reaction pathway from the corresponding precursor aldehyde to PEAI salt.

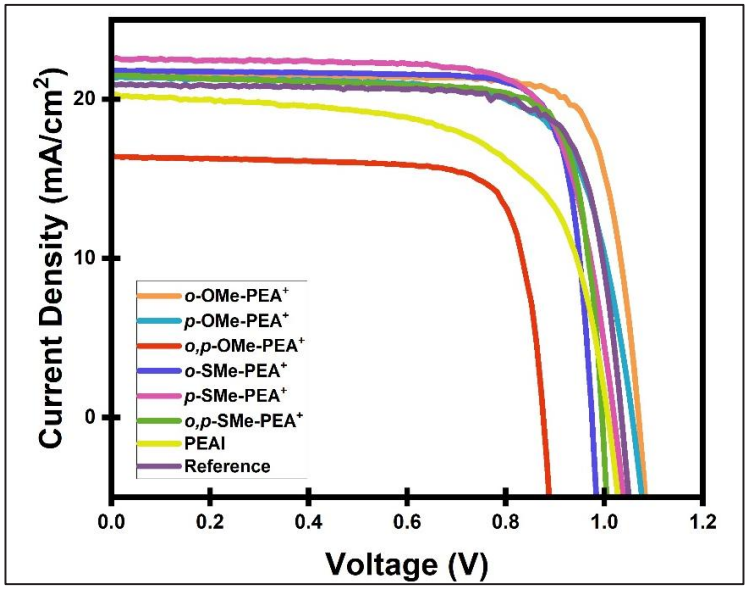


Figure 3. Current density vs. voltage graph of the PEAI salts in a p-i-n device.

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Second Life of Silver: From Waste Photovoltaic Pastes to Transparent Conductive Networks

Serdar Guler[1], Hüseyin Utkucan Kayacı[2,3], Behiye Demirtaş[1], Bülent Arıkan[4], Doga Doganay[3, 5], Sahin Coskun[3, 6], Rasit Turan[4, 7], Husnu Emrah Unalan[*, 1, 2, 3, 4,]

1: Department of Metallurgical and Materials Engineering, Middle East Technical University, Ankara, Türkiye.

2: Department of Micro and Nanotechnology, Middle East Technical University, Ankara, Türkiye

3: Nanovatif Materials Technologies, ODTÜ-TEKNOKENT, Ankara, Türkiye

4: ODTÜ-GÜNAM, Ankara, Türkiye

5: Department of Engineering, University of Cambridge, Cambridge, England.

6: Department of Metallurgical and Materials Engineering, Eskisehir Osmangazi University, Eskişehir, Türkiye.

7: Department of Physics, Middle East Technical University, Ankara, Türkiye

*: Corresponding Author; unalan@metu.edu.tr

Driven by decarbonization goals and energy security concerns, research in the photovoltaic (PV) industry has gained significant momentum in recent years. However, these rapid developments has come with significant environmental and economic challenges. A primary concern arises from the widespread use of silver in solar cell metallization, driven by its superior electrical conductivity. However, the growing consumption of silver leads to concerns regarding material cost, resource availability, and the environmental impact of mining and refining processes. Therefore, recovering silver from PV-related waste streams has become an important strategy for improving the sustainability of solar cell manufacturing. In this study, waste silver pastes produced during solar cell production were used as precursor for the synthesis of silver nanowires (AgNWs). The recycling route starts with the removal of polymeric additives from the paste, followed by conversion of the recovered silver into silver nitrate ($AgNO_3$), a widely used precursor across diverse chemical syntheses, including polyol-based AgNW formation. This precursor was subsequently employed for nanowire synthesis under controlled conditions. The synthesized AgNWs were then used to fabricate transparent conductive films, and their optoelectronic properties were evaluated as an indicator of nanowire quality. The resulting AgNW networks exhibited a sheet resistance of 15 Ω/sq together with an optical transmittance of 85% at 550 nm. These results indicate that $AgNO_3$ derived from recycled silver paste performs comparably to commercial precursors in AgNW production. To sum up, this research offers an alternative pathway to reduce raw material consumption and lower the cost of AgNW-based transparent electrodes.

Keywords: Recycling of PV Materials, Sustainability, Transparent Conductive Electrodes, Silver Nanowire Synthesis, Circular Economy, Life Cycle Assesment.

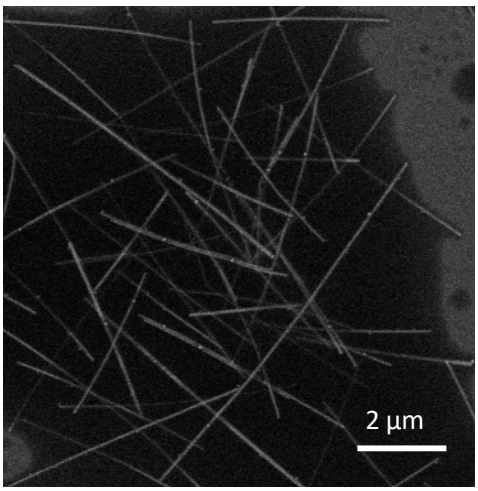


Figure 1. SEM image of synthesized silver nanowires (AgNWs) obtained from recycled PV silver paste.

Floating Photovoltaic Systems : A Promising Renewable Energy Solution

Abstract

In the context of increasing challenges related to land scarcity and rising energy demand, floating photovoltaic (FPV) systems emerge as a promising option for renewable energy production. This work aims to provide a simplified analysis of this technology and highlight its added value compared to ground-mounted PV systems, particularly in terms of utilizing water surfaces and improving performance efficiency due to the natural cooling effect of water.

This paper also explores the potential integration of this technology within energy strategies, especially in countries facing limited resources or difficulties in expanding conventional systems, while emphasizing its future role in supporting the transition toward sustainable energy and the need for further research and development.

Techno-Economic Comparison of Lithium-Ion and Sodium-Ion Battery Storage Systems for a 2 MW PV Power Plant

Ezgi USLAN DOĞAN[1,*], Yağmur BUDAK[1], Ömer Faruk TUNÇBİLEK[1]

[1] Turkish Energy, Nuclear and Mineral Research Agency/ Clean Energy Research Institute, Ankara,Türkiye

*ezgi.uslan@tenmak.gov.tr

The increasing global energy demand and the severe impacts of global warming are accelerating the transition of energy production systems toward alternative and sustainable sources. Renewable energy technologies play a fundamental role in this transition due to their low carbon emissions, sustainability, and utilization of domestic resources. Among these technologies, solar energy has emerged as the fastest-growing energy source worldwide; however, its inherently intermittent and variable nature necessitates increased flexibility in energy systems, highlighting the importance of energy storage technologies as a complementary solution. Energy storage systems play a key role in mitigating power fluctuations, enhancing grid stability, and enabling more efficient utilization of solar energy.

This study presents a techno-economic assessment of a planned 2 MW solar power plant in Kahramankazan, Ankara, Türkiye, considering lithium-ion and sodium-ion energy storage systems as alternative configurations. The hourly load profile and regional meteorological data were analyzed. Comparative evaluations were conducted based on key performance indicators such as the Levelized Cost of Energy (LCOE). The two storage technologies were analyzed separately and compared in terms of efficiency, cost, and environmental impact. The overall system configuration is illustrated in Figure 1. Furthermore, the impacts of different system configurations on the carbon footprint were examined. The findings of this study are expected to contribute to the evaluation and comparison of different energy storage technologies for solar power systems.

Keywords: Solar Energy, Energy Storage Systems, LCOE, Carbon Footprint Mitigation , Techno-Economic Analysis

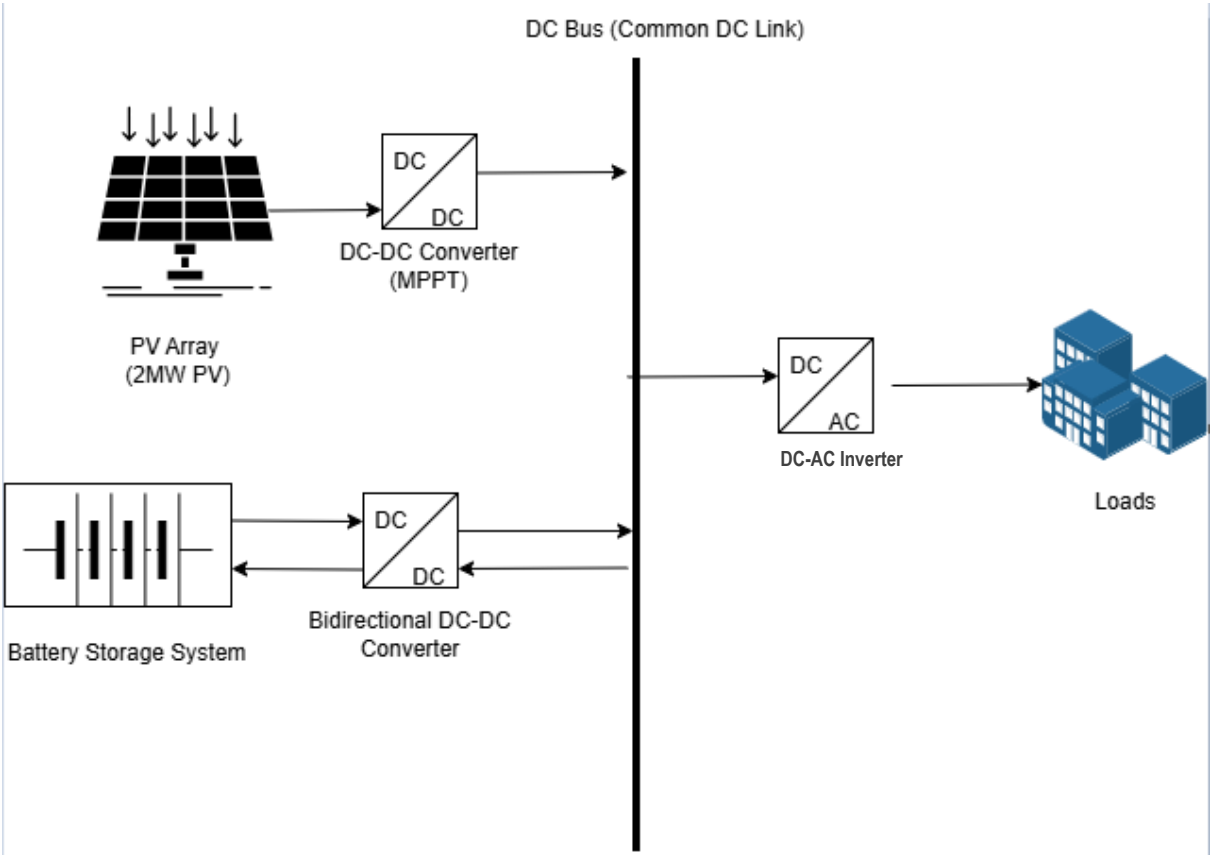


Figure 1. Simplified schematic of a 2 MW PV–BESS system with lithium-ion and sodium-ion batteries connected via a common DC bus

DIGITAL TWIN–BASED HYBRID PV–CSP SYSTEM FOR FLEXIBLE PV INTEGRATION INTO DISTRIBUTION NETWORKS

Farzaneh Bagheri[1,2], Luis J. Yebra[3], Safak Baykal[4], Fatma Nur Vurgec[4], Rabia Nur Kalem[4], Cagdas Akarsu[4], Kardelen Kamisli[4], Gökçen Aydın[4], Ömer Abacı[5], Emin Selahattin Umdu[5,6]

[1] *Department of Electrical and Electronic Engineering, Antalya Bilim University, Antalya, Türkiye*

[2] *Inelso Energy Company, Antalya, Türkiye*

[3] *CIEMAT – Plataforma Solar de Almería, Tabernas, Spain*

[4] *GDZ Elektrik Dağıtım A.Ş., İzmir, Türkiye*

[5] *Unda Engineering Inc., İzmir, Türkiye*

[6] *Yaşar University, İzmir, Türkiye*

**Corresponding Author's E-mail: farzaneh.bagheri@antalya.edu.tr*

The rapid deployment of photovoltaic (PV) generation at the distribution level presents increasing challenges related to power variability, grid flexibility, and secure network operation. Within the scope of the PVCON topic on photovoltaic system integration and hybrid energy systems, this paper presents an extended digital-twin-based framework for the technical and economic assessment of hybrid PV–CSP systems in electrical distribution networks. Building upon a previously developed digital twin of a parabolic trough concentrated solar power (CSP) plant with thermal energy storage presented in [1], the proposed extension introduces a new utility-scale PV plant model integrated into the same distribution network environment. The PV plant is implemented in the Modelica modeling language and validated using experimental data from a real operating facility, ensuring a realistic representation of irradiance-driven power fluctuations. The hybrid framework enables coordinated analysis of variable PV generation and dispatchable CSP operation, with particular emphasis on the role of CSP thermal storage in compensating short-term PV power variations. Using real operational data from a Turkish distribution system, the digital twin performs joint technical and economic simulations, evaluating power flows, storage utilization, grid interaction, and operational revenues. Results indicate that CSP thermal storage can effectively enhance system flexibility, mitigate PV-induced variability, and reduce reliance on conventional generation sources. The proposed digital twin framework provides a scalable and validated tool for planning, operation, and business-model evaluation of hybrid PV–CSP systems in renewable-dominated distribution networks.

Acknowledgements

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Türkiye and Spain (grant PCI2022-134974-2 funded by MCIN/AEI/10.13939/501100011033), and by the European Union ”NextGenerationEU/PRTR”, under the DISOPED project.

Keywords: Photovoltaic Integration, Hybrid PV–CSP Systems, Digital Twin, Thermal Energy Storage, Distribution Networks

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Gender Diversity *in Photovoltaics: Experiences and Support Mechanisms in the EU*

Pinar Derin-Güre (METU, ODTÜ-GÜNAM, METU Climate), Ezgi Pehlivanlı(METU),), Chiara Busto (Eni), Hande Eryılmaz (ODTÜ-GÜNAM), Nikoletta Fodor (SolarPower Europe), Ivan Gordon (imec IUMAT, UHasselt, Energyville), Eren Cihan Gülsoy (METU), Perine Fleury (Biosphere Solar), Ulrike Jahn (Fraunhofer IMWS), Delfina Munoz (CEA), Ioannis Tsanakas (CEA), Busra Yilmaz (Kameleon Solar), Rita Ebner (AIT), Charikleia A. Poravou (CERTH)

Abstract:

The renewable energy transition requires not only technological innovation but also inclusive participation in emerging energy industries. Yet women remain significantly underrepresented in the European photovoltaic (PV) sector, particularly in technical and leadership roles. This study examines the lived experiences of women professionals working across different segments of the PV industry to understand how gendered inequalities shape career pathways, recognition, and professional advancement. Drawing on semi-structured interviews with 28 professionals, the study employs qualitative thematic analysis to explore workplace dynamics, structural barriers, and strategies for navigating the sector. The findings reveal persistent challenges, including gender bias, limited access to leadership networks, wage disparities, and work–life constraints. At the same time, participants highlight the importance of mentorship, professional networks, and institutional support in sustaining careers. The results suggest that addressing gender inequality is critical not only for social equity but also for strengthening workforce capacity, innovation, and governance within renewable energy transitions.

Keywords: Photovoltaics (PV), Gender, Women, Energy, Inclusion, Experiences

Changing Physical and Mineralogical Mechanisms of Greenland and Their Potential Implications For The Economic Framework Of Energy Generation

Dilan Kılınçoğlu*[1], Bulent G. Akinoglu[1,2] and Abdullah Buğrahan Karaveli[1,3]

1. METU-Earth System Science
2. METU Department of Physics
3. TENMAK

The rapid melting of polar ice sheets is one of the biggest unknowns in sea-level-rise models. The instability is not due to a single factor but emerges due to the complex coupling of thermodynamic forcing and mechanical response. The Arctic undergoing much greater warming compared to the global average, which this effect is termed Arctic amplification. Over the past few decades the Arctic has heated approximately four times more rapidly than the entire planet. This propelled by the feedback mechanisms, like the loss of sea ice and snow cover with which boost solar energy absorption (Rantanen et al., 2022).

Geothermal and geochemical mechanisms occurring beneath glaciers in cold regions are considered important factors affecting the dynamics of ice sheets. Reaction-induced dissolution phenomena, the synthesis of clay minerals, and the formation of low-silica melts, even at low temperatures, imply that subglacial geochemical activity is more pronounced than previously expected (Crompton et al., 2015; Graly & Rezvanbehbahani, 2022).

Changes in bedrock composition, transformations in geothermal heat flux, and persistent variations in permafrost stability directly affect the requirements and maintenance costs of energy production facilities. All of these are considered physical constraints, and the effects of these constraints are reflected in the performance of energy systems, which can be measured by the Levelized Cost of Energy (LCOE). These geophysical change processes also impose additional constraints on engineering studies in energy infrastructure. Previous studies have demonstrated that Arctic infrastructure is highly sensitive to environmental processes such as permafrost degradation, ground subsidence, and thermal variability (Streletskiy et al., 2023). The main purpose is to reduce this information to simplified parameters and reveal the potential side effects on the region's energy production economy.

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Recent Trends in Fault Detection for PV Power Plants: A Survey

Masoud Emamian[1], Amir Nedaei[1], Ulaş Karaağaç[1]

[1] Middle East Technical University/Electrical and Electronics Engineering, Ankara, Türkiye

*ulaskar@metu.edu.tr

To enhance the lifespan and reliability of photovoltaic (PV) systems, early identification of problems is crucial. Conventional protection devices often fail to detect electrical faults under critical conditions due to (a) the current-limiting nature and non-linear output characteristics of PV arrays, (ii) the influence of varying environmental conditions such as temperature and irradiance, and (iii) the impact of maximum power point tracking (MPPT), especially in cases of critical fault impedance or mismatch levels. Consequently, modern fault detection and management systems are essential for PV systems.
Reviewing previous studies reveals significant gaps and limitations, including low accuracy, incomplete fault coverage, and limited consideration of low mismatch levels and critical fault impedance values. To address these challenges, this study proposes advanced fault detection methods, featuring a smart, multilayered system that integrates physical and software components to collect, transfer, and analyze data for classifying and determining the severity of electrical faults in PV arrays.
By leveraging advanced sensor technologies and Internet of Things (IoT) devices, these modern fault detection methods aim to enhance data collection and improve the accuracy and reliability of fault detection. Real-time fault diagnosis for large-scale solar arrays will be facilitated through cloud-based data storage and analysis services, thereby increasing efficiency, scalability, and system reliability.
This review indicates various smart fault detection methods that utilize emerging technologies such as IoT, cloud computing, and machine learning to improve fault diagnosis in PV systems. It examines the strengths and limitations of existing approaches while proposing a conceptual architecture for an intelligent fault detection framework.

Acknowledgements

Keywords: Deep neural network, degradation fault (DF), open-circuit fault, Internet of Things (IoT), photovoltaic, cloud computing

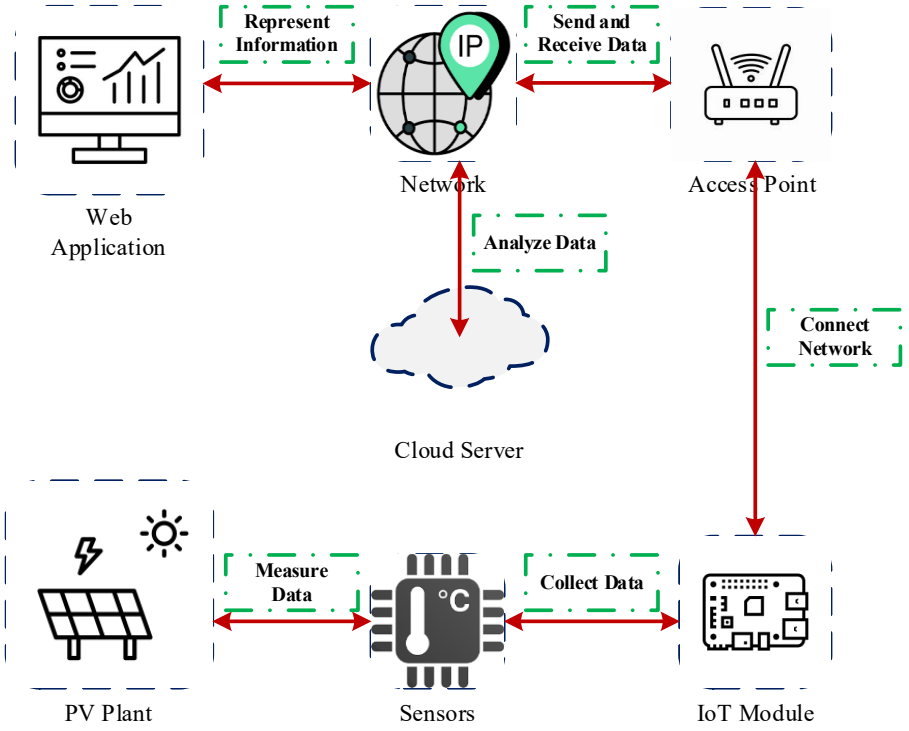


Figure 1. An IoT framework for Smart Fault Detection system

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Solar–Wind Hybrid Energy Integration on Offshore Fish Farm Structures for Sustainable Aquaculture

Hasan Kadir Çalışkan[1,2], Doc. Dr. Numan Sabit Çetin[2], Fırat Salmanoglu[2,3]

[1] Ege University/Solar Energy, City, Country
[2] Ege University/Solar Energy, City, Country
[3] Ege University/Solar Energy, City, Country
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*hasankadir816@gmail.com

Offshore fish farms require continuous electrical energy for feeding systems, monitoring devices, lighting, communication equipment, pumps, and auxiliary loads. In conventional applications, this demand is often supplied by diesel generators or external electricity sources, which increase fuel consumption, operating costs, maintenance needs, and environmental impacts. This study proposes the integration of a solar–wind hybrid renewable energy system into offshore fish farm structures as a sustainable and cost-effective energy solution.

The main advantage of the proposed concept is the use of the existing fish farm construction as a shared support structure for photovoltaic panels and small-scale wind turbines. In this way, the need for an additional offshore platform can be reduced, which may lower the initial installation and construction costs. The hybrid system is expected to meet part of the farm's electricity demand by using local solar and wind resources, while improving energy continuity compared with single-source renewable systems.

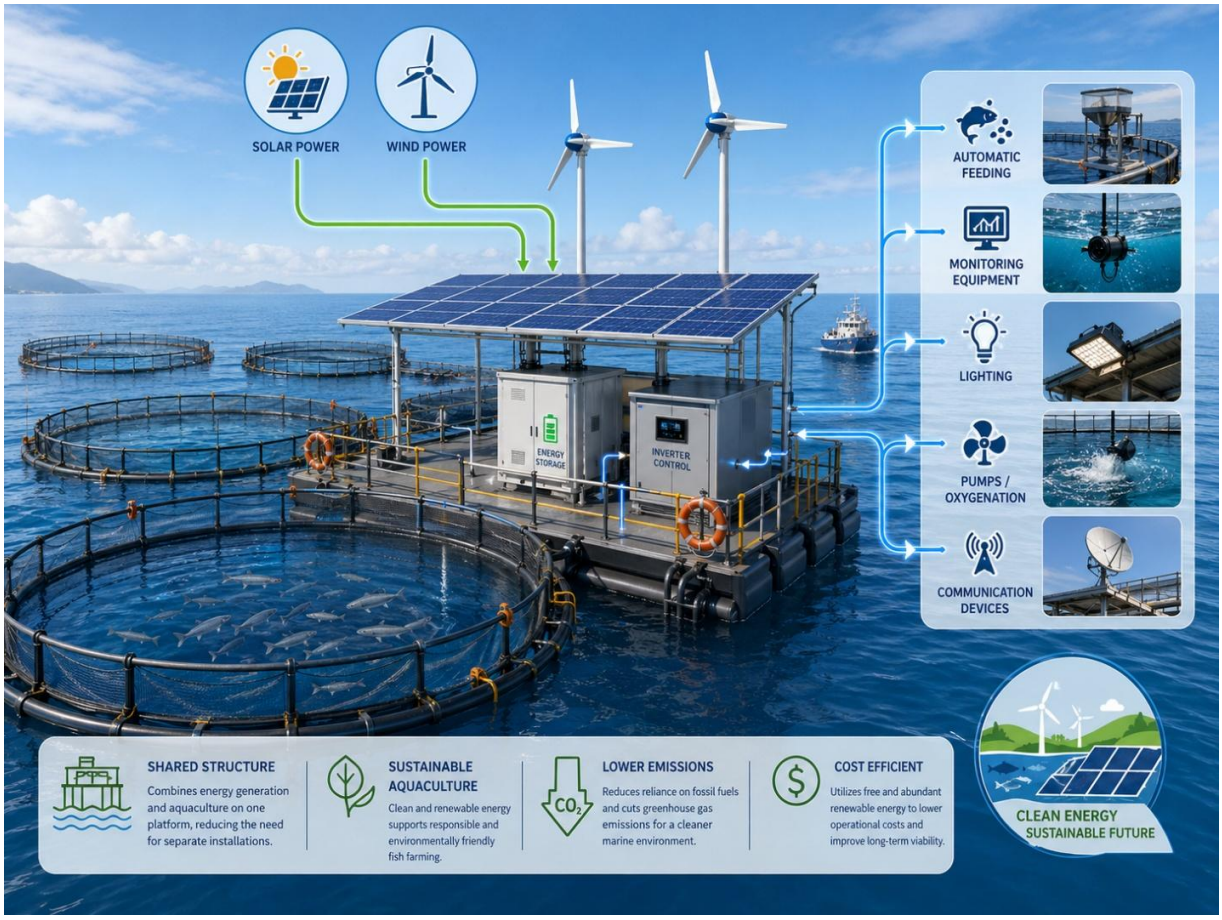
Although detailed numerical analyses have not yet been completed, the proposed system is expected to reduce dependence on diesel fuel and external electricity supply. Therefore, it may decrease operational energy costs, fuel transportation requirements, and greenhouse gas emissions. By reducing energy-related expenses, the system can contribute to lower aquaculture production costs and support a more sustainable and affordable fish supply chain. This preliminary study provides a basis for future techno-economic analysis, structural evaluation, and prototype-scale applications.

Acknowledgements

This is the abstract template document for PVCON2026.

Keywords: Solar energy; Wind energy; Hybrid renewable energy system; Offshore fish farm; Sustainable aquaculture; Cost reduction

Figure 1. Title / Description
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Implementation of a Salt-Functionalized Carbon Electrode in Dopant Free HTM Integrated Planar Perovskite Solar Cells

Zeynep Gozukara Karabag[1], Gorkem Nail Aydin[2], Ali Deniz Ucar[1,3], Figen Varlioglu Yaylali[1], Selcuk Yerci[1,3,4], Husnu Emrah Unalan[1,3,5], Gorkem Gunbas[1,2,3,6*]

[1]ODTU-GUNAM, Middle East Technical University, (METU), 06800, Ankara, Türkiye
[2]Department of Chemistry, METU, Ankara 06800, Türkiye
[3]Department of Micro and Nanotechnology, METU, Ankara, 06800, Türkiye
[4]Department of Electrical–Electronic Engineering, METU, Ankara, 06800, Türkiye
[5]Department of Metallurgical and Materials Engineering, METU, Ankara, 06800, Türkiye
[6]Department of Polymer Science and Technology, METU, Ankara, 06800, Türkiye

*contact author: ggunbas@metu.edu.tr

Solar energy has been widely recognized as a key renewable energy source for addressing global energy demands, and perovskite solar cells have emerged as promising candidates due to their high efficiencies and low fabrication costs; however, the development of stable and scalable device architectures remains a critical challenge. In this work, the use of an **dopant-free nickel phthalocyanine** (**NiPc-OR-1**) hole transport layer (HTL) in n-i-p structured perovskite solar cells is investigated, with emphasis placed on eliminating dopant-induced instability while maintaining efficient charge extraction. Dopant-free HTMs are increasingly preferred due to improved chemical long-term robustness[1]. The NiPc-OR-1 layer was systematically optimized in terms of concentration and thickness, and devices employing a gold (Au) top electrode were fabricated to establish a performance benchmark, achieving a power conversion efficiency (PCE) of **17.84%**, with an open-circuit voltage (V_{OC}) of 1.01 V, a short-circuit current density (J_{SC}) of 23.26 mAcm^{-2}, and a fill factor (FF) of 75.88%. The Au electrode was then replaced with a solution-processed **carbon paste incorporating phenethylammonium chloride (PEACl)** as an interfacial modifier, leveraging the intrinsic advantages of carbon electrodes such as low cost, chemical inertness, and compatibility with scalable printing-based fabrication[2]. A PCE of **16.09**% was obtained for the carbon-based devices, with V_{OC}= 0.99 V, J_{SC}= 22.21 mAcm^{-2}, and FF = 73.09%, demonstrating that efficient operation can be maintained when an undoped HTL is paired with a **PEACl-modified carbon electrode**, while remaining losses are attributed primarily to increased series resistance and interfacial limitations. These results indicate a viable pathway toward scalable, cost-effective, and metal-free perovskite solar cell architectures.

Acknowledgements

This research was carried out with support from the **Horizon Europe PERSEUS** project (Grant Agreement No. 101147547). The authors also acknowledge the consortium partners for providing shared protocols, measurement guidelines, and technical discussions that contributed to this work.

Keywords: Perovskite Solar Cell, Dopant-Free Hole Transport Layer, n-i-p, Salt-Functionalized Carbon Electrode

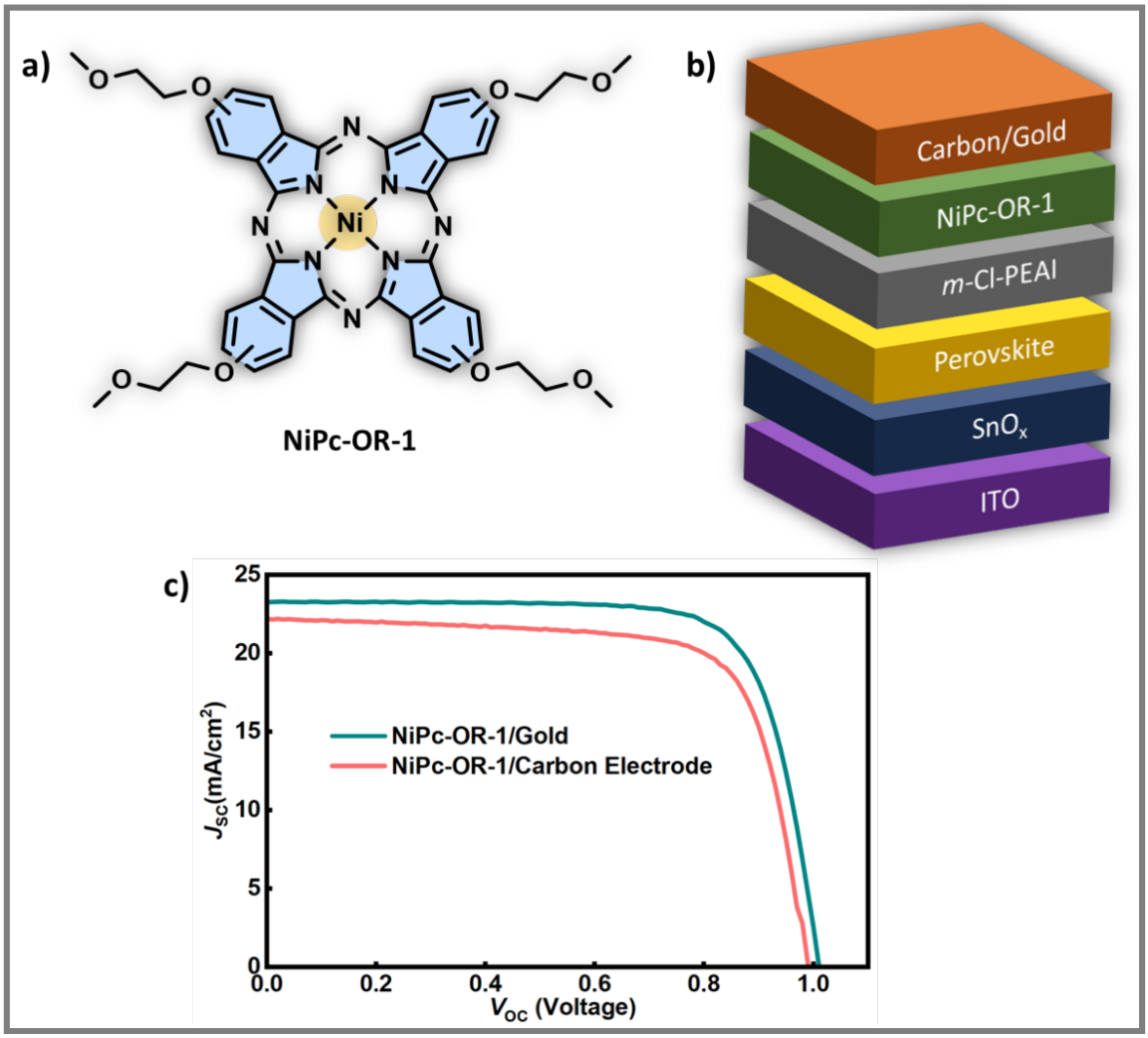


Figure 1. a) Molecule structure of **NiPc-OR-1**. **b)** Device architecture. **c)** *J-V* characteristcis of fabricated n-i-p-based PSCs.

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Comparative Analysis of Light Distribution in Agrivoltaic Systems: Fixed vs. Tracking Systems Based on Multi-Site PPFD Measurements in Türkiye

Ömer Yalçın[1]*, Duygu Kuzyaka[1], Talat Özden[1]

[1] Center of Solar Energy Research and Application (ODTÜ-GÜNAM), Ankara 06800, Turkey

*omer.yalcin@odtugunam.org

Agrivoltaic (AV) systems combine food and energy production on the same land area, offering an innovative approach to increasing land-use efficiency [1,2]. In the design of these systems, the light distribution beneath photovoltaic (PV) panels directly affects the sub-panel microclimate and agricultural yield, making PPFD the most critical parameter [3,4]. This study aims to present a comparative analysis of photosynthetic photon flux density (PPFD) distribution in single-axis solar-tracking and fixed-tilt agrivoltaic systems across different installation configurations.

To enable a site-based comparative analysis, PPFD measurements were carried out annually at three agrivoltaic facilities representing distinct climatic regions of Türkiye, i.e., Ayaş, Erciyes, and Taşarası for semi-arid, cold semi-arid, and Mediterranean to sub-humid transition climate, respectively. Single-axis tracking systems were studied at the Ayaş and Erciyes sites, while the fixed-tilt system was examined at the Taşarası site. At each facility, photosynthetically active radiation (PAR) sensors were installed at crop canopy height both beneath the PV panels and in adjacent unshaded reference areas, enabling simultaneous paired measurements. This setup allowed direct quantification of the shading effect imposed by each system type on incoming PFFD value under real operating conditions. Analysis results demonstrate that the construction type is decisive on spatial and temporal light homogeneity [3]. In fixed-tilt systems, sharp shadow bands with high spatial variation were observed due to solar movement. At the Taşarası site, the annual average PPFD calculated in the reference area was 860 µmol/m²s, but beneath the panels it dropped to the 650 µmol/m²s range. During the summer months, light reaching the area directly beneath the panel fell upto 68% of the reference value. In contrast, with tracking systems, the shaded areas are not fixed but shift position constantly [5,6]. Measurements at Erciyes and Ayaş confirm that tracking systems maintain sub-panel radiation values at high levels (800–1000 µmol/m²s even at the most shaded points during summer at Ayaş; 1500–1600 µmol/m²s at Erciyes) with a significantly more homogeneous spatial distribution of light reaching the plants [5].

In conclusion, this study demonstrates through multi-site PPFD measurements that tracking systems provide a distinct advantage for high-light-demand crops by maximizing light transmittance [5,6], while fixed systems impose consistent shading patterns that can be characterized and managed for site-specific agricultural applications [3,4].

Acknowledgements

This work has been supported by the TÜBİTAK 1004 project "Türkiye Tarımsal Üretiminde Küresel İklim Değişikliğine Uyumlu Sürdürülebilir Tarım Teknolojileri Platformu" (acronym: S-ATP), Project No: 23AG020, and by the Ankara Kalkınma Ajansı Project "Tarımsal arazinin çift yönlü kullanımına uygun yenilikçi GES uygulaması – AgroPV" (acronym: Ayaş TarımGES), Project No: TR51/21/KIRSAL/0018. Additional support was provided by a private sector project in Balıkesir-Taşarası on green leafy plants ("frontag nexus"). The authors gratefully acknowledge the support of the project partners and site owners that made this work possible. The authors gratefully acknowledge the contributions of Dilara Güney and Prof. Dr. İpek Gürsel Dino (Department of Architecture, Middle East Technical University) for the development and validation of the light distribution analysis algorithm used in this study. The authors would also like to thank the site operators of Ayaş, Erciyes, and Taşarası agrivoltaic facilities for their support in field data collection.

Keywords: Agrivoltaic, PPFD, Solar Tracking Systems, Fixed-Tilt Systems, Light Distribution, Microclimate

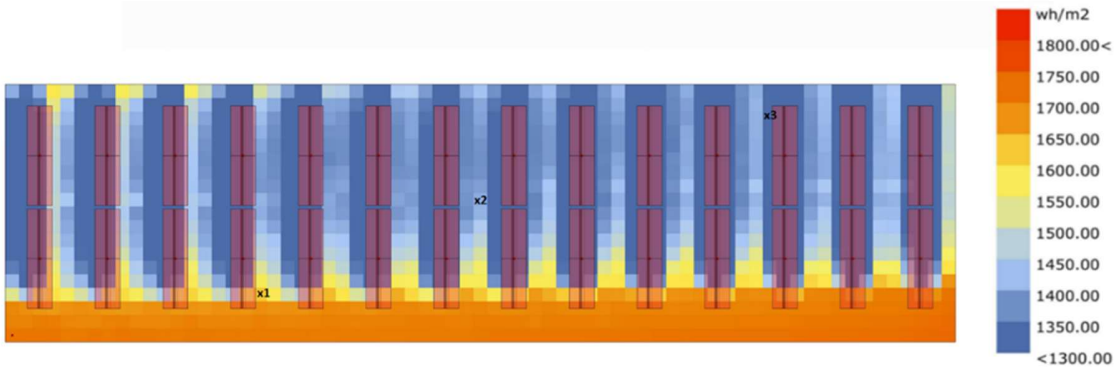


Figure 1. Side view (a) and top view (b) of the solar radiation distribution map of the Ayaş AgriPV system.

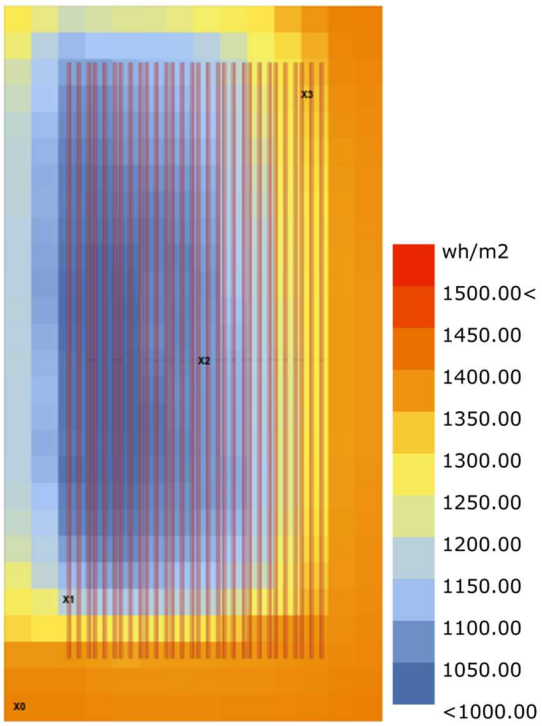


Figure 2. Solar radiation distribution map of the Erciyes AgriPV system.

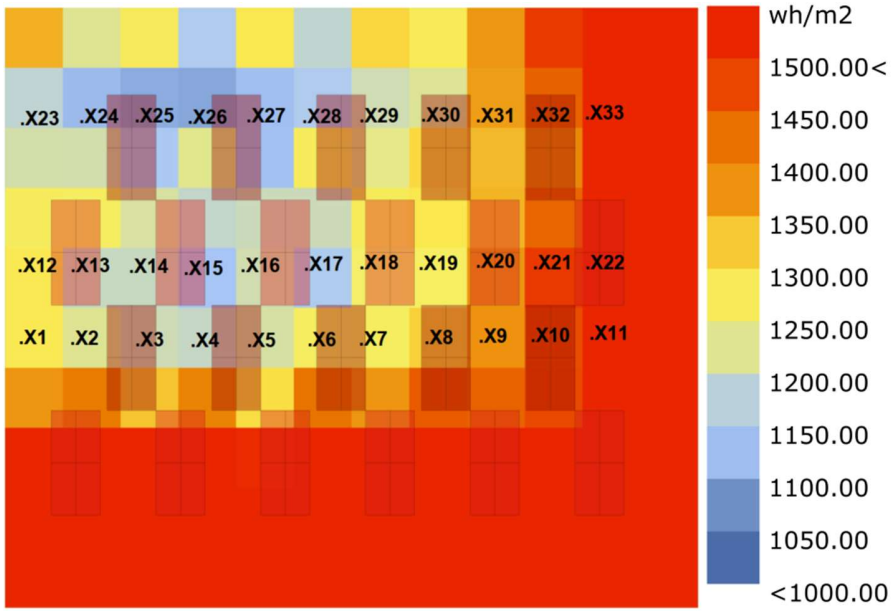


Figure 3. Solar radiation distribution map of the Taşarası AgriPV system.

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Autonomous Photovoltaic Panel Cleaning Robot: Design and Prototype Development

Vahit Cem BOZKAYA[1,2], Can Burak TURCAN[2], Ceyda Aksoy TIRMIKÇI[2,3]

[1] Sakarya University/Department of Electrical and Electronics Engineering/Sakarya/Türkiye
[2]Sakarya University/Department of Electrical and Electronics Engineering/Sakarya/Türkiye
[3] Sakarya University/Department of Electrical and Electronics Engineering/Sakarya/Türkiye

……

cem.bozkaya@ogr.sakarya.edu.tr

can.turcan@ogr.sakarya.edu.tr

caksoy@sakarya.edu.tr

Abstract— Accumulation of dust and particulate matter on photovoltaic panel surfaces is a well-documented cause of efficiency degradation in solar energy systems, with studies reporting power output losses ranging from 15% to over 30% in high-soiling environments. Manual cleaning approaches are labor-intensive, inconsistent, and increasingly impractical as solar installations scale in size. This paper presents the design and prototype development of a low-cost autonomous cleaning robot intended to address this problem at the small-to-medium installation scale.

The proposed system employs a Reuleaux triangular chassis housing three independently controlled 12V DC gear motors arranged at 120° intervals, enabling differential drive maneuverability across panel surfaces without a dedicated steering mechanism. A helical cylinder brush driven by a fourth DC motor provides continuous surface contact and mechanical agitation, supported by a brushless DC water pump delivering controlled fluid flow through a PWM-regulated MOSFET switching circuit. Panel boundary detection is achieved through two HC-SR04 ultrasonic sensors mounted at opposing ends of the chassis, enabling autonomous back-and-forth traversal within panel limits without external navigation input. All subsystems are coordinated by an ESP32-WROOM-32D microcontroller, selected for its dual-core processing capability, 16-channel PWM generation, and integrated WiFi for real-time monitoring.

The prototype demonstrates that a coherent autonomous cleaning system can be realized with commercially accessible components at significantly reduced cost compared to existing commercial solutions. Experimental validation of the cleaning cycle, edge detection response, and motor control accuracy confirms the functional viability of the proposed architecture. The work establishes a hardware and firmware foundation upon which future iterations can incorporate advanced features such as GPS-guided field navigation, computer vision-based soiling assessment, and solar-powered autonomous recharging, forming a scalable pathway toward fully autonomous large-scale PV maintenance.

Keywords: Renewable Energy, PV Cleaning, Photovoltaic Panel Cleaning, Solar Panel Maintenance, Autonomous Cleaning Robot, PV Efficiency Optimization

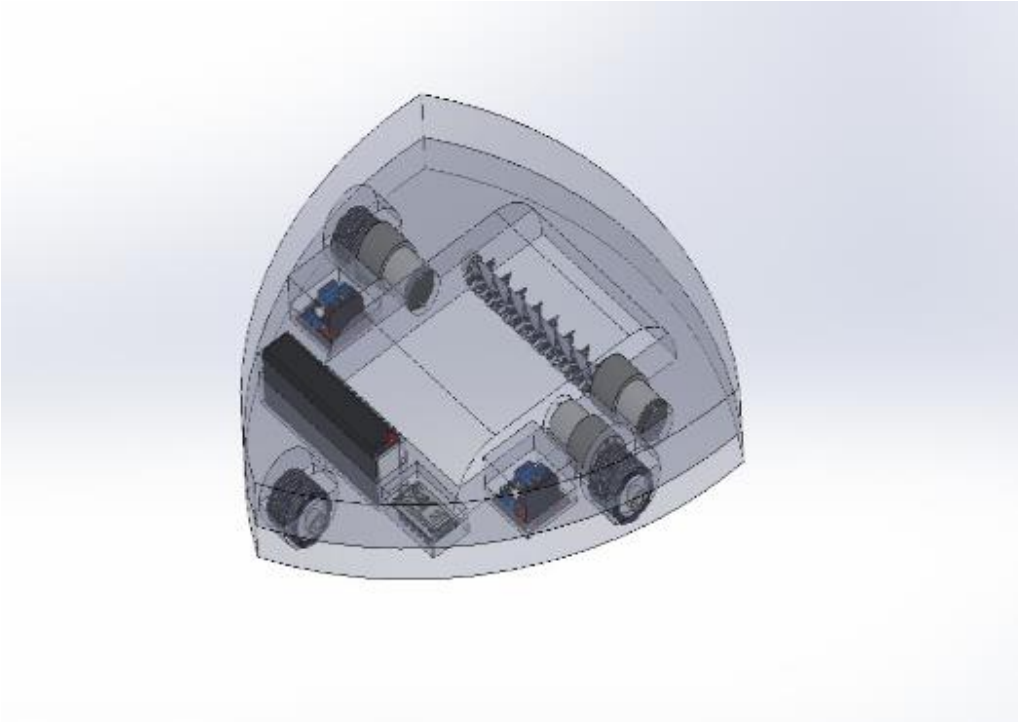


Figure 1. Transparent top view showing internal component layout

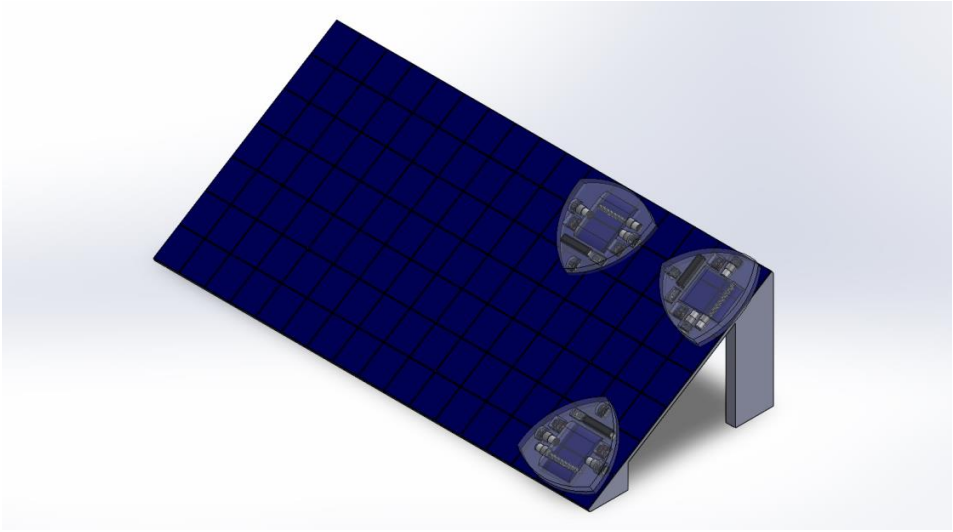


Figure 2. Robot cleaning maneuver on the solar panel

GLOBAL OPTIMIZATION OF THE IMPACT OF ENERGY STORAGE SYSTEMS ON HARMONIC CONSTRAINED HOSTING CAPACITY UNDER UNCERTAIN LOAD AND GENERATION CONDITIONS IN UNBALANCED DISTRIBUTION NETWORK

Semih ATEŞ, Numan Sabit ÇETİN, Fırat SALMANOĞLU

[1] MSc Student, Department of Electrical and Electronics Engineering, Graduate School of Natural and Applied Sciences, Ege University, Izmir, Turkey

smhats251@gmail.com

The rapid integration of photovoltaic (PV) systems into distribution networks presents significant power quality challenges, particularly concerning harmonic distortions that often reach regulatory limits before thermal or voltage constraints.[1] This research focuses on maximizing the "Hosting Capacity" (HC) of unbalanced low-voltage distribution feeders by transforming Energy Storage Systems (ESS) from passive assets into active grid balancers. Unlike traditional static capacity calculations, this study proposes a "Dynamic and Intelligent Operating Model" that leverages the multifunctional capabilities of ESS inverters for active harmonic damping and real-time capacity management.[2]

The methodology employs a high-fidelity digital twin of a three-phase unbalanced feeder, incorporating non-linear domestic and industrial load models through OpenDSS and MATLAB integration. To account for the inherent stochasticity of solar irradiance and consumer demand, the system utilizes Probability Density Functions (PDF) and Monte Carlo simulations to assess harmonic violation risks within a 95-99% confidence interval. The core of the study involves the application of meta-heuristic global optimization algorithms, specifically Particle Swarm Optimization (PSO) or Grey Wolf Optimizer (GWO) [3], to solve the multi-objective problem of maximizing PV penetration while strictly adhering to IEEE 519 harmonic standards and thermal limits.

Acknowledgements

The simulation results are anticipated to demonstrate that the proposed optimized ESS management strategy can significantly expand the feeder's hosting capacity—potentially achieving an improvement of approximately 40% compared to baseline scenarios without storage. By actively injecting harmonic currents in reverse phase to mitigate Total Harmonic Distortion (THD) and dynamically managing charge/discharge cycles, the model aims to prove that existing infrastructure can accommodate substantially higher renewable energy levels without requiring costly physical upgrades. This approach provides a scalable, smart-grid solution aligned with Turkey's "2053 Net Zero" targets and offers a technical roadmap for distribution system operators (DSOs) to optimize grid efficiency and investment.

Keywords: Hosting Capacity, Energy Storage System, Harmonics, Optimization

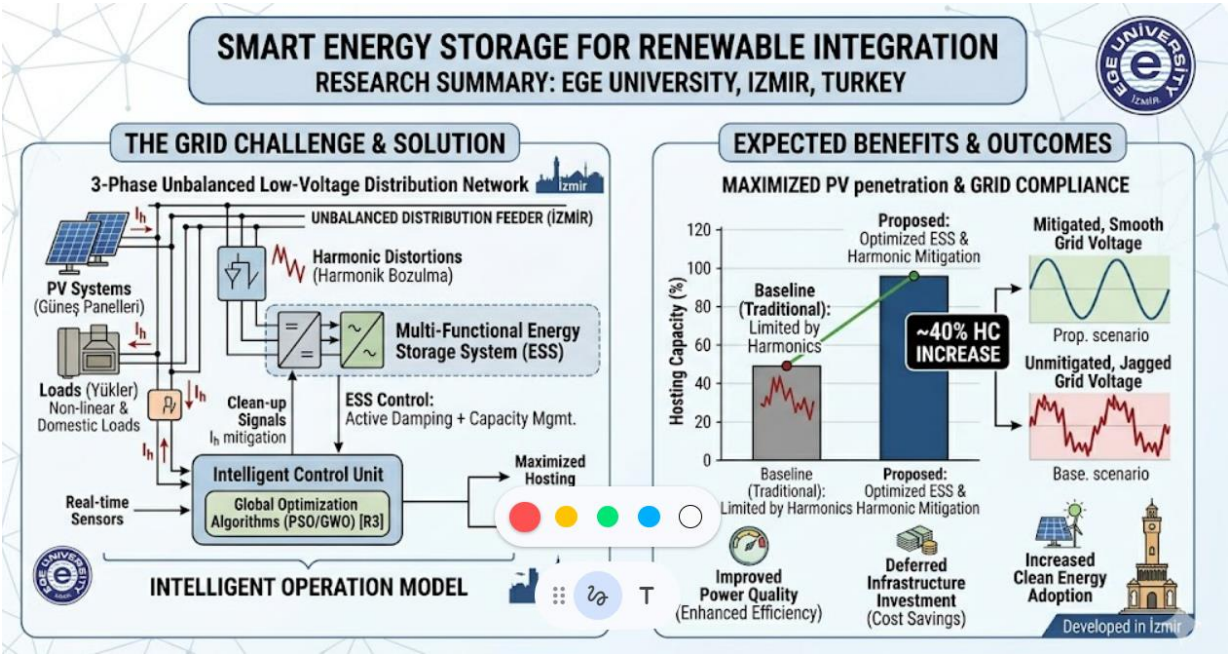
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THE EFFECT OF ENCAPSULANT MATERIALS AND EDGE SEALING ON POTENTIAL-INDUCED DEGRADATION IN PV MODULES

Utku Akbas and Abdulkerim Gok*

Gebze Technical University, Department of Materials Science and Engineering, Gebze/Kocaeli, 41400 Turkey

*agok@gtu.edu.tr

During operation, photovoltaic (PV) modules are exposed to electrical and environmental stress factors that accelerate degradation and reduce long-term performance. Among these, potential-induced degradation (PID) is a critical reliability concern, especially under elevated temperature and humidity, where leakage currents and ionic migration can induce surface polarization effects, leading to enhanced recombination and power loss. Since encapsulation materials strongly affect electrical insulation and humidity ingress, their selection is of utmost importance for improving PID resistance in PV modules.

In this study, PID behavior of one-cell mini-modules based on PERC cells were investigated using four different encapsulant materials: ethylene-vinyl acetate (EVA), ionomer, thermoplastic polyolefin (TPO), and polyolefin elastomer (POE). To evaluate the effect of edge sealing, modules were fabricated both with and without edge seals. PID tests were carried out at 85°C (dry) for 96 h under 1000 $W.m^{-2}$ illumination, and degradation was assessed by current-voltage measurements and electroluminescence imaging. The results revealed clear differences in PID resistance depending on encapsulant type. Polyolefin-based encapsulants showed improved resistance compared with EVA, while the effect of edge sealing was found to depend on the material type. The electrical analysis indicated that PID-related degradation was mainly due to increased leakage currents and shunting behavior. These findings demonstrate that encapsulant selection plays a critical role in reducing PID and improving the long-term reliability of PV modules.

Keywords: PV modules, potential-induced degradation, encapsulant materials, edge sealing, reliability

Characterization of Sputtered Metal Oxides as an Electron Selective Contacts for Flexible Gallium Arsenide Solar Cells

Hazal Zaimler[1*], Burcu Arpapay[2,3], Mustafa Kulakcı[2,4]

[1]Department of Physics, Institute of Graduate Education, Eskişehir Technical University
[2]Nanoboyut Research Laboratory, Department of Physics, Eskişehir Technical University,
[3]Depatment of Advanced Technologies, Institute of Graduate Education, Eskişehir Technical University
[4]Institute of Earth and Space Sciences, Eskişehir Technical University

*hazalzaimler@gmail.com

Electron selective contact layers (ESC) are attracting attention as non epitaxial, cost effective structures developed as an alternative to traditional doped active layers in solar cells. These layers enhance photovoltaic performance by enabling the efficient separation and collection of carriers through their asymmetric band structures[1]. This energy band asymmetry and the resulting carrier selectivity are schematically illustrated in Figure 1. The success of an ESC layer depends on striking a delicate balance between high optical transmittance which maximises the number of photons reaching the absorber layer and low series resistance, which minimises electrical losses. In this study, the characterization of TiO_2 and ZnO thin films was carried out for use as non epitaxial electron-selective contacts in GaAs based flexible solar cells[2]. These selected metal oxides exhibit Type II band alignment with GaAs; this creates a low conduction band offset for electron flow, while providing a high valence band barrier that blocks hole flow. Furthermore, due to their wide bandgaps, they minimise parasitic absorption losses by enhancing the transmission of short wavelength light to the absorber layer. Moreover, in recent studies on InP and GaAs solar cells, they have proven themselves as ESCs by achieving high efficiency values [3,4].

During the experimental process, thin films were grown on both glass and SI-GaAs substrates using the RF magnetron sputtering method under different plasma atmospheres (Ar, Ar-O_2). Taking into account the low-temperature tolerance of the flexible polyamide substrates, a Rapid Thermal Annealing (RTA) system was used at low temperatures to improve the structural and electrical properties of the films. The thermal treatments were carried out at temperatures compatible with the thermal tolerance of the flexible substrate, under different gas atmospheres (N_2, O_2/N_2, H_2/N_2).

Experimental findings have demonstrated that ZnO films exhibit high electron conductivity performance due to their high crystallinity and low resistivity values. XRD analyses have confirmed that the films possess a robust structure in which the (002) orientation is predominant. In particular, annealing in a N_2 atmosphere has minimised the resistivity by improving crystal quality and increased optical transmittance in the visible region to the 80–90% range. The crystal promoting effect of the GaAs substrate has enabled an efficient electron flow by producing sharper diffraction peaks compared to samples on glass. On the other hand, TiO_2 films exhibited higher resistivity due to the nature of the material; while maintaining its amorphous structure on glass, the formation of the rutile phase on GaAs confirmed the substrate effect. Although its structural development is limited, it provides a critical functional contribution to the system through the strong hole blocking capability offered by its wide bandgap.

In conclusion, the bilayer ESC structure, which combines the high conductivity of ZnO with the barrier properties of TiO_2, has been identified as the most efficient strategy for flexible GaAs cells. The reference parameters for cell fabrication have been determined as annealing conditions of 300°C in a N_2 atmosphere for ZnO and around 300°C for TiO_2.

Acknowledgements

This work was supported by the Scientific and Technological Research Council of Türkiye (TÜBİTAK) under project number 124F405, and by Eskişehir Technical University under Scientific Research Project (BAP) number 25ADP085.

Keywords: electron selective contacts, TiO_2, ZnO, GaAs solarcell, flexible photovoltaics, RF magnetron sputtering

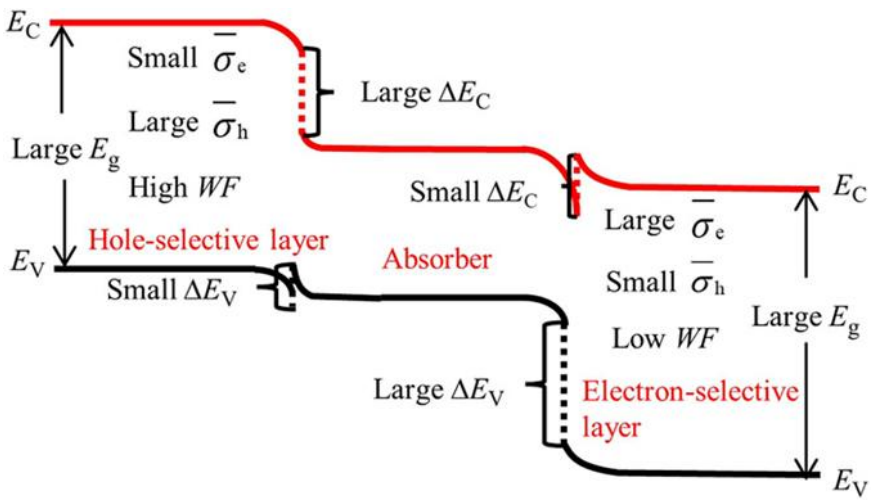


Figure 1. The energy band structure and carrier transport mechanism that determine carrier selectivity in a solar cell structure [2].

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VIPV SYSTEM DESIGN, DEVELOPMENT AND PERFORMANCE TESTS FOR AN ELECTRIC COURIER MOTORCYCLE

Ahmet Hamdi Aksoy[1,2], Yunus Çay[1], Talat Özden[1], Ahmet Necati Özsezen[2]

[1] Middle East Technical University, Solar Energy Research and Application Center (ODTÜ-GÜNAM), Ankara, Türkiye
[2] Kocaeli University, Department of Automotive Engineering, Kocaeli, Türkiye

*Corresponding Author's E-mail: [ahmet.aksoy@odtugunam.org]

IIn this study, an integrated system based on shingled cell technology is developed within the framework of Light Vehicle Integrated Photovoltaic (VIPV) applications to extend the range of an electric motorcycle. The research encompasses the design and fabrication of PERC-based shingled cells, the development of a Multiple Maximum Power Point Tracking (MMPPT) charging circuit, the prototyping of a reference cell-based irradiance sensor, and full system integration.

Four distinct ETFE-based flexible panels are designed and integrated onto the surfaces of the motorcycle's delivery box. The shingled cell architecture is optimized by controlling the overlap width to maximize power output [1], while addressing the specific challenges and advantages of cut solar cells in high-efficiency modules [2]. The selection of encapsulation strategies and polymer materials is critical for ensuring mechanical reliability and managing optical and current variations in these semi-flexible, lightweight modules [3, 4]. Specifically, the encapsulation design must be carefully investigated for specialized vehicle applications like solar racing or delivery systems [5].

The system architecture employs a custom MMPPT charging unit consisting of independent boost converters for each panel, which went through comprehensive simulation and prototyping to address urban driving dynamics and achieve highly efficient energy conversion [6]. To enhance experimental precision, a custom irradiance sensor, comprising PERC-type reference cells and calibrated outdoors against thermopile sensors, is also developed according to international standards [7].

Field tests conducted under real-world conditions validated the shingled panel performance, charging efficiency, and range enhancement parameters. These evaluations specifically accounted for the dynamic output variations inherent in vehicle-mounted photovoltaic modules under diverse driving conditions [8]. The results demonstrate that the driving range increased by approximately 20% over an 11-hour period, with 45.1% of the total energy being generated by the top surface panel. This study contributes an innovative, self-charging electric micro-mobility concept to the literature, supported by optimized solar power generation technology and advanced control strategies for electric vehicle charging [9].

Acknowledgements

The author would like to thank iTECH Solar and ODTÜ GÜNAM for their technical support and contributions to this research.

Keywords: Electric motorcycle, vehicle-integrated photovoltaics (VIPV), shingled PV modules, multiple maximum power point tracking (MMPPT), reference cell, PV mobility monitoring systems



Figure 1. The electric courier motorcycle equipped with flexible shingled PV panels (top, front, right, left surfaces), reference irradiance sensors, and data acquisition system before real-world driving and parking tests.

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LEVELIZED PROFITABILITY AND NET FEASIBILITY ANALYSIS OF PV-INTEGRATED ZERO EMISSION FERRIES IN TÜRKİYE

Caner Pense[1], Bülent G. Akınoğlu[2,3,4]

[1] Department of Maritime Transportation Engineering, Bandırma Onyedi Eylül University, Balıkesir, Turkey
[2] Earth System Sciences, Graduate School of Natural and Applied Sciences, Middle East Technical University, Ankara, Turkey

*cpense@bandirma.edu.tr

The decarbonization of maritime transportation requires precise economic metrics to assess the viability of electric ferries. This research bridges solar energy economics with maritime intelligent transportation systems, establishing a standardized financial blueprint for green maritime transition. This study adapts advanced levelized financial parameters -specifically Levelized Cost of Energy (LCOE), Levelized Revenue of Energy (LROE), and Levelized Profitability of Energy (LPOE)- to electric ferry operations, utilizing real-world and simulated data from high-density routes in İzmir. Moving beyond standard static feasibility studies, the methodology applies the Net Feasibility Measure (NFM) to evaluate PV-integrated onboard and shore-based charging infrastructure over a 20-year operational horizon. Findings demonstrate that the NFM framework provides a more granular assessment of regional economic viability for electric ferries than conventional payback periods.

Keywords: Electric Ferries, Photovoltaic Integration, Levelized Profitability (LPOE), Net Feasibility Measure (NFM), Techno-Economic Analysis

Advanced Photoluminescence Imaging Method: Investigating Recombination-Generation Mechanisms in Perovskite Solar Materials via Pixel-Wise k-factor Mapping

Muhammed Çoban

Middle East Technical University, ODTÜ - GÜNAM/ Department of Physics, Ankara, Turkiye
muhammed.coban@metu.edu.tr

Photoluminescence-based imaging methods are highly applicable in solar cell research, providing a contactless and rapid means to evaluate the quality of perovskite thin films. By utilizing the power-law relationship and performing a pixel-wise assignment of the proportionality constant k, it is possible to examine the dominant recombination-generation (R-G) mechanisms and assess the localized quality of the film. The aim of this project was to determine the parameter k, also known as the optical ideality factor, which allowed for the distinction between the R-G processes of different regions within the solar cell. These calculations were performed by collecting multiple data points of the photoluminescence intensity using a camera, while monitoring excitation intensity via the current values of the light source for each pixel. Following these calculations, as shown in Figure 1 & 2, k-factors were found to be closer to 1 for modules dominated by band-to-band recombination, whereas values around 2 were observed for regions where Shockley-Read-Hall (SRH) recombination was the dominant mechanism.

Keywords: Perovskite Modules, Photoluminescence, Recombination-Generation, Photovoltaics, Imaging Methods, k-factor, k-mapping

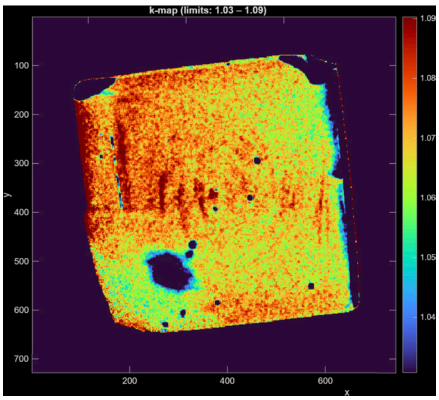


Figure 1: Generated k-map

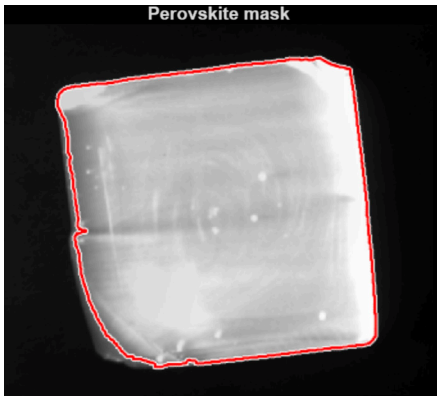


Figure 2: Photoluminescence Image

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Performance Engineering of Two-Terminal Perovskite/Silicon Heterojunction Tandem Solar Cells

N. S. Bozkurt[1,2], A. Arslan[2,3], A. Yildiz[1,2]

[1] *Department of Energy Systems Engineering, Faculty of Engineering and Natural Sciences, Ankara Yildirim Beyazit University, Ankara 06010, Türkiye*
[2] *The Center for Third Generation Solar Cells Research and Applications (SOLAR 3.0), Ankara Yıldırım Beyazıt University, Ankara 06010, Türkiye*
[3]Department of Electronics and Automation, Technical Sciences Vocational School, *Ankara Yildirim Beyazit University, Ankara 06010, Türkiye*

* nsbozkurt@aybu.edu.tr

Perovskite/silicon tandem solar cells have attracted significant attention as a promising approach to overcome the efficiency limitations of single-junction photovoltaic devices. In this study, a two-terminal (2T) tandem structure is investigated using the solar cell capacitance simulator in one dimension (SCAPS-1D) simulation software. The top sub-cell is based on a planar FTO/ETL/perovskite/HTL configuration, while the bottom sub-cell is designed as a silicon heterojunction (SHJ) structure consisting of a-Si(p^+)/a-Si(i)/c-Si/a-Si(i)/a-Si(n^+) layers. This configuration enables effective carrier separation and reduced recombination losses. Key device parameters, including absorber thickness, bandgap energy, defect density, and interface properties, are varied to evaluate their influence on overall device performance. Particular attention is given to current matching between the top and bottom sub-cells, which is essential for maximizing efficiency in 2T tandem structures. In addition, recombination mechanisms at interfaces and within absorber layers are considered. The aim of this work is to provide a clearer understanding of the relationship between material properties and tandem device performance. The results are expected to offer useful insights for the design and optimization of high-efficiency perovskite/silicon tandem solar cells.

Keywords: perovskite, SCAPS-1D, tandem solar cells, silicon, simulation

Design and Optimization of Current-Matched Lead-Free Two-Terminal Perovskite Tandem Solar Cells

A. Arslan[1,2], N. S. Bozkurt[2,3], A. Yildiz[2,3]

[1] Department of Electronics and Automation, Technical Sciences Vocational School, *Ankara Yildirim Beyazit University, Ankara 06010, Türkiye*
[2] *Department of Energy Systems Engineering, Faculty of Engineering and Natural Sciences, Ankara Yildirim Beyazit University, Ankara 06010, Türkiye*
[3] *The Center for Third Generation Solar Cells Research and Applications (SOLAR 3.0), Ankara Yıldırım Beyazıt University, Ankara 06010, Türkiye*

* aykutarslan@aybu.edu.tr

The perovskite materials with high absorption coefficients and tunable bandgaps in tandem solar cells are highly promising to exceed the theoretical efficiency limits (Shockley-Queisser limit) of conventional silicon (Si)-based solar cells. The optoelectronic performance of monolithic two-terminal (2T) tandem solar cells with lead-free and mixed-halide perovskite top cells and crystalline silicon (c-Si) or narrow-bandgap perovskite bottom cells through theory aided by experiments are investigated. Herein, using the solar cell capacitance simulator in one dimension (SCAPS-1D) simulation software, the basic device parameters such as thickness, bandgap, bulk defect density, and carrier doping concentration of both sub-cells were optimized systematically to investigate their impact on overall device performance. The optimum power conversion efficiency was achieved using a current matching strategy. The optimization results reveal that the existing matching between the sub-cells and the minimization of the carrier-recombination losses are attained by carefully tuning the bandgap and thickness of the top cell. The optimization processes demonstrated significant improvements in the open circuit voltage, short circuit current density and fill factor of the designed tandem structures. It was shown that power conversion efficiency was significantly enchanced, depending on the material configuration. These findings provide a critical guidance for the design, interface engineering and practical fabrication of high-efficiency, stable and eco-friendly next generation tandem solar cells.

Keywords: Tandem Solar Cells, Perovskite, Silicon (c-Si), SCAPS-1D, Lead-free Perovskites

Institutionalizing Circularity and Resource Sovereignty in the PV Industry: A Cross-Country Comparative Analysis

Tayfun HIZ[1,2]

[1] ODTU-GUNAM, Middle East Technical University, 06800, Ankara, Turkiye
[2] Middle East Technical University, Department of Earth System Science, 06800, Ankara, Turkiye

*hiz@metu.edu.tr

The exponential expansion of the global solar photovoltaic (PV) industry has firmly secured its role as the backbone of the clean energy transition. To sustain this unprecedented growth and ensure the long-term strategic position of PV in the sector, a paradigm shift from linear resource consumption to robust circular value chains is now imperative. Nations increasingly recognize the approaching massive wave of end-of-life PV panels [1] not as future liabilities, but as critical assets for industrial sovereignty and resource security [2]. However, the profound lack of institutionalization across the sector demands a strategic pivot towards structuring and formalizing circularity. While technological advancements in material recovery are globally driven, the institutional environments governing these circular transitions present a distinct heterogeneity shaped by national dynamics. To systematically understand how this divergence in national policies, industry norms, and societal perceptions shapes varying circularity strategies, this study presents a cross-country comparative analysis utilizing Richard W. Scott's 'Three Pillars of Institutions' [3] (Regulative, Normative, and Cultural-Cognitive) as the theoretical framework (Figure 1). Methodologically, the research employs a rigorous qualitative design to model the institutionalization of solar circularity, developing a comprehensive multi-level coding hierarchy that identifies the structural building blocks within each pillar as proposed by institutional theory. Serving as empirical input data for this framework, a diverse corpus of legislative texts, industry standards, and policy position papers from mature and emerging markets is structurally coded and analyzed. While the regulative framework is often viewed as the cornerstone of institutional maturity, the weakness or complete absence of the other pillars results in an uneven foundation, preventing the construction of an effective circular PV value chain. Ultimately, the study provides a strategic blueprint for policymakers and industry stakeholders to align these three pillars. The findings offer vital insights for PV panel manufacturers to secure long-term resource sovereignty, guide the technological research and development activities, and pinpoint the opportunities for entrepreneurs.

Acknowledgements

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Keywords: Solar Photovoltaics, Circular Economy, Institutional Theory, Comparative Policy Analysis, End-of-Life Management, Recycling

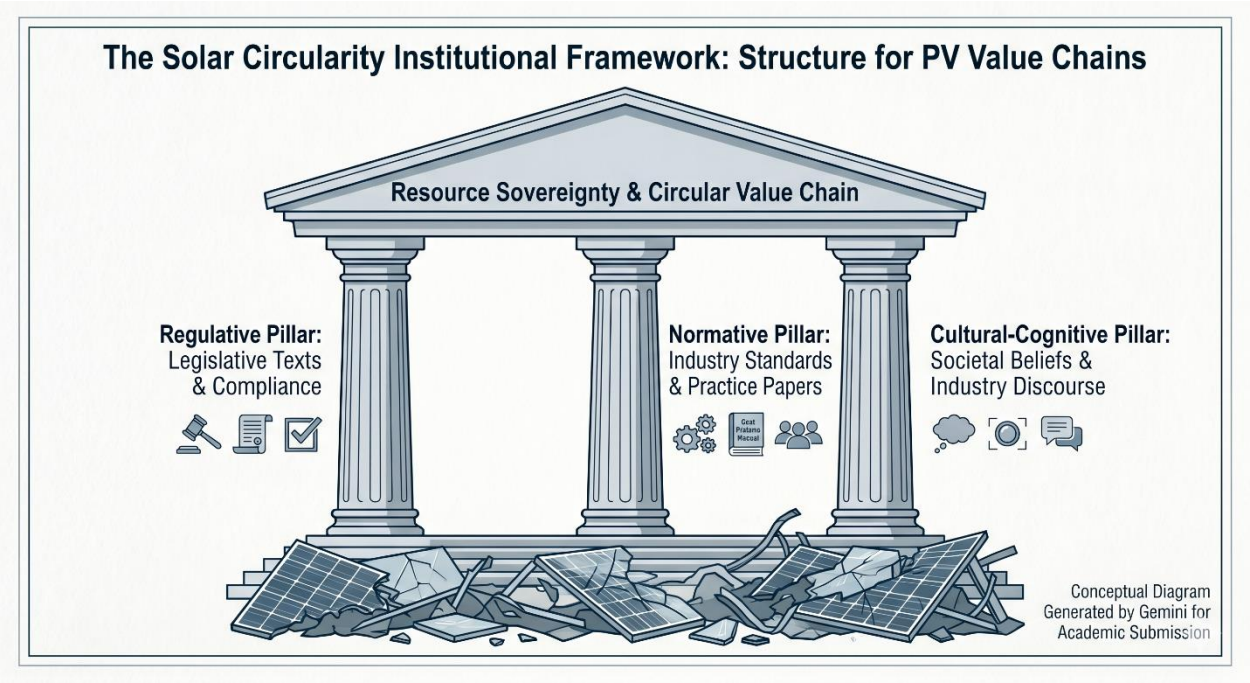


Figure 1. Figure 1: Conceptual Framework for Institutionalizing PV Circularity

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ROOM TEMPERATURE, ANNEAL-FREE RF MAGNETRON SPUTTERED SnO_x ELECTRON TRANSPORT LAYERS FOR PLANAR PEROVSKITE SOLAR CELLS

Busra Ileri[1], Aliekber Karabag[1], Selcuk Yerci[1,2], Gorkem Gunbas[1,3]

[1] ODTU GUNAM, Middle East Technical University, Çankaya, Ankara 06800, Türkiye
[2] Department of Electrical Electronics Engineering, Middle East Technical University, Cankaya, Ankara 06800, Türkiye
[3] Department of Chemistry, Middle East Technical University, Cankaya, Ankara 06800, Türkiye
* syerci@metu.edu.tr

Perovskite solar cells (PSCs) have high efficiency potential but face significant challenges in long-term stability and scalability. High-quality, cost-effective, and efficient electron transport layers (ETL) are crucial for addressing these issues. Tin oxide (SnO_2) is the most widely used electron transport layer (ETL) material in PSCs due to its suitable band alignment, high transparency, and excellent electron mobility. Various deposition methods, such as spin-coating, chemical bath deposition, and magnetron sputtering, have been utilized for the fabrication of SnO_2 films. Each deposition technique has its own advantages and suitable applications. Different from the solution method, magnetron sputtering is one of the most mature film deposition techniques in industry with many advantages and such as a fast deposition speed, uniform and dense film formation, and solvent-free deposition process. All these advantages make magnetrons puttering an attractive option for future industrial production [1].

In this study, RF magnetron sputtering parameters (RF power, oxygen ratio, thickness and annealing temperature) were systematically optimized to fabricate SnO_x thin films using a metallic Sn target. These films were employed as electron transport layers (ETLs) in a planar PSC architecture. Optimized conditions included 100% O_2, 6 mTorr process pressure, and 50 W RF power. The ultra-thin (12.8 nm) anneal-free sputtered-SnO_x layer was confirmed to have an amorphous structure by Grazing Incidence X-ray diffraction (GI-XRD) (Figure 1). Despite its amorphous structure, the champion device delivered a power conversion efficiency (PCE) of 20.50%, with a V_{OC} of 1.09 V, a J_{SC} of 23.63 mA/cm², and a fill factor (FF) of 79.35%, as shown in the current density–voltage (J–V) characteristics in Figure 2. A comparison with solution-processed SnO_x films was also performed to evaluate the impact of the deposition method on surface chemistry and defect density. X-ray photoelectron spectroscopy (XPS) analyses (Figure 3) revealed that, compared to solution-processed SnO_x, the sputtered-SnO_x had over 50% lower hydroxyl content and a Sn:O ratio of 1:2.30, indicating minimised surface defects. These results demonstrate that thin, anneal-free, vacuum-based SnO_x provides a robust ETL approach for highly efficient, flexible, and scalable PSCs. This method is suitable for industrial applications.

Acknowledgements

This study was supported by Scientific and Technological Research Council of Türkiye (TUBITAK) under the Grant Number of 124N957. The authors thank to TUBITAK for their supports. The authors also thank ODTU-GUNAM for access to synthesis, characterization, and cell fabrication facilities.

Keywords: RF Magnetron Sputtering, Tin Oxide, Electron Transport Layer (ETL), Perovskite Solar Cell (PSCs)

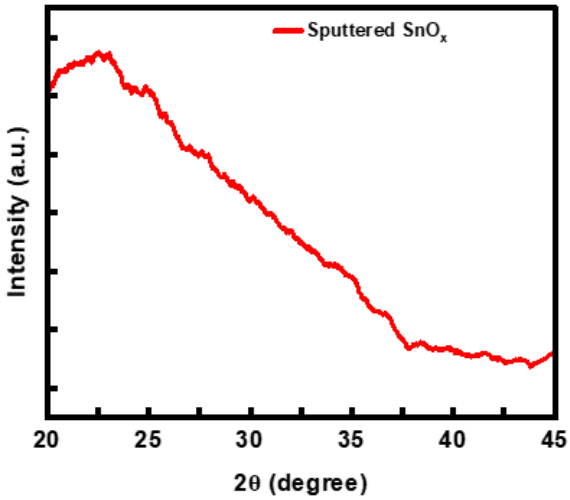


Figure 1. Grazing incidence X-ray diffraction (GI-XRD) pattern of the sputtered SnO_x layer.

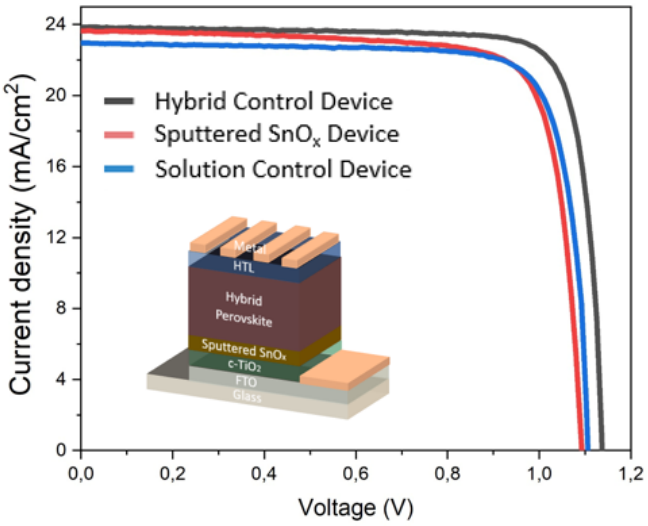


Figure 2. XPS analysis of solution-processed and sputtered SnOx films: (a) O 1s spectra and (b) Sn 3d spectra.

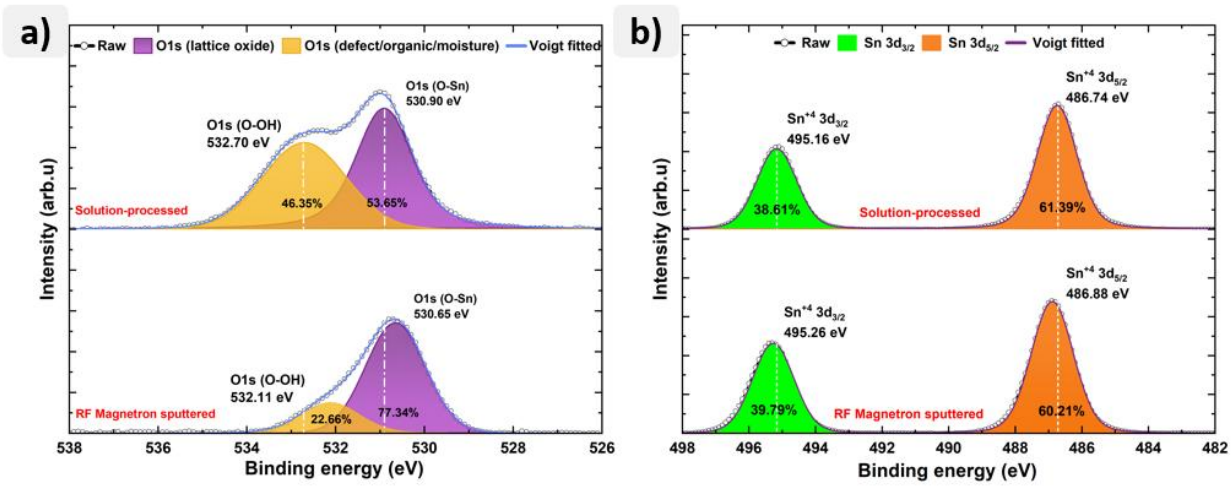


Figure 3. XPS analysis of solution-processed and sputtered SnO_x films: (a) O 1s spectra and (b) Sn 3d spectra.

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Interface Engineering of C_{60} and PCBM for Reduced Recombination in Lead-Free Cs_2AgBiX_6 (X = Cl, Br, I) Perovskite Solar Cells Using SCAPS-1D

Marzieh Shirazi[1,2]

[1] *Department of Converging Technologies, Khatam University, Tehran, Iran*
[2] *Pasargad Institute for Advanced Innovative Solutions (PIAIS), Tehran, Iran*

Abstract

Enhancing the performance of environmentally sustainable perovskite solar cells using lead-free double perovskites such as Cs_2AgBiX_6 (where X = Cl, Br, I) requires effective strategies to reduce interfacial recombination losses that hinder device efficiency. In this study, we utilize numerical simulations with SCAPS-1D to explore the effects of electron transport layer (ETL) interfaces, particularly C_{60} and PCBM, on charge transport, recombination dynamics, and photovoltaic performance.

The simulations systematically examine the influence of energy level alignment, interface defect density, and carrier mobility at the Cs_2AgBiX_6/ETL interface. Our results reveal that interfacial energetics play a critical role in suppressing nonradiative recombination. The C_{60}, PCBM as Cs_2AgBiX_6/ETL interface improves band alignment with Cs_2AgBiX_6 absorbers, facilitating more efficient electron extraction and reducing carrier accumulation at the interface. Additionally, lowering interface defect density significantly suppresses Shockley–Read–Hall recombination, leading to notable improvements in open-circuit voltage and fill factor.

The research underscores the significance of interface engineering and the careful selection of ETL in effectively minimizing recombination losses and improving device performance.
These results offer important perspectives on the design and enhancement of lead-free perovskite solar cells, highlighting the critical role of interface management in achieving stable, high-efficiency photovoltaic devices.

Keywords: Lead-free double perovskites, Cs_2AgBiX_6, SCAPS-1D, Interfacial recombination losses

Emails: shirazi.marzieh@gmail.com
m.shirazi01@khatam.ac.ir

AGRIVOLTAICS AS A TOOL FOR JUST TRANSITION IN CARBON-INTENSIVE RURAL AREAS: AN ASSESSMENT OF YOUNG FARMERS' PERSPECTIVES IN SOMA, TÜRKİYE

Bilge Senturk[1], Tolga Senturk*[2],

[1] Middle East Technical University, Center for Solar Energy Research and Applications (ODTU-GUNAM), Ankara, Türkiye
[2] Izmir Katip Celebi University/Department of Media and Communication, İzmir, Türkiye

*tolga.senturk@ikc.edu.tr

In the context of demographic aging of agricultural populations across Europe and the Mediterranean basin, ensuring farming continuity and establishing viable agricultural conditions have become critical imperatives. Agrivoltaic systems (APV)—the co-location of solar photovoltaics and agricultural production—represent a strategic innovation with the potential to incentivize younger generations to remain in the sector. While existing scholarship has predominantly investigated general farmer receptivity, the specific perspectives of young farmers—key actors for agricultural resilience—remain conspicuously underrepresented.

This study investigates young farmers' perceptions of APV as a response to structural impediments, including land tenure barriers, income volatility, and complexities of generational succession. Utilizing a qualitative methodology, the research draws upon semi-structured, in-depth interviews to explore the motivations, expectations, and anxieties shaping their engagement with agricultural innovation. Crucially, the inquiry focuses on an under-researched context: rural communities reliant on thermal power generation navigating coal phase-out processes. Centering on the Soma district in western Türkiye—a region characterized by intensive agriculture and just transition pressures—the study includes young practitioners from coal-sector households. This "dual embeddedness" positions them at the nexus of energy transition dynamics and rural livelihood vulnerability. By centering the lived experiences of this demographic, the study contributes original empirical evidence to contemporary discourse on agrivoltaic diffusion, just transition equity, and the conditions under which renewable energy integration fosters authentic rural development.

Keywords: agrivoltaics, renewable energy, agriculture, just transition, young farmers, Türkiye

EXPLORING OF THE VIABILITY OF POTENTIAL BUSINESS MODELS FOR AGRIVOLTAIC SYSTEMS IN TÜRKİYE: A QUALITATIVE INVESTIGATION THROUGH MULTI-STAKEHOLDER PERSPECTIVES**

Betul Ergun[1], Bilge Senturk[2*], Cisel Ekiz Gokmen[3], Talat Ozden[4]**

[1] Mugla Sıtkı Kocman University, Labor Economics and Industrial Relations, Muğla, Türkiye

[2] Middle East Technical University, Center for Solar Energy Research and Applications (ODTU-GUNAM), Ankara, Türkiye

[3] Mugla Sıtkı Kocman University, Labour Economics and Industrial Relations, Muğla, Türkiye

[4] Middle East Technical University, Center for Solar Energy Research and Applications (ODTU-GUNAM), Ankara, Türkiye

*bilge.senturk@odtugunam.org

Agrivoltaic systems offer strategic potential by enabling simultaneous agricultural and energy production on the same land, reducing energy costs while enhancing resilience against climate risks. However, realizing this potential depends on developing appropriate institutional structures, governance mechanisms, and sustainable business models. While global applications vary among farmer, private sector, and cooperative-based models, facilities in Türkiye remain largely at the R&D and pilot stages, creating a significant research gap regarding which business models are viable in the local context.

Addressing this gap, this study aims to investigate the feasibility of potential business models based on the perspectives, motivations, and institutional capacities of key actors central to the expansion of agrivoltaics in Türkiye. Adopting a qualitative research methodology, in-depth interviews were conducted with 35 participants from 27 different organizations, including renewable energy companies, renewable energy, agricultural and irrigation cooperatives, local governments, public research centers, private investors, and NGOs. Within the scope of the analysis, the institutional readiness of the organizations, their strategic strengths, and the structural challenges they face in operationalizing these systems were examined through a multi-layered stakeholder analysis. The study analyzes each actor's position and potential complementary roles within the ecosystem—ranging from the organizational capacity of cooperatives and the local service visions of municipalities to the financial competencies of the private sector and the technical guidance of R&D centers. Consequently, the research aims to identify which business model approaches best align with existing institutional capacities under Türkiye's specific regulatory, financial, and ownership structures, and how sectoral collaborations can generate synergy.

Keywords: Agrivoltaic Systems, Solar Energy, Agricultural Production, Business Models, Türkiye.

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**This study is derived from the ongoing doctoral dissertation of Betül Ergün.

*** Corresponding author

Anthranilic Acid-Functionalized UiO-66-NH_2 Interfaces for Improved Crystallinity and Charge Transport in Perovskite Solar Cells

Dilek ÇIRAK [1], Selin YILMAZ YILDIRIM [1], Burak GÜLTEKİN [1]

[1] EgeUniversity Solar Energy Institute, Izmir, Türkiye

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* dilekcirak89@gmail.com

Metal–organic frameworks (MOFs) are crystalline porous materials composed of organic linkers coordinated to metal ions or clusters. Due to their high surface area, tunable pore structure, and chemical versatility, MOFs have gained significant attention in energy-related applications [1]. In perovskite/MOF hybrid systems, MOFs can act as microporous interfacial scaffolds that regulate perovskite film formation, improve crystallinity, facilitate charge extraction, suppress recombination, and enhance device stability [2].

In this work, UiO-66-NH_2, a zirconium-based MOF, was synthesized and functionalized with anthranilic acid, which contains both carboxylic acid and amino groups. This modification was designed to improve interfacial charge transfer, reduce defect density, and enhance the photovoltaic performance of perovskite solar cells. FTIR and Raman spectroscopy were used to investigate the structural changes and chemical interactions involved in the functionalization process. Powder XRD confirmed that the MOF framework was preserved after functionalization, while thin-film XRD showed improved perovskite crystallinity on the functionalized MOF scaffold. In addition, UV–Vis absorption, photoluminescence emission, and scanning electron microscopy analyses were performed to evaluate the optical properties, charge recombination behavior, surface morphology, and film quality of the perovskite films after incorporation of the functionalized MOF layer. Perovskite solar cells with the architecture FTO/SnO_2/Functional-MOF/Perovskite/Spiro-OMeTAD/MoO_3/Ag were fabricated and characterized by current–voltage and IPCE measurements. Compared with reference devices, the functionalized MOF-based cells showed increased short-circuit current density and improved power conversion efficiency. Electrochemical impedance spectroscopy was further performed to examine recombination and charge transport processes.

Overall, anthranilic acid-functionalized UiO-66-NH_2 serves as an effective interfacial layer for enhancing charge transfer and device efficiency, offering a promising strategy for high-performance and scalable perovskite solar cells.

Acknowledgements

I would like to acknowledge the Presidency of Turkey, the Department of Strategy and Budget for infrastructure, and some of the consumables. In addition, I would like to acknowledge the EGE UNIVERSITY Office of Scientific Research Projects (Project No: 32665) for providing financial support for the manufacture of solar cells and the supply of some consumables. The author acknowledge TÜBİTAK 2211-C National PhD Scholarship Program for its financial support.

Keywords: metal organic frameworks, perovskite solar cell, interface layer.

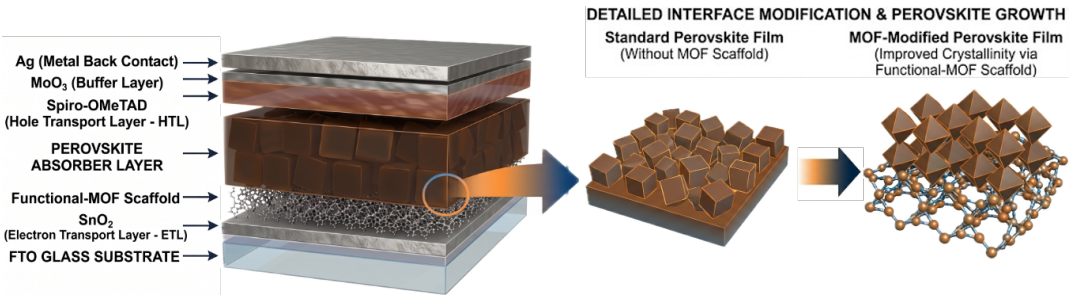


Figure 1. Schematic illustration of the perovskite solar cell architecture (FTO/SnO2/Functional-MOF/Perovskite/Spiro-OMeTAD/MoO3/Ag) and the comparative crystallization mechanism of the perovskite film with and without the functionalized UiO-66-NH2 scaffold.

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Effect of ALD-Based Nickel and Aluminum Interfacial Modifications on Charge Transfer Dynamics in Perovskite Solar Cells

Selin YILMAZ YILDIRIM, Dilek ÇIRAK, Burak KAHRAMAN,Burak GÜLTEKİN

Ege Unıversity ,Solar Energy Institute
*seliinyyilmaz@gmail.com

Interface engineering has emerged as a crucial strategy for enhancing the performance of perovskite solar cells (PSCs) by facilitating efficient charge extraction and suppressing non-radiative recombination losses. Among the available techniques, Atomic Layer Deposition (ALD) stands out as a powerful method due to its ability to produce conformal, pinhole-free thin films with precise thickness control at the atomic scale. Recent studies have demonstrated that ALD-deposited NiO_x layers significantly improve hole extraction kinetics (Kim et al., 2024), while ultra-thin Al-based metal oxide interlayers provide effective surface passivation and favorable energy level alignment (Zhang et al., 2023). In addition, ALD-engineered interfacial architectures have also been reported to further enhance charge transport and device stability in advanced perovskite solar cell structures (Lee et al., 2023).

In this study, Ni- and Al-based interfacial layers were fabricated via ALD to systematically investigate their synergistic effects on charge carrier dynamics. The structural and morphological properties of the deposited films were characterized by spectroscopic ellipsometry and X-ray diffraction (XRD), confirming their uniformity and phase purity. The optical properties of the modified interfaces were further analyzed using absorbance (Abs) and photoluminescence (PL) spectroscopy, revealing improved band alignment and reduced trap-assisted recombination.

Device performance was evaluated through current density–voltage (J–V) and incident photon-to-electron conversion efficiency (IPCE) measurements, which demonstrated enhanced short-circuit current density and overall power conversion efficiency compared to control devices. Additionally, electrochemical impedance spectroscopy (EIS) was employed to probe charge transfer resistance and recombination dynamics. The results confirm that the integration of ALD-engineered Ni and Al interfacial layers effectively enhances charge collection and transport, offering a scalable and high-precision approach for the development of high-performance PSCs.

Acknowledgements

I would like to acknowledge the Presidency of Turkey, the Department of Strategy and Budget for infrastructure, and some of the consumables.

Keywords: Perovskite solar cells, Atomic layer deposition (ALD), Interface engineering, Charge transfer dynamics, Nickel oxide, Aluminum oxide, Electrochemical impedance spectroscopy (EIS).

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Development of MXene/PEDOT:PSS Hybrid Electrodes as an Alternative to ITO for Flexible Optoelectronic Devices

Gulsah Yilmaz[1] Burak Gultekin[1]

[1] Ege University Solar Energy Institute, İzmir, Türkiye

*ylmazgulsah1982@gmail.com

This study focuses on developing $Ti_3C_2T_x$ (MXene) and PEDOT:PSS-based hybrid structures as an alternative to Indium Tin Oxide (ITO) electrodes, which are traditionally used in flexible perovskite solar cells (FPSCs) but tend to crack and break when bent.

In rigid solar cells, ITO is generally preferred on glass substrates, and in flexible photovoltaic solar cells, it is preferred on flexible substrates such as PET and PEN. Commercially available electrode materials like ITO have limitations. Due to the high cost of the raw material, high roughness, and brittleness of ITO, it exhibits limited mechanical performance [1]. For these reasons, MXenes, which benefit from advantages such as low cost, high transparency, flexibility, and simple manufacturing, are a promising alternative to expensive electrodes. MXenes, a versatile class of two-dimensional materials, also possess superior properties such as excellent metallic conductivity, abundant surface functional groups, tunable operating functions, high optical transparency, and mechanical robustness [2]. Furthermore, in this study, PEDOT:PSS will be used in conjunction with MXene. The reason for using PEDOT:PSS is that the polymer chains intercalate between the MXene layers, physically preventing the re-aggregation of these layers [3].

In the first stage of the study, aluminum layers were successfully removed by etching the Ti_3AlC_2 MAX phase with HF, and well-delaminated MXene flakes at nanoscale dimensions were obtained by sonication. The prepared MXene/PEDOT:PSS hybrid films were applied to PET and glass substrates by spin coating. Characterization studies showed that pure MXene films exhibited high surface resistance due to their layered agglomeration structure, but PEDOT:PSS polymer chains interbedded between these layers, preventing re-aggregation. SEM and XRD analyses confirmed that the MXene layers were successfully embedded into the PEDOT:PSS matrix and that this interaction strengthened the conductive network structure.

According to the results obtained, the surface resistance in the optimized hybrid films was dramatically reduced to levels of 10^2 Ohm/sq, and the conductivity was calculated as 1.2×10^4 S/m. These findings reveal that MXene/PEDOT:PSS composite structures are a promising electrode alternative offering high stability and conductivity for flexible optoelectronic devices.

Acknowledgements

This work was supported by the **Ege University Scientific Research Projects Coordination Unit (BAP)** under Project Number **32608**. Additionally, **Gülşah Yılmaz** acknowledge the financial support provided by **The Scientific and Technological Research Council of Türkiye (TÜBİTAK)** through the **2211-C** National PhD

Scholarship Program for Priority Areas. Furthermore, **Burak Gultekin** would like to acknowledge the **Presidency of Turkey, Department of Strategy and Budget** for providing the infrastructure and essential consumables (Project No: **2016 K121200—16DPT002**).

Keywords: MXene, PEDOT:PSS, Hybrid Electrodes, ITO (Indium Tin Oxide), Thin Film Characterization.

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DFT-Generated Theoretical Framework for the Predictive Screening of Self-Assembled Monolayers

Feyza Güler[1], Cem Maden[2,3], Hande Toffoli[1,3]

[1] *Middle East Technical University, Department of Physics, Çankaya, Ankara 06800, Türkiye*
[2] *ODTU GUNAM, Middle East Technical University, Çankaya, Ankara 06800, Türkiye*
[3] *Middle East Technical University, Micro and Nanotechnology Program, Çankaya, Ankara 06800, Türkiye*
*feyza.guler@metu.edu.tr

Self-assembled monolayers (SAMs) have emerged as highly promising interfacial modifiers in perovskite solar cells, as their molecular properties are crucial for both interfacial stability and efficient charge transport. While experimental studies in the literature help to understand how SAM molecules work, testing so many candidates in a laboratory takes too much time and is very expensive.

To build a reliable foundation, a dataset of approximately 200 SAM molecules was initially collected. Using the RDKit library, 217 molecular descriptors were generated for each molecule. A systematic correlation analysis was then performed to identify the dominant physical features that influence device performance, such as the impact of specific functional groups on the fill factor (Figure 1).

In this project, Density Functional Theory (DFT) calculations are used to study potential SAM molecules found in the literature and evaluate their physical stability and electronic properties. Although the initial Random Forest model predicted current density (J_{sc}) with an R-value of 0.724 (Figure 2), structural features alone were not enough for a complete physical model. Therefore, departmental computing resources are used to calculate and fill the missing data gaps in the existing literature. For each molecule, basic electronic properties like HOMO/LUMO levels and band gaps are calculated. Their binding energies are also investigated to see how well they stick to target surfaces.

Currently, these computational results are being collected to build a reliable dataset consisting of approximately 200 SAM molecules. Next, machine learning will be used to analyze this newly generated data and predict device parameters based on molecular structure. The plan is to identify the top 5 to 10 best-performing candidates and look closely at their common structural features and molecular descriptors. Once these key features are found, they will be verified using further DFT calculations.

Using these pure computational results, the aim is to build a solid physics-based model. Specifically, the most promising candidates will be those that bind strongly to the surface and have the ideal band gap for efficient charge transfer. Ultimately, this theoretical approach will allow SAM candidates to be easily screened and the best molecules to be predicted for highly efficient and stable perovskite solar cells.

Keywords: Perovskite solar cells, Self-assembled monolayers (SAMs), Density Functional Theory (DFT), Machine learning, Computational screening, Interface engineering

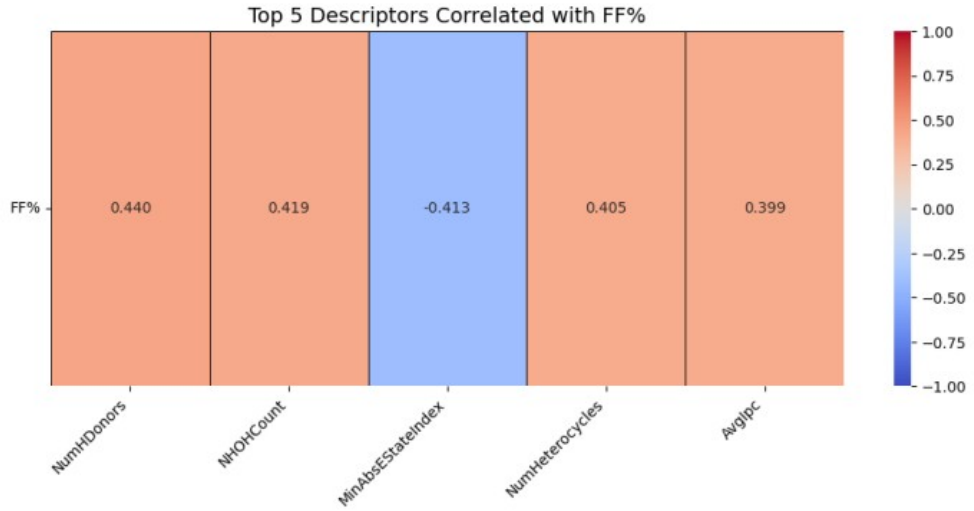


Figure 1: Top 5 molecular descriptors correlated with Fill Factor (FF). Red indicates positive correlation, while blue indicates negative correlation.

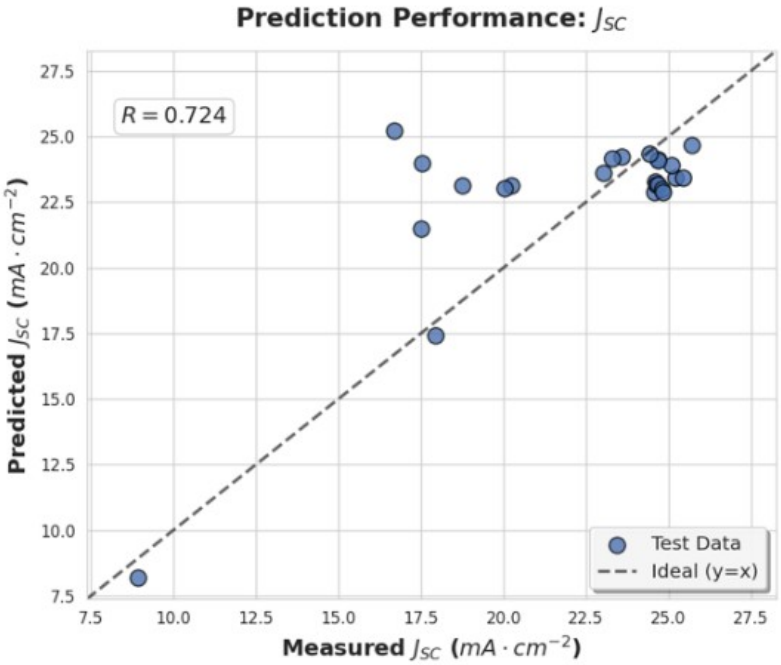


Figure 2: Predicted vs. Measured values for Short-Circuit Current Density (J_{sc}) using the Random Forest model (R = 0.724).

Optimizing Self-Assembled Monolayer Deposition via Machine Learning for Enhanced p–i–n Perovskite Solar Cells

Gulay Zeynep Gunel[1,*], Sevdiye Başak Turgut[1], Burak Kahraman[1], Ceylan Zafer[1]

[1] Ege University Solar Energy Institute, Izmir, Turkey.

*zeynepgunel94@gmail.com

Self-assembled monolayers (SAMs) have emerged as a key strategy for improving energy level alignment and reducing interfacial defects in p–i–n perovskite solar cells (PSCs).[1–3] However, determining optimal deposition conditions for newly developed SAM molecules typically requires extensive and time-consuming experimental efforts. In this study, we present a systematic, data-driven optimization of the deposition process for a triazatruxene-based SAM on transparent conductive substrates. To explore the complex, multi-dimensional parameter space—including solution concentration, solvent composition, and thermal annealing conditions—we employed Bayesian optimization to guide the experimental workflow. A surrogate model, progressively refined through experimental feedback, successfully captured the relationship between processing parameters and device performance. Initial optimization cycles resulted in a maximum power conversion efficiency (PCE) of 15.9%, highlighting the capability of the model to identify promising processing windows with a limited number of experiments. The chemical anchoring of the SAM onto the substrate was verified by X-ray photoelectron spectroscopy (XPS). Moreover, steady-state and time-resolved photoluminescence (PL/TRPL) measurements indicated enhanced charge extraction and suppressed non-radiative recombination at the SAM/perovskite interface compared to non-optimized devices. These findings demonstrate that Bayesian optimization provides an effective and scalable approach for accelerating the development of high-performance interfacial layers in next-generation photovoltaics.

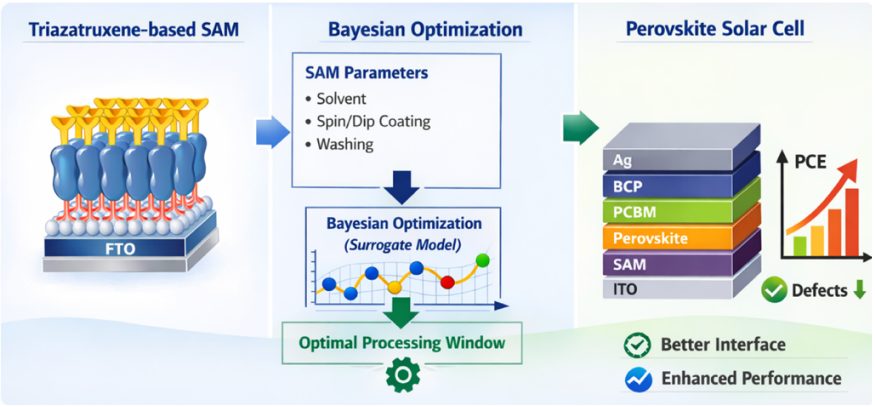


Figure 1. Bayesian optimization-assisted tuning of triazatruxene-based SAM deposition enables optimal processing conditions, reduced interfacial defects, and enhanced PCE in p–i–n perovskite solar cells.

Acknowledgements

The authors acknowledge financial support from the Strategy and Budget Department of the Presidency of the Republic of Türkiye (Grant No. 16DPT002), Ege University Scientific Research Projects (BAP, Project No: 32965), and TÜBİTAK 1002 – Rapid Support Program (Project No: 125Z201). Gülay Zeynep Günel also acknowledges support from the TÜBİTAK 2211-C National PhD Scholarship Program.

Keywords: perovskite solar cells, self assembled mololayer, hole transport materials, triazatruxene, passivation layer.

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Optimizing PbI_2/CsBr Seed Layer Thickness for Conformal Coverage on Saw-Damaged Silicon for Perovskite/Si Tandem Applications

Bahri Eren Uzuner[1,*], Görkem Günbaş[1], Selçuk Yerci[1]

[1] ODTU-GUNAM, Ankara, Turkiye

*eren.uzuner@odtugunam.org

Perovskite/Silicon tandem solar cells have garnered significant attention for their potential to surpass the theoretical efficiency limits of single-junction devices by broadening the spectral absorption range.[1,2] However, the transition from planar substrates to textured surfaces, such as saw-damaged (SD) silicon wafers, presents challenges in maintaining thin-film conformality. In this work, we provide a guideline for the thickness optimization of the PbI_2/CsBr seed layer to ensure full surface coverage on rough SD surfaces. To mimic the electrical environment of a 2T tandem structure, boron-doped SD silicon wafers were utilized as substrates. The stack was initiated with a double-layered ITO contact (150 nm RF-sputtered and 15 nm DC-sputtered) to simulate the recombination layer. Subsequently, PbI_2/CsBr mixed layers of 400 nm and 650 nm were deposited via thermal co-evaporation.[3] To evaluate the coverage, 100 nm of point-shaped Copper (Cu) was deposited as a top contact (**Figure 1A**). Our methodology relies on a straightforward electrical diagnostic: incomplete coverage leads to direct contact between Cu and the underlying Si/ITO stack, resulting in an ohmic response. Conversely, a continuous PbI_2 layer, being a semiconductor with a direct bandgap (PL peaks at 2.35 eV and 2.43 eV), is expected to form a Schottky contact with Cu, exhibiting characteristic diode behavior (**Figure 1B**). Experimental IV measurements revealed that Si/ITO/NiO_x/Cu reference layers exhibited ohmic behavior across all contacts, likely due to the inadequate coverage of the thin NiO_x on the SD surface morphology (**Figure 1C**). For the PbI_2/CsBr templates, the 400 nm layer showed ohmic characteristics in over 50% of the pixels, indicating significant shunting where the Cu metal penetrated the seed layer (**Figure 1D**). In contrast, the 650 nm template demonstrated diode behavior in 6 out of 7 pixels, confirming successful PbI_2 coverage and the elimination of direct metal-to-substrate shunting (**Figure 1E**).

In conclusion, this electrical screening method provides a robust, low-complexity approach to optimizing the initial stages of hybrid perovskite deposition without the need for full tandem device fabrication. Further optimization will focus on varying deposition rates to enhance film conformality at lower thicknesses for high-performance 2T tandem integration.

Acknowledgements

This study was supported by the Scientific and Technological Research Council of Türkiye (TUBITAK) under the Grant Number 124N957. The authors thank TUBITAK for their support. The authors also thank ODTU-GUNAM for access to synthesis, characterization, and cell fabrication facilities.

Keywords: tandem, perovskite, hybrid approach, conformal coating, schottky-contact, ohmic-contact

Figures

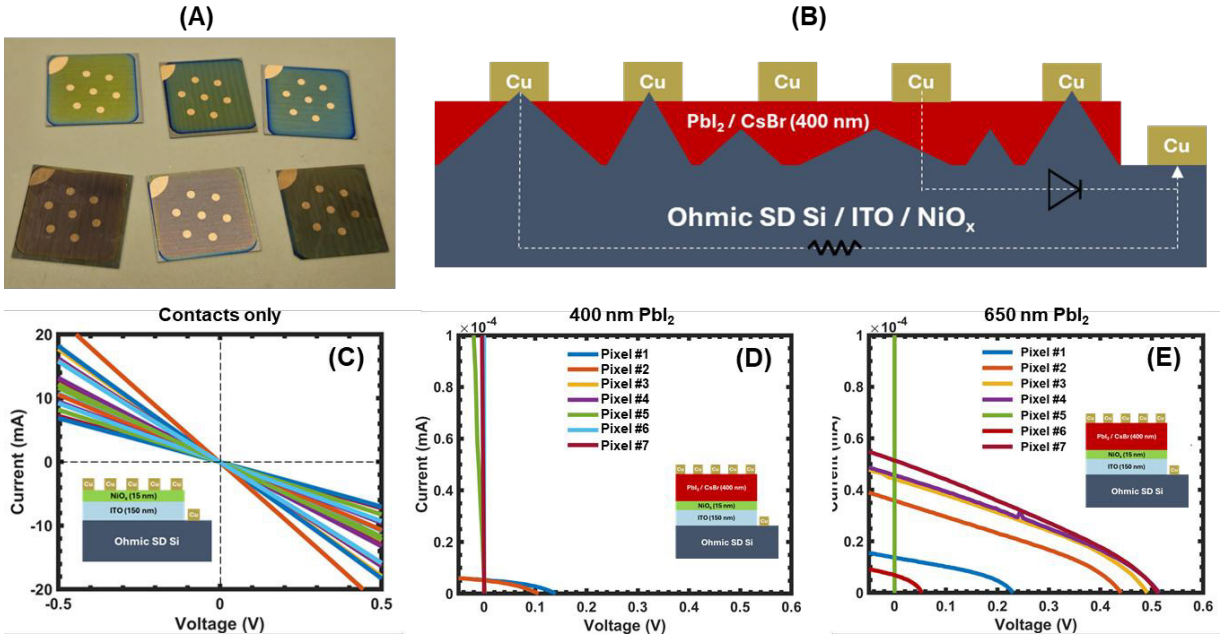


Figure 1. (A) Photographs of the samples with only contact layers (top) and contacts with PbI2/CsBr seed layers **(B)** Cross-sectional schematic of the formation of ohmic and Schottky contacts on the designed multi-layers. IV curves of **(C)** Si / ITO / NiO_x / Cu, **(D)** Si / ITO / NiO_x / PbI_2-CsBr (400 nm) / Cu, **(E)** Si / ITO / NiO_x / PbI_2-CsBr (650 nm) / Cu multi-layers. Insets, the cross-sectional schematics of the fabricated multi-layers are given.

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Picosecond Laser-Assisted Selective Poly-Si Patterning for TOPCon Solar Cells via Alkaline Etching

Shojaa Abusakha[1,2], Bülent Arıkan[1], Mert Yiğit Kaplan[1], Gökhan Altıner[1], Hisham Nasser[1], Raşit Turan[1,3]

[1]Center for Solar Energy Research and Applications - GÜNAM, Ankara, Türkiye
[2]Micro and Nanotechnology, Middle East Technical University, Ankara, Turkey
[3]Department of Physics, Middle East Technical University, Ankara, Turkey

Shojaa.nafeth@odtugunam.org

TOPCon solar cells leverage a doped poly-Si/SiO_2 passivating contact to achieve outstanding surface passivation[1], yet full-area poly-Si introduces broadband parasitic absorption that limits photocurrent. Confining poly-Si to narrow fingers beneath the metal contacts mitigates this loss while preserving passivation quality[2,3]. This work presents two maskless, industrially compatible picosecond laser-based routes for selective poly-Si finger formation followed by alkaline wet etching. In the first route (Laser Oxidation), a green ps laser irradiates the HF-cleaned poly-Si surface, triggering surface amorphization and oxygen incorporation to form a thin a-SiO_x etch barrier[4] that locally protects the poly-Si during KOH etching while the surrounding field poly-Si is selectively removed. Etch selectivity is confirmed by the contrasting response of laser-defined regions to KOH-only versus HF + KOH treatments. In the second route, PSG Ablation, the native phosphosilicate glass formed during $POCl_3$ diffusion is selectively ablated in the inter-finger regions at higher laser fluences, leaving the unirradiated PSG as a natural alkaline-resistant mask during subsequent KOH etching. Both routes yield well-defined finger structures confirmed by sheet resistance mapping, ECV carrier concentration profiling, optical microscopy, and profilometry. Etch kinetics studies reveal non-linear poly-Si removal behaviour governed primarily by temperature, and a sequential KOH–HF–KOH strategy is shown to ensure complete poly-Si elimination. The ps pulse regime further limits laser-induced subsurface damage to a considerably shallower depth than nanosecond equivalents[5], preserving the integrity of the passivating contact. The approach is maskless, vacuum-free, and fully compatible with standard LPCVD-based TOPCon fabrication sequences, offering a scalable pathway toward high-efficiency selective-contact cells. Further improvements, together with the effects and outcomes of the demonstrated process on the optical and electrical parameters of TOPCon solar cell precursors, will be presented at the conference.

Keywords: TOPCon, poly-Si patterning, picosecond laser, laser oxidation, PSG ablation

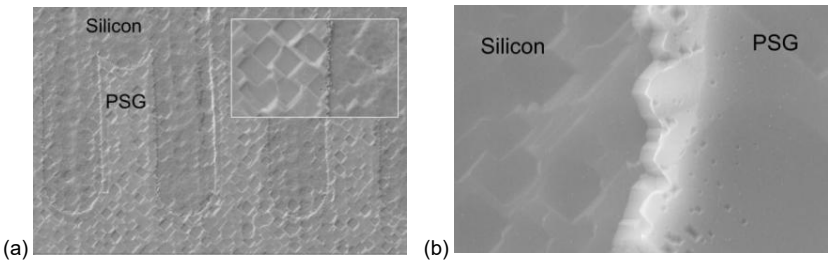


Figure 3.(a) shows the finger-like structure formed after PSG removal, while (b) highlights the step height difference between the etched and untreated PSG regions.

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Computational Study of Hydrophobic Ammonium Salts for Defect Passivation in $FAPbI_3$-Based Indoor Perovskite Solar Cells

Cem Maden[1,2], Esra Eroğlu[1], Hande Toffoli[2,3], Gorkem Gunbas[1,3,4] , Selcuk Yerci[1,2,5], Aliekber Karabag[*1]

[1] ODTU GUNAM, Middle East Technical University, Çankaya, Ankara 06800, Türkiye
[2] Middle East Technical University, Micro and Nanotechnology Program, Çankaya, Ankara 06800, Türkiye Country
[3] Middle East Technical University, Department of Physics, Çankaya, Ankara 06800, Türkiye
[4] Department of Polymer Science and Technology, METU, 06800 Ankara, Turkiye
[5] Electrical Engineering Department, METU, 06800, Ankara, Turkiye

*Corresponding author: aliekber.karabag@odtugunam.org

Perovskite solar cells (PSCs) have gained significant interest for indoor photovoltaic applications due to their high power conversion efficiencies under low light conditions. Defect passivation remains one of the key challenges for long term device stability. In this work, a series of phenylethylammonium iodide (PEAI)-based mono- and di-ammonium salts with hydrophobic substituents (F, Cl, Br, CF_3, CH_3) were studied as passivating agents for $FAPbI_3$ perovskite surfaces using Density Functional Theory (DFT). Structural optimizations were performed on both pristine and iodine defected surfaces to understand how vacancy defects effects the adsorption behavior of each salt. Charge density difference maps showed how electrons redistribute at the salt and perovskite interface, and density of states (DOS) calculations revealed the electronic changes brought by different functional groups. Binding energies between −4.17 and −7.00 eV indicate strong molecule surface interactions for all configurations, with defective surfaces showing consistently stronger adsorption. The type, position, and number of hydrophobic groups, as well as mono- versus di-ammonium character, were found to directly influence passivation efficiency and interfacial charge transfer. To evaluate the thermal stability of the most promising configurations, ab initio molecular dynamics (AIMD) simulations will be carried out at finite temperatures, both in vacuum and in humid conditions. These results offer a practical computational basis for designing better passivating agents for indoor PSCs.

Keywords: perovskite solar cells, defect passivation, phenylethylammonium iodide, density functional theory, charge density difference, density of states, ab initio molecular dynamics, indoor photovoltaics

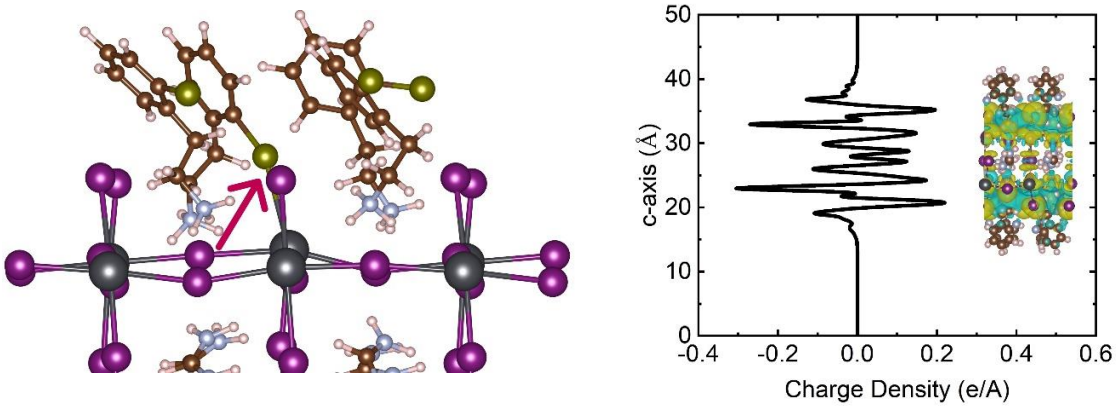


Figure 1. (Left) Optimized adsorption geometry of o-Br-FEAI on the defective $FAPbI_3$ perovskite surface. The red arrow indicates the interaction between the functional group of the salt and the exposed Pb atom at the iodine vacancy site. (Right) Planar-averaged charge density difference profile along the c-axis for the o-Br-FEAI/$FAPbI_3$ interface. Positive and negative values correspond to charge accumulation and depletion, respectively. The inset shows the three-dimensional charge density difference isosurface of the optimized system.

ROOM TEMPERATURE, ANNEAL-FREE RF MAGNETRON SPUTTERED SnO_x ELECTRON TRANSPORT LAYERS FOR PLANAR PEROVSKITE SOLAR CELLS

Busra Ileri[1], Aliekber Karabag[1], Selcuk Yerci[1,2,3], Gorkem Gunbas[1,2,3]

[1] ODTU GUNAM, Middle East Technical University, Çankaya, Ankara 06800, Türkiye
[2] Micro and Nanotechnology Department, METU, 06800, Ankara, Türkiye
[3] Department of Electrical Electronics Engineering, Middle East Technical University, Cankaya, Ankara 06800, Türkiye
[4] Department of Chemistry, Middle East Technical University, Cankaya, Ankara 06800, Türkiye

Perovskite solar cells (PSCs) have high efficiency potential but face significant challenges in long-term stability and scalability. High-quality, cost-effective, and efficient electron transport layers (ETL) are crucial for addressing these issues. Tin oxide (SnO_2) is the most widely used electron transport layer (ETL) material in PSCs due to its suitable band alignment, high transparency, and excellent electron mobility. Various deposition methods, such as spin-coating, chemical bath deposition, and magnetron sputtering, have been utilized for the fabrication of SnO_2 films. Each deposition technique has its own advantages and suitable applications. Different from the solution method, magnetron sputtering is one of the most mature film deposition techniques in industry with many advantages and such as a fast deposition speed, uniform and dense film formation, and solvent-free deposition process. All these advantages make magnetrons puttering an attractive option for future industrial production [1].

In this study, RF magnetron sputtering parameters (RF power, oxygen ratio, thickness and annealing temperature) were systematically optimized to fabricate SnO_x thin films using a metallic Sn target. These films were employed as electron transport layers (ETLs) in a planar PSC architecture. Optimized conditions included 100% O_2, 6 mTorr process pressure, and 50 W RF power. The ultra-thin (12.8 nm) anneal-free sputtered-SnO_x layer was confirmed to have an amorphous structure by Grazing Incidence X-ray diffraction (GI-XRD) (Figure 1). Despite its amorphous structure, the champion device delivered a power conversion efficiency (PCE) of 20.50%, with a V_{OC} of 1.09 V, a J_{SC} of 23.63 mA/cm², and a fill factor (FF) of 79.35%, as shown in the current density–voltage (J–V) characteristics in Figure 2. A comparison with solution-processed SnO_x films was also performed to evaluate the impact of the deposition method on surface chemistry and defect density. X-ray photoelectron spectroscopy (XPS) analyses (Figure 3) revealed that, compared to solution-processed SnO_x, the sputtered-SnO_x had over 50% lower hydroxyl content and a Sn:O ratio of 1:2.30, indicating minimised surface defects. These results demonstrate that thin, anneal-free, vacuum-based SnO_x provides a robust ETL approach for highly efficient, flexible, and scalable PSCs. This method is suitable for industrial applications.

Acknowledgements

This study was supported by Scientific and Technological Research Council of Türkiye (TUBITAK) under the Grant Number of 124N957. The authors thank to TUBITAK for their supports. The authors also thank ODTU-GUNAM for access to synthesis, characterization, and cell fabrication facilities.

Keywords: RF Magnetron Sputtering, Tin Oxide, Electron Transport Layer (ETL), Perovskite Solar Cell (PSCs)

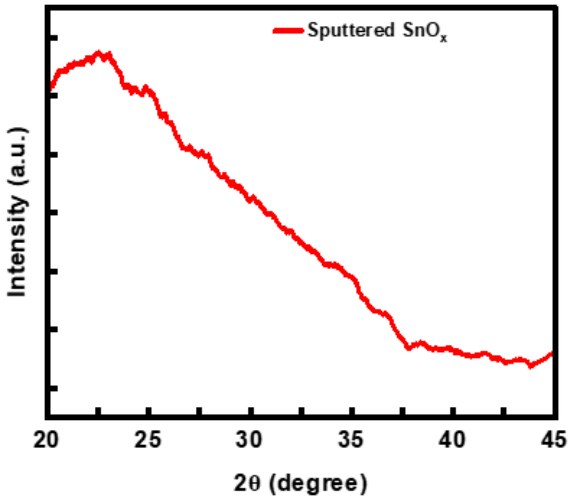


Figure 1. Grazing incidence X-ray diffraction (GI-XRD) pattern of the sputtered SnO_x layer.

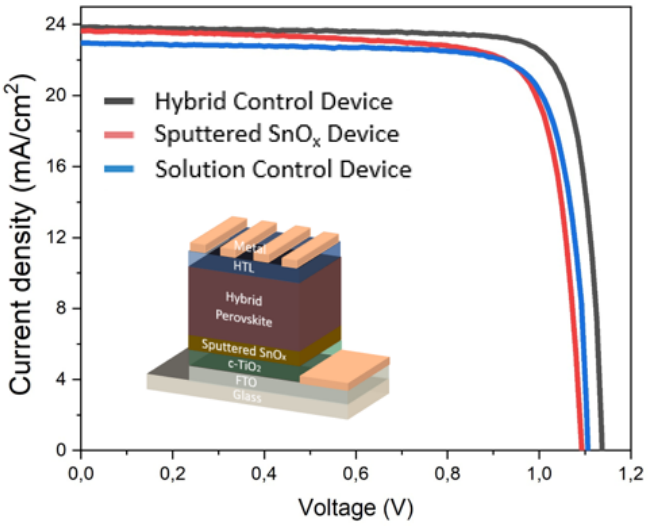


Figure 2. XPS analysis of solution-processed and sputtered SnOx films: (a) O 1s spectra and (b) Sn 3d spectra.

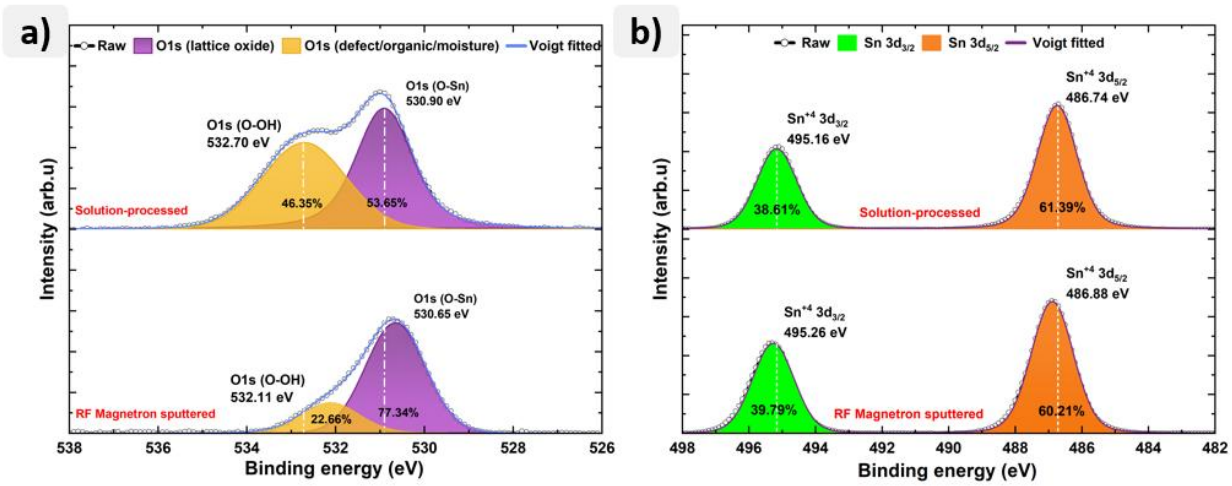


Figure 3. XPS analysis of solution-processed and sputtered SnO_x films: (a) O 1s spectra and (b) Sn 3d spectra.

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Metal Oxide/GaAs Heterojunctions for Flexible Solar Cells: Fabrication and Characterization

Hazal Zaimler[1*], Burcu Arpapay[2,3], Mustafa Kulakcı[2,4]

[1]Department of Physics, Institute of Graduate Education, Eskişehir Technical University
[2]Nanoboyut Research Laboratory, Department of Physics, Eskişehir Technical University,
[3]Depatment of Advanced Technologies, Institute of Graduate Education, Eskişehir Technical University
[4]Institute of Earth and Space Sciences, Eskişehir Technical University

*hazalzaimler@gmail.com

Gallium arsenide (GaAs)-based solar cells play a critical role in photovoltaic technologies, offering efficiencies close to theoretical limits thanks to their high absorption coefficients and low recombination rates. However, the main barrier to the widespread use of these III-V group cells is their high production costs. The Epitaxial Layer Offset (ELO) technique has significantly reduced this cost barrier by enabling the reuse of expensive substrates and the production of flexible, lightweight devices[1]. In this study, to further enhance cost-effectiveness, the use of non epitaxial carrier selective contacts (CSCs) is proposed as an alternative to the complex epitaxial layers in the cell structure. In this context, the selected ZnO and TiO_2 act as electron-selective contacts (ESC) by allowing electron flow due to their Type-II band alignment with GaAs, whilst effectively blocking hole transport through their wide bandgaps and valence band offsets. The aim of this study is to demonstrate the potential of GaAs/ESC hybrid cells in III-V group cell technologies based on initial results obtained from the fabricated cells[2,3].

The fabrication of flexible GaAs/ESC hybrid cells began with epitaxial growth in an inverted structure on a GaAs substrate within an MBE system, followed by the metallisation of the back ohmic contacts using an e-beam evaporator. The structures, fixed to a 25–50 µm polyamide carrier using a metal-to-metal fusion bonding method, were separated from the substrate via selective etching (ELO) of the sacrificial AlAs layer. Following post-transfer surface preparation, ZnO and TiO_2 electron-selective contacts were integrated into the thin-film structures using the sputtering technique with invested parameters. The structural and electrical properties of the ZnO film layers were optimised through heat treatment processes carried out in a nitrogen (N_2) atmosphere. The fabrication process was completed by depositing the front grid contacts, defined by photolithography, using thermal or e-beam evaporation methods(Figure1).

The photovoltaic performance of the fabricated GaAs/ESC hybrid solar cells was characterised under AM1.5G irradiation conditions using a solar simulator and EQE systems. Among the conventional substrate based devices, the ZnO-contacted cell exhibited the highest performance with an efficiency of 2.44%, J_{SC}=21.72 mA/cm², V_{OC}=0.27 V, FF=41.6%), while the TiO_2 based cell offered an efficiency of 2.11%. In flexible thin-film structures, ZnO (1.39%) and TiO_2 (1.38%) yielded similar results, although a general loss in efficiency was observed compared to their substrate-based alternatives. The data obtained indicate that the V_{OC} values, in particular, remained below theoretical limits due to the high defect density at the

interface. This is assessed to be related to surface damage caused by the power applied during the sputtering process of

the ESC layer. While TiO_2 was expected to be more efficient, the superior performance of ZnO compared to TiO_2 is attributed to its process compatibility at lower deposition power and a partial passivation effect. Furthermore, XRD analyses confirm that TiO_2 forms the rutile phase rather than the anatase phase on GaAs, creating an additional carrier barrier in band alignment.

In conclusion, this study has demonstrated the potential for integrating non-epitaxial ZnO and TiO_2 contacts into GaAs cell technologies. Future research will focus on optimising sputtering and heat treatment parameters to improve the properties of ESC films, and on enhancing cell performance parameters.

Acknowledgements

This work was supported by the Scientific and Technological Research Council of Türkiye (TÜBİTAK) under project number 124F405, and by Eskişehir Technical University under Scientific Research Project (BAP) number 25ADP085.

Keywords: electron selective contacts, flexible solar cell, GaAs, ZnO, TiO_2

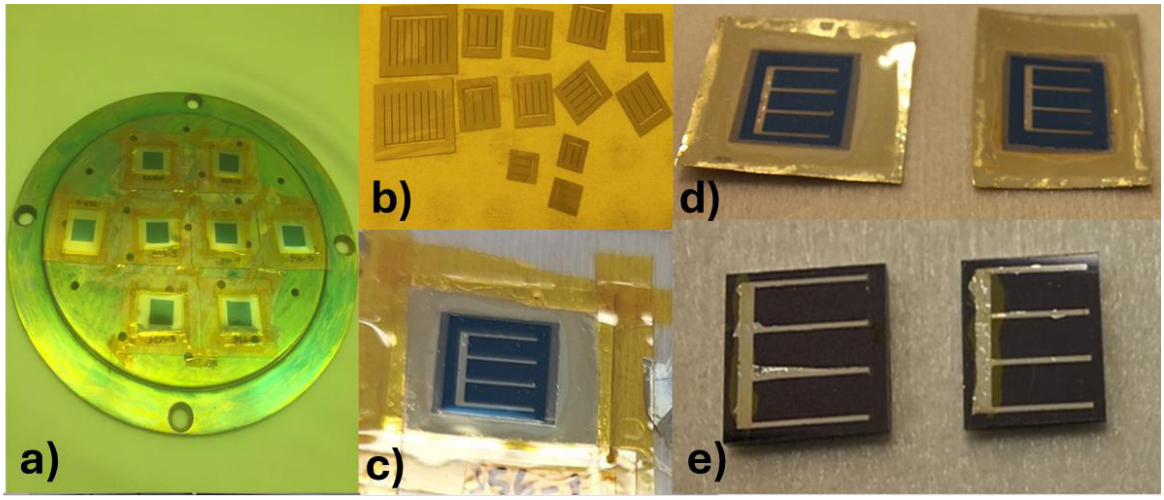


Figure 1. Overview of the fabrication steps: a) sample mounting on the substrate holder for ESC layer deposition in magnetron sputtering system; (b) front grid contact definition using shadow masks; (c) edge isolation process; (d) and (e) completed GaAs-based solar cell devices with contact geometries

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MACHINE LEARNING-BASED FAULT PREDICTION IN ELECTRICITY DISTRIBUTION NETWORKS: A RELIABILITY ANALYSIS FRAMEWORK FOR POTENTIAL PHOTOVOLTAIC INTEGRATION

Mustafa Kemal Ayas[1,*], Prof. Dr. M. Cengiz Taplamacıoğlu[1]

[1] *Gazi University, Graduate School of Natural and Applied Sciences, Department of Electrical and Electronics Engineering, Ankara, Türkiye*

* Corresponding Author E-mail: 24830601066@gazi.edu.tr

Abstract

The increasing penetration of photovoltaic (PV) generation in distribution networks introduces challenges such as bidirectional power flows, generation variability, and operational uncertainty, which complicate fault detection and reduce the reliability of conventional protection schemes [1]. Consequently, robust fault prediction frameworks based on existing operational data are a prerequisite for the reliable operation of smart grids with high PV shares. In this study, such a prediction framework is developed using real operational data from the Kahramankazan distribution region of Ankara, Türkiye, providing a methodology that can be directly extended to PV-integrated systems.

The dataset integrates outage records, Outage Management System (OMS) events, and SCADA measurements from the 2021–2025 period together with meteorological variables including temperature, humidity, wind, and precipitation. Engineered features include temporal patterns (hour, day, season), recent event intensities at the district and feeder level, SCADA alarm activity, environmental change indicators (lagged and rolling-mean statistics), and KMZ (Keyhole Markup Language Zipped) based network context (transformer, feeder, MV/LV indicators). Logistic Regression, Random Forest, XGBoost [2], LightGBM [3], and CatBoost [4] models are compared on a chronologically separated 80/20 train/test split. CatBoost is selected as the final model due to its effective handling of categorical and heterogeneous tabular data through its ordered boosting approach [5].

Considering that preventive maintenance and investment decisions require high-confidence alarms rather than capturing every event, a precision-oriented decision threshold optimization is applied. Among candidates satisfying precision ≥ 0.90, the threshold maximizing the F0.5 score is selected, and the value of 0.75 is determined as the final decision threshold. At this operating point, the model achieves an accuracy of 0.7565, precision of 0.9167, recall of 0.6915, F1 score of 0.7883, and F0.5 score of 0.8606 on the test set, with a confusion matrix of true negatives (TN) = 2333, false positives (FP) = 317, false negatives (FN)

= 1556, and true positives (TP) = 3487. The resulting high-confidence alarm list (3804 records), together with risk summaries by district, distribution center, cause, and source, is reported as input for operational decision support processes.

Although the present case study is derived from a conventional distribution network with limited PV penetration, the developed methodology is designed to be naturally extensible to systems with high PV shares. As a planned extension, global horizontal irradiance (GHI) data — a source whose reliability for solar energy applications has been validated [7] — obtained from the NASA POWER reanalysis archive [6] will be integrated into the model as an additional environmental feature to capture PV-induced variability. The framework thus provides a transferable foundation for fault prediction and reliability planning in distribution networks with increasing photovoltaic shares.

Acknowledgements

The authors thank the Department of Electrical and Electronics Engineering, Gazi University, for academic support; the operational distribution network for providing the data used in this study; and the NASA POWER project for the solar irradiance data to be used in the ongoing extension of this work.

Keywords: *Fault prediction, distribution networks, machine learning, CatBoost, gradient boosting, threshold optimization, smart grid reliability, photovoltaic integration*

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A MULTI-DIMENSIONAL ARCHITECTURAL ASSESSMENT OF COLORED BIPV: AESTHETIC, TECHNICAL, AND CONTEXTUAL DRIVERS OF ADOPTION

Tuğçe Aladı[1], Bilge Şentürk[1], Güneş Kurtuluş[2], Pınar Derin Güre[1]

[1] ODTU-GUNAM Center for Solar Energy Research & Applications, Ankara, Türkiye
[2] Artvin Çoruh University/Department of Economics, Artvin, Türkiye

tugce.aladi@metu.edu.tr

Building-Integrated Photovoltaics (BIPV) has evolved from a technical add-on into a recognized architectural material, yet conventional dark-blue modules continue to limit its visual acceptance in the built environment. Colored BIPV, produced through interference coatings, ceramic digital printing, and emerging chromogenic technologies, has been positioned as the bridge between energy generation and architectural expression. The existing literature, however, remains dominated by manufacturers and energy engineers, while the perspectives of architects who ultimately specify and legitimize these systems within the building envelope are largely absent. This study addresses that gap by investigating how architects assess colored BIPV across multiple decision scales.

A qualitative study was adopted, based on semi-structured interviews with twenty architects drawn from complementary segments of the Turkish building sector: architectural glass manufacturing, façade consultancy, design and construction practice. The protocol captured decision drivers across six dimensions: technical literacy, building-system integration, aesthetic preferences, urban-scale implications, regulatory context, and sectoral acceptance.

Four acceptability metrics emerged as decisive: (a) chromatic performance, including hue accuracy, homogeneity, and long-term color fastness; (b) efficiency trade-off awareness; (c) tectonic integration, covering module dimensioning and compatibility with adjacent envelope materials; and (d) lifecycle and risk factors. Regulatory ambiguity, the absence of targeted incentives, high upfront costs, uncertain payback periods, and an immature market in Türkiye were identified as systemic constraints, while building type, urban context, and collective design awareness emerged as contextual determinants shaping architects' willingness to specify colored BIPV.

Acknowledgements

This study is conducted within the scope of the project titled 'Development of a Colored Photovoltaic Panel for BIPV Applications with Selective Transmissive and Absorptive Metal Oxide Nanoparticles', supported by TÜBİTAK (123F372) under the 1001 Scientific and Technological Research Projects Funding Program

Keywords: architectural decision-making, building envelope, colored BIPV, social acceptance criteria

"Agrivoltaics and Sustainable Agricultural Transitions: Farmers' Perceptions and Adoption Constraints in Türkiye "*

Pinar Derin-Güre[1,2,3], Hande Eryılmaz[1] **, Talat Özden[1], Duygu Kuzyaka[1], Güneş Kurtuluş[1], Evangelos Rikos[4], Atila Polat[5], Mehmet Yüksel[5],Mahmut Sami Çiftçi[6], Zeynep Dilan Deniz[7], Zeynep Demir[5]

[1] ODTÜ-GÜNAM, Ankara, Türkiye
[2] Middle East Technical University/Economics, Ankara, Türkiye
[3] METU Climate, Ankara, Türkiye
[4] CRES, Athens, Greece
[5] TAGEM, Ankara, Türkiye
[6] Solimpeks, Konya, Türkiye
[7] TAT, Bursa, Türkiye

**Corresponding Author: hande.eryilmaz@odtugunam.org

Agrivoltaics is a promising application area of Photovoltaics as it enables the dual use of land for both energy production and farming. As technical studies suggest, agrivoltaics is not just a compromise in using land for farming and electricity production. It can provide additional benefits in the farming process, especially when farmers' perception and market uptake are better shaped and understood by the primary end-users of the technology. Limited information that farmers receive on the technology, as well as the lack of co-creation that would allow tailoring of the solution to their needs, are factors worth researching from a socioeconomic viewpoint. This paper aims to understand farmers' perception and acceptance of technology in Türkiye for Agrivoltaics. The analysis aims at understanding farmers' expectations, concerns, and considerations, while it showcases what is still needed towards specific activities that could raise more awareness. The methodology followed to reflect the farmers' perceptions is through two focused group studies done by local farmers in Ankara and Bursa in 2025, emphasizing the points of interest for the specific technology. The detailed presentations on the farmers' perspective highlight their expectations and concerns regarding the use of technology. Currently, agrivoltaics are perceived as more of a risk mitigation and resilience tool, rather than a profit-maximising agricultural innovation due to the required resources for its implementation.

Acknowledgements

The research was funded by the EU Horizon Europe Project SolarHub 'A Greek-Turkish Solar Energy Excellence Hub to Advance the European Green Deal' under Grant Agreement No:101086110, website: https://horizonsolarhub.eu/.

Keywords: Agrivoltaics, Agriculture, PV, Türkiye, Farmers, Perceptions

"Solar Energy Ecosystem in Greece: Opportunities and Challenges"*

Nihad Mammadli[1], Selin Piravadili[4] , Pinar Derin-Güre[1,2,3]**, Evangelos Rikos[5], George Karagianis[6]

[1] Middle East Technical University/Economics, Ankara, Türkiye
[2] ODTÜ-GÜNAM, Ankara, Türkiye
[3] METU Climate, Ankara, Türkiye
[4] TÜBİTAK, Ankara, Türkiye
[5] CRES, Athens, Greece
[6] CERTH, Theseloniki, Greece

**Corresponding Author: pderin@metu.edu.tr

Greece has undergone serious transformations in its energy sector and is one of the top performers in solar energy deployment across Europe. Today, renewable energy sources cover more than 50% of domestic electricity demand, and photovoltaic and solar thermal technologies play a dominant role. Based on semi-structured interviews with key stakeholders across industry and academia, this study analyzes the current state and challenges of solar energy technologies, and opportunities for further expansion of the Greek Solar Energy Ecosystem. According to preliminary findings, Greece has massive PV capacity; however, this oversupply cannot be accommodated by domestic demand and grid capacity. Thus, to solve this, the focus must be shifted from grid deployment to the expansion of grid capacity to deter grid congestion. In addition to infrastructural problems, this process is also adversely affected by bureaucracy and long permitting processes. Social acceptance was highlighted as one of the obstacles to the deployment of Agri-PV systems, particularly large-scale installations, due to land-use conflicts and their perceived environmental effects. A set of recommendations was offered regarding the prioritization of energy storage, especially investments in battery and thermal storage, fostering agrivoltaics through legal frameworks, the empowerment of energy communities, and the creation of a centralized online platform to navigate paperwork to avoid delays and lengthy permitting processes.

Acknowledgements

The research was funded by the EU Horizon Europe Project SolarHub 'A Greek-Turkish Solar Energy Excellence Hub to Advance the European Green Deal' under Grant Agreement No:101086110, website: https://horizonsolarhub.eu/.

Keywords: Solar Energy, Opportunities, Challenges, Semi-Structured Interviews, Greece

RESOLVING RECOMBINATION PATHWAYS IN PEROVSKITE SOLAR CELLS USING AN IMPEDANCE SPECTROSCOPY-BASED IDEALITY FACTOR

Mehmet Cem Şahiner[1,2], Elshan Asadi[2,3], Zeynep Gözükara Karabağ[2], Görkem Günbaş*[2,3,4,5], Selçuk Yerci*[1,2,3]

[1] Department of Electrical and Electronics Engineering, Middle East Technical University, Ankara, Turkey
[2] ODTU-GUNAM, Middle East Technical University, Ankara, Turkey
[3] Department of Micro and Nano Technology, Middle East Technical University, Ankara, Turkey
[4] Department of Chemistry, Middle East Technical University, Ankara, Turkey
[5] Department of Polymer Science and Technology, Middle East Technical University, Ankara, Turkey

*ggunbas@metu.edu.tr; syerci@metu.edu.tr

Accurate identification of recombination pathways in perovskite solar cells (PSCs) remains challenging due to ionic motion, which compromises the reliability of conventional ideality factors derived from steady-state measurements. While a theoretical framework for impedance spectroscopy (IS)-based electronic ideality factor (n_{el}) has been established [1], its experimental validation and practical implementation are still limited.

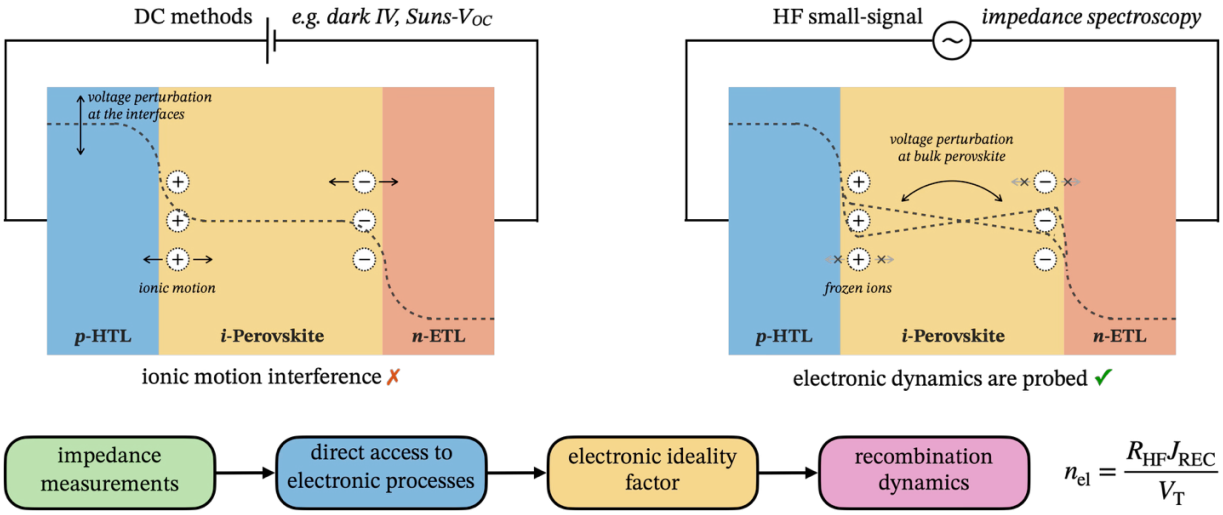
Here, we experimentally demonstrate that n_{el}, extracted from the high-frequency small-signal resistance of PSCs, provides a reliable and physically consistent metric for identifying dominant recombination pathways. By operating in the high-frequency regime, ionic contributions are suppressed, allowing the impedance response to reflect intrinsic electronic recombination processes. The steady-state recombination current, together with the high-frequency response, enables quantitative evaluation of n_{el}.

The method is validated through controlled interface engineering. We show that n_{el} sensitively tracks changes in recombination pathways: bare NiO_x p-i-n devices exhibit $n_{el} \approx 1$, indicative of interfacial recombination dominance, whereas surface passivation with phosphonic acid-based self-assembled monolayers (SAMs) increases n_{el} toward ~1.5, consistent with a transition to a mixed recombination regime. In addition, phenethylammonium iodide (PEAI)-treated n-i-p PSCs exhibit a transition from $n_{el} \approx 1$ to ~2, demonstrating effective suppression of interfacial recombination. Complementary analysis of low-frequency impedance response further identifies contact-induced degradation in silver electrodes without the PEAI-derived 2D perovskite interlayer, as well as its mitigation through the formation of favorable energetic barriers.

Our findings validate IS-based ideality factor as a robust diagnostic framework for PSCs and highlight its potential for broadly applicable recombination analysis in ionically active semiconductors.

Keywords: electronic ideality factor, impedance spectroscopy, interface passivation, ionic effects, perovskite solar cells, recombination mechanisms

Figure 1. Conceptual Illustration of Ionic and Electronic Responses in PSCs



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Multi-Objective Analysis of Semi-Transparent Photovoltaic Façades: Balancing Energy Generation and Indoor Visual Comfort in a Mediterranean Climate

Amirhossein Karimizadeh[1], **Ercan Hoskara**[1]

[1] Department of Architecture, Faculty of Architecture, Eastern Mediterranean University, North Cyprus via Mersin 10, Gazimağusa 99628, Türkiye ; ercan.hoskara@emu.edu.tr

*Corresponding Author's E-mail: amirhossein.karimizadeh@emu.edu.tr

Photovoltaic (PV) façades represent a promising approach to transform building envelopes into on-site renewable energy generators while influencing indoor environmental quality. Beyond energy performance, design parameters significantly influence the indoor environment, including daylight availability and glare risk, which are critical for occupant visual comfort. While PV technologies are commonly optimized at the module scale, their performance in building-integrated applications remains insufficiently explored, especially regarding the trade-offs between energy generation and occupant comfort. This study investigates how variations in Visible Transmittance (VT) of semi-transparent PV modules and tilt angles affect both energy generation and indoor visual conditions on a South-facing façade. A mid-rise building in Northern Cyprus, representing a Mediterranean climate with high solar radiation potential, is considered as a case study. A parametric simulation-based approach is adopted, utilizing Ladybug, Radiance, and PVsyst to evaluate multiple PV façade configurations. Performance indicators include annual energy yield (kWh), spatial Daylight Autonomy (sDA), and Daylight Glare Probability (DGP). By analyzing the impact of VT levels and tilt angles, the study explores design strategies that maximize energy generation while optimizing occupant visual comfort. This research addresses a critical gap between architectural and engineering perspectives, contributing to the performance-driven integration of PV systems within the built environment.

Acknowledgements

This is the abstract template document for PVCON2026.

Keywords: PV façades, semi-transparent PV, tilt angle, energy generation, visual comfort, Mediterranean climate

Optimization of DCB-BOM Self-Assembled Monolayers for High-Efficiency p–i–n Perovskite Solar Cells

Elif Sude Camkiran[1,2], Nisa Ferlibas[1,2], Bahri Eren Uzuner[2], Zeynep Gozukara Karabag[2], Gorkem Gunbas[1,2,3,4] , Selcuk Yerci[1,2,5], Aliekber Karabag[*2]

[1] Micro and Nanotechnology Department, Middle East Technical University (METU), 06800, Ankara, Turkiye
[2] Center for Solar Energy Research and Applications, ODTU-GUNAM, METU, 06800, Ankara, Turkiye
[3] Department of Chemistry, METU, 06800, Ankara, Turkiye
[4] Polymer Science And Technology Department, METU, 06800, Ankara, Turkiye
[5] Electrical Engineering Department, METU, 06800, Ankara, Turkiye

*Corresponding author: aliekber.karabag@odtugunam.org

The performance of p–i–n perovskite solar cells (PSCs) is strongly managed by interfacial properties, where self-assembled monolayers (SAMs) play a critical role in tuning energy alignment and reducing recombination losses. Careful control over SAM formation on cell architecture, including parameters such as concentration is therefore essential for achieving optimal cell performance.

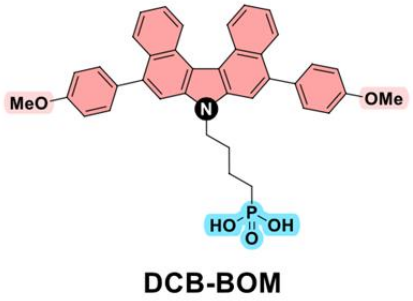
In this study, a novel SAM, denoted as **DCB-BOM**, was designed and synthesized by functionalizing a **7*H*-Dibenzo[c,g]CarBazole (DCB)-based molecular backbone** with a **para-methoxybenzene (BOM) unit** to extend the π-conjugated framework through the conventional literature protocols (**Figure 1**). The resulting **DCB-BOM** molecule was subsequently employed as an interfacial passivation layer, sandwiched between the NiO_x hole-transport layer (HTL) and the CsFAMA (Cs: Cesium; FA: formamidinium; MA: methylammonium) perovskite layer and systematically evaluated in inverted **p–i–n structured PSCs** with the cell architecture Glass/ITO/**NiO_x/DCB-BOM/CsFAMA**/LiF/C_{60}/BCP/Cu. For concentration-dependent optimization, **DCB-BOM** was **spin-coated** onto ITO/NiO_x substrates at concentrations of **0.3, 0.5, 0.8, 1.0, and 1.2 mg mL^{-1}**, followed by two-step hybrid deposition of the CsFAMA perovskite layer and vacuum thermal evaporation of the **LiF/C_{60}/BCP/Cu** stack. All **DCB-BOM**-modified PSCs outperformed the reference cell, which delivered a power conversion efficiency (PCE) of 19.15% (**Figure 2**). The optimum concentration for **DCB-BOM**-modified PSCs was identified as 0.8 mg mL^{-1}, affording a maximum PCE of 22.58%, with enhanced open-circuit voltage (V_{OC}) of 1.14–1.17 V and fill factor (FF) up to 84.05%, confirming the beneficial role of SAM-mediated interfacial engineering (**Table 1**). Statistical analysis further revealed improved device reproducibility at this concentration, indicating more homogeneous SAM coverage and reduced interfacial energetic disorder.

These results demonstrate that precise control over SAM concentration is essential for maximizing interface quality and photovoltaic output in p–i–n type PSCs, providing practical processing guidelines for the rational implementation of molecular interlayers in high-performance perovskite photovoltaics.

Acknowledgements

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Keywords: Self-Assembled Monolayers (SAMs), P–i–n Perovskite Solar Cells (PSCs), Concentration Optimization, Power Conversion Efficiencies (PCEs)



DCB-BOM

Figure 1. Chemical structure of the **DCB-BOM**.

Table 1. Photovoltaic performances obtained from different concentrations of **DCB-BOM** in p-i-n type PSCs.

Device	V_{OC} (V)	J_{SC} (mA/cm^2)	FF (%)	PCE (%) (Avg.)
Reference	1.02	23.12	80,89	19.15 (17.85)
0.3 mg/mL	1.15	23.67	82.68	22.51 (21.45)
0.5 mg/mL	1.16	22.71	84.05	22.10 (21.30)
0.8 mg/mL	1.14	23.86	82.77	22.58 (21.70)
1.0 mg/mL	1.17	23.27	80.43	21.82 (21.17)
1.2 mg/mL	1.15	23.28	79.64	21.31 (20.93)

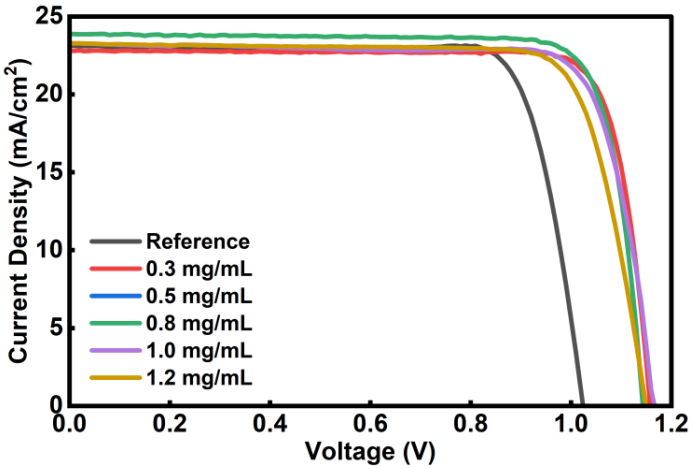


Figure 2. *I–V* curves of the best-performing **DCB-BOM** in p–i–n type PSCs.

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ReSolarize

A Multi-Stream Circular Recovery Framework for High-Purity Photovoltaic Material Upcycling

D. Asarkaya[1], S. Özgen[2], N. Kızak[3]

[1]Department of Mechanical Engineering, Middle East Technical University, Ankara, 06800, Türkiye
[2]Department of Environmental Engineering, Hacettepe University, Ankara, 06800, Türkiye
[3]Department of Political Science and Public Administration; and Economics, Middle East Technical University, Ankara, 06800, Türkiye

Keywords: Circular Economy, Critical and Strategic Raw Materials, Urban Mining, Photovoltaic Recycling.

Introduction

Tackling the global energy problem is one of the most critical issues of the 21st century. Rapid digitalization, driven by artificial intelligence, semiconductors, electric vehicles, and data centers, is significantly increasing global energy demand. According to the International Energy Agency (IEA), electricity demand is projected to rise by around 40% by 2035. In this context, solar energy has emerged as one of the most scalable solutions to meet this growing demand while reducing greenhouse gas emissions.

However, despite its environmental advantages, the solar energy industry faces structural challenges, particularly its unsustainable dependence on global raw material supply chains and the rising cost of these inputs.

The convergence of the COVID-19 pandemic, global tariff tensions, and the conflict in Ukraine exposed the fragility of global supply chains. For an industry as vital as energy, these dependencies threaten strategic autonomy and economic security. China controls more than 60% of rare-earth mining, and its 2023 export restrictions on gallium and germanium, critical for PV, caused price increases of around 40%. At the same time, the EU's Carbon Border Adjustment Mechanism (CBAM) adds 10–15% to mining costs. These developments highlight the need to shift toward more circular, resilient, and localized supply chains to ensure a sustainable solar ecosystem.

Raw material costs also represent a major challenge for the clean energy transition, accounting for approximately 60–70% of total manufacturing expenses. Industrial demand continues to grow, while limited supply flexibility intensifies price pressure. Silver, a key material for PV cell contacts, saw a 130% annual price increase by late 2025 (Maysun Solar, 2025). The IEA describes this trend as "material-driven inflation." In response, many manufacturers introduced dynamic pricing models with escalation clauses, passing 70–80% of price spikes directly to buyers. This volatility pushes final prices beyond initial contracts, creating financial risks for both manufacturers and customers.

Simultaneously, the rapid expansion of solar installations is generating a parallel end-of-life (EOL) challenge. By 2050, millions of tons of PV modules are expected to reach the end of their operational lifetime annually. However, current recycling practices predominantly follow downcycling pathways, where high-value materials degrade into low-grade outputs. Mechanical shredding often compromises glass transparency, while uncontrolled chemical treatments risk contaminating high-purity silicon streams. As a result, the circular potential of photovoltaic materials remains largely underutilized.

*Winner of **the HelioHub Innovation Challenge 2025,** ReSolarize was developed under the academic advisement of Prof. Dr. Derek K. Baker, Assoc. Prof. Pınar Derin-Güre, and Dr. Hande Eryılmaz.*
The project was formally presented at the SolarHub General Assembly in Athens.

Material and Methods

In response to these structural and technical challenges, this study proposes an integrated circular recovery framework designed to maximize material value retention across the photovoltaic lifecycle. Rather than treating end-of-life panels as uniform waste, the approach prioritizes value-based triage and high-purity recovery pathways. The following section outlines the material flow architecture and engineering protocols developed to preserve optical integrity, maintain material purity, and minimize environmental impact throughout the reuse, repair, and recycling stages.

The ReSolarize platform begins with an AI-supported testing program to triage the panels. During this stage, the system determines which path a panel should follow: reuse, repair, or recycle. In the reuse stage, if a panel is still functional, it is used again for its original purpose to preserve its maximum value. If a panel has minor issues, it can be repaired. A defining feature of this project is the industrial synergy created by using components recovered from E-waste and Electric Vehicle (EV) battery waste streams for these repairs. Finally, if a panel has reached its absolute end-of-life, it is sent to recycling centers. However, certain challenges arise during conventional recycling, such as the reduction of glass optical transparency and the risk of silicon impurities damaging high-purity materials.

Results and Discussions

The ReSolarize circular coordination framework improves both material recovery efficiency and value chain resilience by integrating reuse, repair, and high-purity recycling within a hierarchical model that prioritizes value retention over material downgrading (Geissdoerfer et al., 2017). AI-supported triage directs panels first to reuse, then repair, and only lastly to recycling, mitigating the structural “downcycling trap” observed in conventional PV recovery systems (IRENA, 2023).

Beyond technical optimization, the digital B2B marketplace enables coordinated material flows among waste suppliers, recyclers, manufacturers, and end-users. The multi-stream urban mining approach: combining PV waste, E-waste, and EV battery streams, facilitates recovery of strategic materials such as silver, copper, aluminum, and silicon within an integrated ecosystem. This model supports emerging policy objectives promoting domestic recovery of critical raw materials (European Commission, 2023).

With PV lifetimes averaging 25–30 years and increasing end-of-life volumes anticipated in the coming decades, scalable circular infrastructures are becoming essential (IEA, 2024). High-quality recovery preserving glass transparency and silicon integrity enables cost-competitive recycled modules while reducing resource dependency (Cambridge University Sustainability Project, 2024; QUASAR Project, 2023). By combining advanced recovery engineering with digital coordination and inclusive transaction mechanisms, the framework strengthens environmental performance and strategic economic resilience across the solar value chain.

By combining advanced recovery engineering with digitally coordinated value chain governance, the framework moves beyond incremental recycling improvements and proposes a systemic shift toward a circular solar infrastructure. In doing so, it reframes photovoltaic waste not as an environmental burden, but as a strategic resource base for the next generation of renewable energy systems.

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Conclusions

This study proposes and evaluates an integrated circular coordination framework for the photovoltaic sector that bridges material science, digital infrastructure, and industrial symbiosis.

By addressing structural inefficiencies such as grinding-induced downcycling and silicon contamination, the ReSolarize model preserves high-value material streams while simultaneously improving carbon performance. The integration of AI-based triage, advanced delamination and recovery techniques, and a B2B digital marketplace enables systemic coordination across the quadruple helix actors: industry, government, academia, and community.

The results demonstrate that circularity in the solar sector cannot rely solely on improved recycling technologies; it requires coordinated value chain governance and digital infrastructure capable of aligning economic incentives with material recovery priorities.

As solar deployment accelerates globally, establishing resilient domestic material loops will be essential for reducing dependency on volatile global supply chains and critical raw material imports.

The ReSolarize framework offers a scalable, technically feasible, and socio-economically inclusive pathway toward a circular and democratized solar energy transition.

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Extended Field Performance Analysis of Three Different Photovoltaic Technologies Over a 14-Year Period Under Semi-Arid Climate Conditions

Ahmet Hekim[1,*], Ahmet Hamdi Aksoy[1], Talat Ozden[1]

[1] ODTU-GUNAM, Middle East Technical University, 06800, Ankara, Turkiye

*ahmet.hekim@odtugunam.org

This study presents an extended long-term performance analysis of three grid-connected photovoltaic (PV) systems—mono-crystalline silicon, microcrystalline/amorphous silicon, and CdTe thin-film—installed in Central Anatolia and originally commissioned in 2012[1], [2]. The dataset has been expanded to include energy production records up to 30 November 2025, corresponding to an operational period of nearly 14 years.

Performance assessment is carried out using the IEC 61724 standard framework[3], focusing on key indicators such as performance ratio, outdoor efficiency, and degradation rates. The analysis is based on measured production data, and filtered time-series datasets to ensure reliability. Degradation trends are derived through regression-based evaluation of normalized performance metrics.

Without presenting numerical values, the recalculated results are directly compared with those reported in the original study. The extended dataset enables a more robust evaluation of long-term behavior and reveals the consistency and evolution of performance across different PV technologies.

The findings underline the importance of long-duration field data in accurately quantifying degradation and validating earlier projections[4]. This work contributes to improved confidence in PV performance assessments under real operating conditions and supports better decision-making for future PV deployments.

Keywords: Photovoltaic Systems, Long-Term Performance, Degradation Analysis, Performance Ratio, Outdoor Efficiency

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A MULTI-DIMENSIONAL ARCHITECTURAL ASSESSMENT OF COLORED BIPV: AESTHETIC, TECHNICAL, AND CONTEXTUAL DRIVERS OF ADOPTION

Tuğçe Aladı[1], Bilge Şentürk[1], Güneş Kurtuluş[2], Pınar Derin Güre[1,3]

[1] Middle East Technical University, Center for Solar Energy Research and Applications (ODTU-GUNAM), Ankara, Türkiye
[2] Artvin Çoruh University, Economics, Artvin, Türkiye
[3] Middle East Technical University, Economics, Ankara, Türkiye

tugce.aladi@metu.edu.tr

Building-Integrated Photovoltaics (BIPV) has evolved from a technical add-on into a recognized architectural material, yet conventional dark-blue modules continue to limit its visual acceptance in the built environment. Colored BIPV, produced through interference coatings, ceramic digital printing, and emerging chromogenic technologies, has been positioned as the bridge between energy generation and architectural expression. The existing literature, however, remains dominated by manufacturers and energy engineers, while the perspectives of architects who ultimately specify and legitimize these systems within the building envelope are largely absent. This study addresses that gap by investigating how architects assess colored BIPV across multiple decision scales.

A qualitative study was adopted, based on semi-structured interviews with twenty architects drawn from complementary segments of the Turkish building sector: architectural glass manufacturing, façade consultancy, design and construction practice. The protocol captured decision drivers across six dimensions: technical literacy, building-system integration, aesthetic preferences, urban-scale implications, regulatory context, and sectoral acceptance.

Four acceptability metrics emerged as decisive: (a) chromatic performance, including hue accuracy, homogeneity, and long-term color fastness; (b) efficiency trade-off awareness; (c) tectonic integration, covering module dimensioning and compatibility with adjacent envelope materials; and (d) lifecycle and risk factors. Regulatory ambiguity, the absence of targeted incentives, high upfront costs, uncertain payback periods, and an immature market in Türkiye were identified as systemic constraints, while building type, urban context, and collective design awareness emerged as contextual determinants shaping architects' willingness to specify colored BIPV.

Acknowledgements

This study is conducted within the scope of the project titled 'Development of a Colored Photovoltaic Panel for BIPV Applications with Selective Transmissive and Absorptive Metal Oxide Nanoparticles', supported by TÜBİTAK (123F372) under the 1001 Scientific and Technological Research Projects Funding Program.

Keywords: architectural decision-making, building envelope, colored BIPV, social acceptance criteria

Assessment of PAR Distribution in Vineyard Agrivoltaic Systems under Different Panel Density Configurations

Faruk Öner[1], Neslihan Çolak[1,2]

[1]Solar Energy Institute, Ege University, Izmir, Turkiye

[2]Center for Solar Energy Research and Applications (ODTU- GUNAM), Middle East Technical University, Ankara, Turkiye

Agrivoltaic systems are increasingly recognized as a practical approach for the simultaneous use of land for crop production and solar energy generation. However, the installation of photovoltaic panels inevitably alters both the magnitude and spatial distribution of incident radiation, which can influence plant development. This is particularly important in vineyard systems, where light conditions strongly influence photosynthesis, yield, and grape quality.

In this study, the impact of different agrivoltaic configurations on the distribution of photosynthetically active radiation (PAR) was evaluated using a scenario-based modelling approach. Three scenarios were considered: a conventional open-field vineyard (reference), a low-density agrivoltaic system, and a high-density agrivoltaic system. Incident PAR was adjusted based on panel coverage ratio and shading geometry to estimate effective canopy-level PAR (PAR_eff). The spatial distribution of PAR was assessed using a grid-based approach and compared with known physiological thresholds for grapevine photosynthesis.

The results indicate that open-field conditions often exceed optimal PAR levels, with values typically ranging between 1200 and 1800 µmol m^{-2} s^{-1}. In contrast, the low-density agrivoltaic configuration reduces PAR to approximately 600–1000 µmol m^{-2} s^{-1}, bringing light conditions closer to the optimal photosynthetic range. The high-density configuration further reduces PAR to 200–600 µmol m^{-2} s^{-1}, which is likely to limit photosynthesis despite reducing excessive light exposure.

Overall, the findings indicate that agrivoltaic system design should focus not only on reducing radiation levels but also on redistributing light to align with crop-specific physiological requirements. This approach can support the development of more balanced and crop-sensitive agrivoltaic vineyard systems that optimize both energy production and plant performance.

Keywords: Agrivoltaics, Vineyard, Photosynthetically Active Radiation (PAR), Panel Density, Light Distribution

Environmental Performance and Design Considerations of Agrivoltaic Systems: A Life Cycle Perspective for Photovoltaic-Agricultural Co-Production

Res. Asst. İpek Gülçin Uysal[a], Assoc. Prof. Talat Özden[b], Asst. Prof. Neslihan Çolak[a,b]

a: Ege University Solar Energy Institute, b: ODTÜ GÜNAM (Center for Solar Energy Research and Applications)

The rapid expansion of photovoltaic (PV) deployment has intensified the competition for land resources, particularly in regions where agricultural productivity and renewable energy development intersect. Agrivoltaic systems, which enable the co-location of PV electricity generation and agricultural production, have emerged as a promising strategy to increase land-use efficiency while supporting the large-scale integration of solar energy. However, the environmental implications of agrivoltaic deployment are strongly influenced by PV system design parameters, structural configurations, and material requirements associated with elevated mounting systems.

This study investigates the environmental performance of agrivoltaic systems from a life cycle assessment (LCA) perspective, with a particular focus on photovoltaic infrastructure and system configuration. The assessment focuses on the life-cycle implications of key PV system components, including modules, mounting structures, and balance-of-system elements, together with the agricultural activities occurring within the agrivoltaic configuration. An integrated functional unit capturing both electricity generation and agricultural production is adopted in order to represent the dual-output nature of agrivoltaic systems.

The analysis examines the life-cycle contributions of photovoltaic infrastructure and identifies environmental hotspots associated with agrivoltaic system deployment. Special attention is given to the structural and material requirements of elevated PV mounting systems and their implications for the overall environmental footprint of agrivoltaic installations. In addition, the environmental performance of agrivoltaic configurations is discussed in relation to conventional ground-mounted PV systems in order to highlight potential design trade-offs associated with photovoltaic–agricultural integration.

The results indicate that while agrivoltaic systems provide an opportunity to combine renewable electricity generation with agricultural land use, the additional structural components required for PV elevation and spacing can significantly influence life-cycle environmental impacts. These findings underline the importance of integrating environmental assessment into the design phase of agrivoltaic systems and demonstrate the role of life cycle assessment as a decision-support tool for environmentally optimized PV deployment.

Overall, this study contributes to the growing body of research on integrated photovoltaic applications and provides insights into the environmental implications of agrivoltaic system design for sustainable solar energy deployment.

Keywords: Agrivoltaic systems, photovoltaic systems, life cycle assessment, PV system design, sustainable PV deployment

CETP-TANDEM project, IES-UPM contribution / Abstract for the PVCon 2026 conference.
David Fuertes Marrón

Title: Insights into the potential gettering effect of n-polySi TOPCon on recharged Cz wafers and degradation studies of bottom cell substrates for the TANDEM project.

Authors: Nerea Dasilva Villanueva, Luis Jaime Caballero, Usman Ali Shah, Andrés Pardo Perdomo, Cristian Antoine Ortiz, Nathan Muller, Carlos del Cañizo, David Fuertes Marrón

Abstract:

The CETP-TANDEM project aims at developing a silicon/perovskite tandem solar cell production route combining low cost, sustainability, high efficiency and high productivity. Key aspects to reach these goals are (i) the use of a modified PERC technology applied and optimised for the silicon bottom cell; (ii) the use of green solvents for solution-processed perovskites and spatial-ALD deposition techniques for selective and recombination layers in top cells, and (iii) the overall minimization of the use of critical raw materials.

In this contribution we will present results related to the first key point, namely the quality improvement of the PERC bottom cell provided with a TOPCon-type front emitter by advanced defect-gettering and annealing. The reason is that, while in conventional PERC cells the diffused emitter is known to getter impurities from the wafer, in our modified PERC bottom cell, the poly-Si of the TOPCon has to fulfill this role. So far this has been barely studied or optimized. We have thus checked the impact on the sample quality of such defect engineering processes, and we have done so at two different stages; firstly, at wafer level, as a function of bare wafer properties, cut from recharged Czochralski (R-Cz) grown ingots used in the project, namely the dopant type (p-type -B, Ga- and n-type -P-) and the resistivity (0.8 – 3.5 Ω·cm). Secondly, as a result of the TOPCon-modification processing, with dedicated symmetrical structures fabricated on identical RCz-wafers provided with TOPCon contacts and SiNx referencces. This knowledge is a landmark towards the achievement of high Voc target values for the project's intended bottom cells.

The eventual occurence of a measurable effective gettering effect associated to TOPCon processing of RCz wafers has been studied by means of minority carrier lifetime measurements, comparing results from bare wafers and samples with and without (etched) passivating contacts. The latter measurements were carried out using non-permanent, iodine-alcohol based liquid passivation, thereby ensuring an effective minimization of surface recombination such as to access bulk properties. Preliminary results point, at best, to a very limited measurable gettering effect of n-polySi TOPCon, largely independent of the substrate type.

Additionally, we have monitored the potential bottom cell degradation and recovery due to LID and LeTID by cycling bare wafers under high/low irradiance and temperature in a dedicated platform. Results from B- and n-type doped samples have reproduced the expected results, whereas Ga-doped samples show a more complex behaviour, partly undergoing little or no degradation after illumination at 25 ºC, and thereby revealing the presence of light-activated metastable states, while degrading further upon subsequent thermal treatment in dark. Light-soaking at 70 ºC has a severe impact on the carrier lifetime of Ga-doped samples, inducing a drop in carrier lifetime of around 34% on average. We conclude that the eventual recovery upon dark-annealing of such light-induced degradation of Ga-doped wafers may require significantly high activation energies, well above those of B-doped samples, since no healing evidence has been found for dark-annealing temperatures up to 200ºC.

Developing Sub-micron Pyramidal Texturing Approach on Large Area for Next-Generation Perovskite/Silicon Tandem Cells

1. Summary

An effective technique for creating sub-micron pyramid patterns is presented in this paper, which is a crucial development for next-generation cells. In contrast to conventional texturing, this sub-micron morphology is especially intended for sophisticated structures such as HJT cells and perovskite/silicon tandems, guaranteeing superior conformal coating of sensitive thin-film layers and reducing electrical shunt concerns. Because the method uses chemicals that have been shown to work in the industry, it is both inexpensive and very scalable for large-scale production. Additionally, this approach provides a more sustainable route to the production of high-efficiency silicon solar cells by optimizing chemical utilization.[1]

2. Introduction

Light management, crucial for c-Si solar cell efficiency, is mostly done by texturing the wafer surface. Conventional alkaline texturing creates random, light-capturing pyramids, usually a few μm in size. However, advanced cell ideas require smaller, controlled sub-micron features[2]. While achieving uniform morphology with low reflectance is difficult, sub-micron texturing can improve compatibility with deposition steps and reduce surface recombination.[3] The process window is often small and sensitive to temperatures, concentrations, and times. This work focuses on optimizing a sub-micron texturing procedure and its post-texturing treatment to remove remaining layers and improve pyramid tips.[4]

3. Experimental Methodology

In this study, commercial Cz-Si wafers ((100), 156.75 × 156.75 mm², 180 μm) were used. Three different texturing recipes were investigated, and all processes were initiated with a standardized Pre-SDE pre-treatment stage. This initial step involved immersing the wafers in KOH solution at 80°C for 1 minute, which was then followed by an acidic cleaning and drying sequence. For the main texturing step, three distinct recipes, all containing KOH and an additive, were evaluated: the first used 0.4% KOH at 80°C for 7 minutes; the second employed 0.5% KOH at 75°C for 5 minutes; and the third utilized 1% KOH at 70°C for 5 minutes. After assessing these results, only the recipe demonstrating the best performance was carried forward to the post-treatment stage. Two alternative post-treatment methods were then explored: first, exposure to a KOH-containing solution at 28°C for varying durations (15, 25, 50, 75, and 100 seconds), and second, a cyclic method involving an ozone step followed by an HF bath, repeated for 1, 2, 3, and 5 cycles

4. Results and Discussion

All experiments were carried out using an industrial-scale wet bench. The texturing step was performed according to the process flow shown in Figure 1.

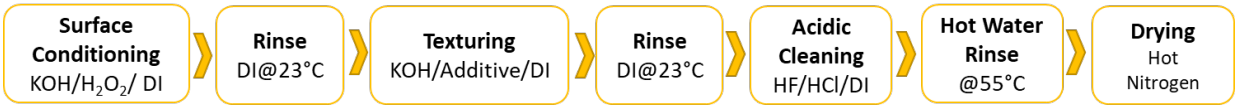


Figure1. Standard texturing procedure used in the work.

The SEM images of the pyramidal surfaces, the corresponding pyramid size distribution derived from these images, and the measured reflection values are presented in Figure 2. Among the three

texturing recipes, the most homogeneous and optimally sized pyramidal morphology was obtained with Recipe 3. Although the reflection values of all three recipes were relatively similar, the superior morphological quality achieved with Recipe 3 led to its selection for the subsequent steps. The most uniform and appropriately sized pyramidal morphology was formed by Recipe 3, according on an analysis of the size distribution histograms. With a prominent peak between 700 and 800 nm, its distribution is more unimodal and narrower. Recipes 1 and 2, on the other hand, display wider, more erratic distributions with sizable pyramidal sections that are larger than 1000 nm.

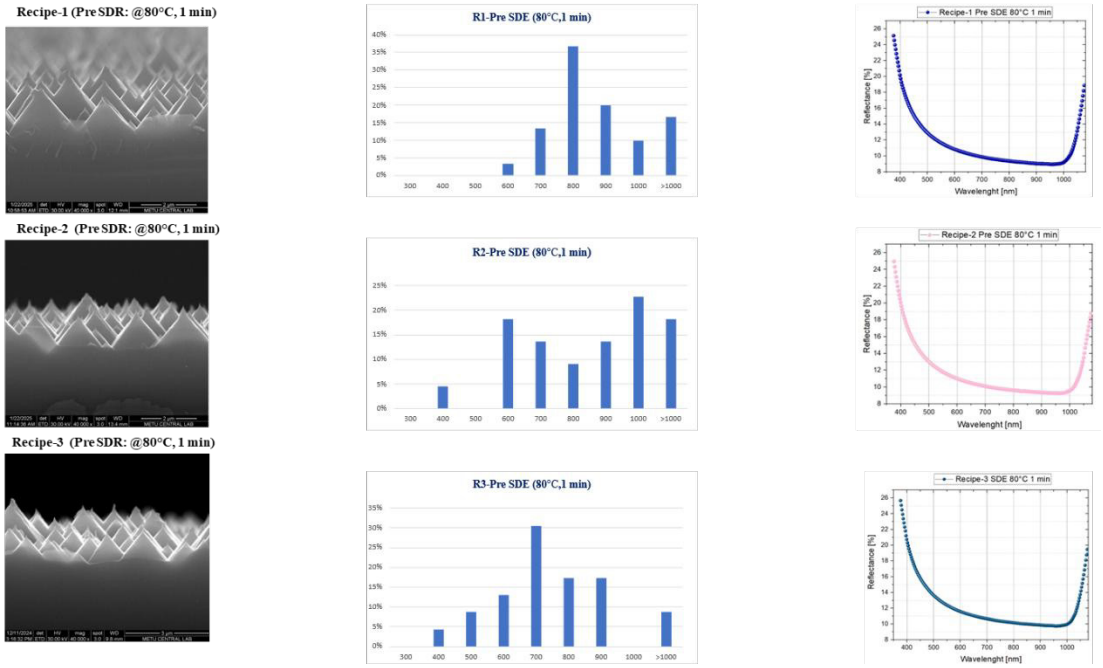


Figure2. SEM images and size distribution of pyramidal structures of all three recipes.

To reduce the sharp tips of the pyramidal structures, a post-treatment step was applied. Two different approaches were tested for optimization. In the first approach, a KOH-based post-treatment was used.

The second approach, involving O_3/HF cycling, produced more favorable results. In this method, no deformation was observed in the existing pyramid geometry; moreover, the sharp pyramid tips were effectively reduced as intended. As the number of cycles increased—most prominently at 5×—a progressive reduction in pyramid tip sharpness was observed.

As shown in Figure 3, the O_3/HF process did not lead to significant changes in reflection values. In contrast, the KOH-containing post-treatment exhibited a clear trend of increasing reflectance with longer treatment durations.

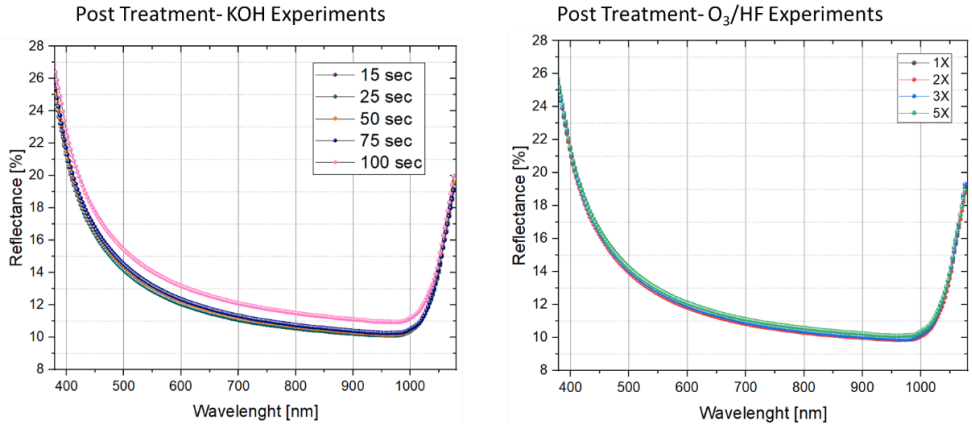


Figure3. Reflectance vs Wavelength graphs of post treated KOH and O_3/HF experiments.

Overall, the combination of the 3rd texturing recipe and the 5× O_3/HF post-treatment cycle yielded the best results in this study. Further work is ongoing to optimize the post-treatment processes for improved surface morphology and optical performance.

5. Conclusion

On an industrial batch-type system, a reliable sub-micron texturing method was successfully demonstrated. O_3/HF cycling outperformed KOH etching for post-treatment because it successfully removed sharp pyramid tops.

The study is in underway to measure the electronic impact of these morphological developments. The work continues to measure the quality and electronic effects of coatings to be deposited on sub-micron textured surfaces. After passivation layers are deposited on optimized textured surfaces, the quality of the passivation will be measured using photoluminescence (PL), lifetime, and iVoc measurements. These results, as well as further improvements to the texturing process, will be presented at the conference.

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Optimising Solar PV Resource Efficiency and Sustainability

Karl-Anders Weiß[1], Estelle Gervais[1], Sina Herceg[1], Yijiang Xu[2], Elsen Aydin[3], Tayfun Hiz[3], Burak Demir[3], Alexis Barrou[4], Alessandro Virtuani[4], Claire Agraffeil[5], José María Medianero Martín[6]

[1] Fraunhofer Institute for Solar Energy Systems ISE, Freiburg 79110, Germany
[2] Sintef AS, Trondheim, Norway
[3] ODTU-GUNAM, Middle East Technical University, 06800, Ankara, Turkiye
[4] CSEM PV-Center, Jaquet-Droz 1, 2000 Neuchâtel, Switzerland
[5] CEA, Liten, Univ. Grenoble Alpes Campus INES, Le Bourget du Lac, 73375, France
[6] IDENER Research & Development Agrupacion de Interes Economico, Seville, Spain

**karl-anders.weiss@ise.fraunhofer.de*

As photovoltaic (PV) systems emerge as the primary pillar of the global energy transition, they inevitably introduce critical challenges regarding raw material securing, resource intensity, and end-of-life waste management. Addressing sustainability, resource efficiency, environmental impacts, criticality, and circularity is therefore an inescapable necessity to prevent shifting environmental burdens and to secure long-term industrial resilience. To tackle these challenges, the EU-funded SOLARIS project aims at supporting the efficient and sustainable deployment of PV as a central pillar of the European energy system. With a holistic approach, the project combines PV market and technology development scenarios with data on supply chains, resource requirements and end-of-life management to achieve a better understanding of the environmental impacts, criticality and circularity linked to future PV. Ultimately, SOLARIS project highlights the opportunities for improving PV sustainability and European resilience, and provides recommendations on policy measures. A major outcome of the project is a database and decision-making tool enabling the PV industry, policy and broader audience to compare different future scenarios (e.g. PV processes, materials, cell technologies, production locations) in terms of their environmental impact and supply resilience.

Acknowledgements

This work is funded by the European Union's Horizon Europe research and innovation programme under the SOLARIS (Supporting Optimisation of Photovoltaic Resource Efficiency and Sustainability) project, Grant Agreement No. 101235545.

Keywords: Solar Photovoltaics, Life Cycle Analysis, Sustainability, Circular Economy, Resource Efficiency

Novel Dye-Sensitized Solar Cell Architecture Based on Er-Doped TiO_2 Nanorods and Pt/Pd Catalytic Counter Electrodes

S. Kaya[1*], T. Çetinkaya[2,3,4,5]

[1]Central Research Laboratory, Kastamonu University, 37100, Kastamonu, Turkiye
ORCID: https://orcid.org/0000-0002-6894-9082
[2]Department of Metallurgical and Materials Engineering, Engineering Faculty, Sakarya University, Esentepe, Sakarya, 54050, Turkiye
[3]Research, Development and Application Center (SARGEM), Sakarya University, Esentepe, Sakarya, 54050, Turkiye
[4]NESSTEC Energy & Surface Technology Inc., Technology Development Zones, Sakarya University, Esentepe, Sakarya, 54050, Turkiye
[5]Nanotechnology Centre, CEET, VŠB -Technical University of Ostrava, Ostrava, Poruba, Czech Republic
ORCID: https://orcid.org/0000-0001-7509-8856

*Corresponding Author's E-mail: seydanurkaya@kastamonu.edu.tr

In this study, a different architectural approach was proposed for conventional dye-sensitized solar cells (DSSCs) by redesigning both the electron transport structure and the counter electrode layer. Instead of the conventional mesoporous TiO_2 paste, vertically aligned TiO_2 nanorods were directly grown on FTO substrates. For the counter electrode, Pt/Pd catalytic layers were deposited using the sputtering technique. In addition, the structural and optical properties of TiO_2 nanorods were improved by erbium (Er) doping. With Er incorporation, the average nanorod diameter decreased from 73 nm to 38 nm, while the surface roughness significantly decreased from 36.6 nm to 28 nm. Furthermore, the initially crack-rich morphology transformed into a more homogeneous and uniform structure, indicating a substantial improvement in film quality. Optical measurements revealed that especially 1% and 3% Er-doped samples exhibited enhanced visible light transmittance. Moreover, a noticeable band gap narrowing was observed, decreasing from 3.21 eV to 3.09 eV. For the counter electrode, Pt/Pd coatings with different deposition durations were fabricated, and the photovoltaic performances of various coating thicknesses were comparatively investigated. According to the J-V measurements, relatively thicker coatings obtained at 120 s and 150 s deposition times exhibited superior photovoltaic performance, leading to higher fill factor and open-circuit voltage values.

Acknowledgements

This research was supported by the Scientific Research Projects Unit of Sakarya University under Grant No. 2022-7-25-132.

Keywords: Dye-Sensitized Solar Cells (DSSCs), TiO2 Nanorods, rare-earth doping, Pt/Pd Counter Electrodes

An Innovative Business Model Approach: Cooperatives and Private Investors in Agrivoltaics*

Dila AYERDEM[1,2,**], Nazenin Miray ÇAKMAK[1], Azra Verda KOÇAK[1]

[1]Middle East Technical University/Economics, Ankara, Türkiye
[2] ODTÜ-GÜNAM, Ankara, Türkiye
** Corresponding Author: dila.ayerdem@metu.edu.tr

ABSTRACT

This study examines the integration of agrivoltaic (AV) systems into Turkish agricultural practices through an innovative business model that combines agricultural cooperatives and private renewable energy investors under a Special Purpose Vehicle (SPV) structure. The main aim of the study is to evaluate how agrivoltaic systems can simultaneously contribute to renewable energy generation, agricultural productivity, food security, and rural development while reducing barriers to entry for farmers. In addition to technical and economic dimensions, the study also emphasizes governance, social inclusion, and gender perspectives within the energy transition process. The methodology follows an analytical and comparative research design based on existing literature, sectoral applications, policy documents, and regulatory frameworks. Cooperative and SPV models are comparatively analyzed in terms of institutional structure, governance, financial sustainability, and social benefits. Rather than focusing on a single field observation, the study develops a scenario-based model using secondary data and simulation methods. To support the analysis, a case study was conducted on a one-hectare vineyard in Denizli, Türkiye. Agricultural production costs and revenues were derived from previous vineyard studies, while electricity generation and agrivoltaic performance data were estimated through the AgriPV Tool using parameters adapted from a successfully implemented agrivoltaic vineyard project in Southern Italy. The study investigates the technical efficiency of AV systems, electricity production potential, agricultural yield changes, irrigation savings, and additional income opportunities created through energy sales. It further evaluates how cooperative-based governance and SPV partnerships can improve financial feasibility, farmer participation, and long-term sustainability in Türkiye's renewable energy transition.

**This study was prepared within the scope of the EU Horizon Europe Project "A Greek-Turkish Solar Energy Excellence Hub to Advance the European Green Deal" under Grant Agreement No:101086110,) "SolarHUB Project Innovation Challenge" activities. The project received a Certificate of Excellence and was awarded an Honorable Mention under the "Leave No One Behind" category for its innovative and inclusive business model approach to agrivoltaic systems in Türkiye.*

Key Terms: Agrivoltaic systems (AV systems), Renewable energy, Photovoltaics (PV), Cooperatives, SPV (Special Purpose Vehicle), Business model, Turkiye

Development of Highly Transparent and Conductive In-free AZO:H

Gökhan Altıner*[1], Furkan Eren Yılmaz[1,2], Yiğit Mert Kaplan[1], Raşit Turan[1,2], Hisham Nasser[1]

[1]ODTÜ-GÜNAM, Middle East Technical University, 06800, Ankara, Türkiye
[2]Department of Physics, Middle East Technical University (METU), 06800 Ankara, Türkiye
*gokhan.altiner@odtugunam.org

Aluminum-doped zinc oxide (AZO:H) has emerged as a highly versatile and cost-effective material in photovoltaic architectures. It is utilized as transparent conductive oxide (TCO), anti-reflective coating (ARC), and carrier-selective passivating contact or recombination junction for tandem applications due to its excellent optical, electrical, and passivating properties [1], [2]. The conductivity of the AZO:H arises mainly from Al dopants. While aluminum acts as an effective dopant in the ZnO lattice, excessive Al incorporation leads to the formation of detrimental AlO_x clusters. These insulating clusters act as carrier traps and significantly reduce overall doping efficiency. Additionally, the conductivity of AZO:H is enhanced by the decreased oxygen partial pressure in the deposition and annealing environment. Here, the hydrogen atoms bonded to oxygen vacancies (H_O) act as shallow multicenter donors, providing a crucial boost to electrical conductivity [3]. Consequently, preserving oxygen vacancies during the deposition process is highly important, as they provide the essential host sites for hydrogen to effectively contribute to the free charge carrier concentration. In this study, we investigate the effects of atmosphere exposure during AZO:H deposition via spatial atomic layer deposition (sALD).

To investigate the impact of environmental exposure on defect formation and optoelectronic properties, we fabricated two AZO:H layers (87 nm) on glass substrates using a sALD tool by SALD. Both samples were deposited utilizing an identical recipe; however, one sample was deliberately exposed to the atmosphere during each deposition cycle, while the other was maintained in a controlled, non-exposed environment. The deposition took place at 230°C with H_2O being used as the co-reactant, and diethylzinc (DEZ) and dimethylaluminum isopropoxide (DMAI) being used as the precursors.

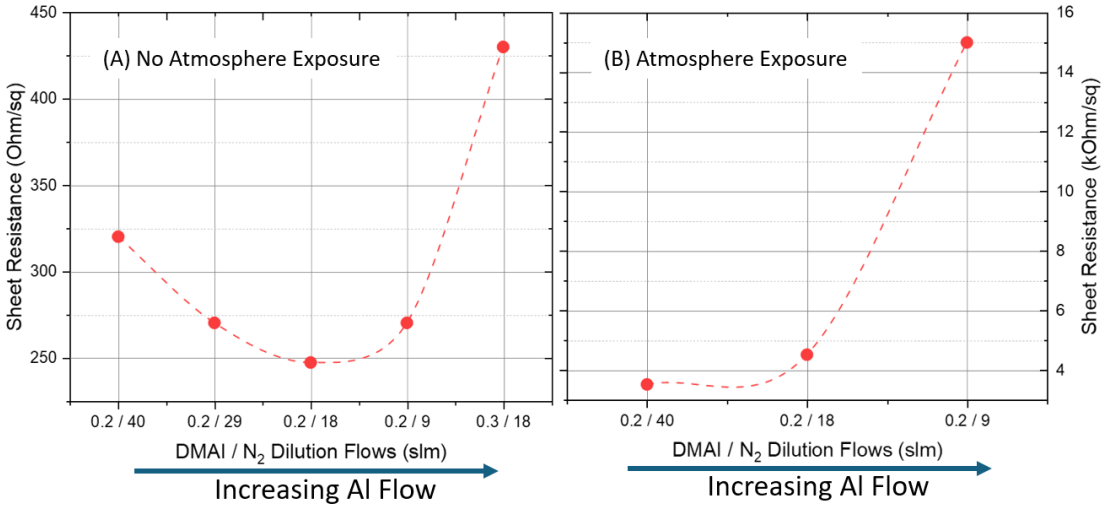


Figure 1 Sheet resistance vs DMAI / N_2 dilution gas flows for (A) AZO:H deposited with no atmosphere exposure and (B) AZO:H deposited with atmosphere exposure (The overall Al flow increases towards right for each plot)

Figure 1 shows the sheet resistance values measured by four-point-probe (PVTools FPP-scan) for increasing overall Al flow during deposition. Figure 1 (A) clearly shows an under-doping / over-doping trend for AZO:H deposited with no atmosphere exposure around the optimal DMAI / N_2 dilution flow of 0.2 slm / 18 slm, which results in 240 Ohm/sq. Below this optimal flow, the useful Al doping increases with more flow; and above the optimal flow, too much Al flow results in AlO_x clusters within the ZnO

matrix. However, in Figure 1 (B) for the AZO:H deposited with atmosphere exposure, the sheet resistance keeps decreasing with lower Al flow and results in relatively high values around 3.8 kOhm/sq at the lowest possible Al flow that can be sent by the tool while preserving mechanical stability.

This significant decrease in conductivity for the AZO:H deposited with atmosphere exposure could be explained by:

1. Easier AlO_x cluster formation of Al dopants when exposed to the atmosphere,
2. Decreased O vacancy in the ZnO matrix, and
3. Contaminant incorporation into the layer that prevents high-quality crystallization.

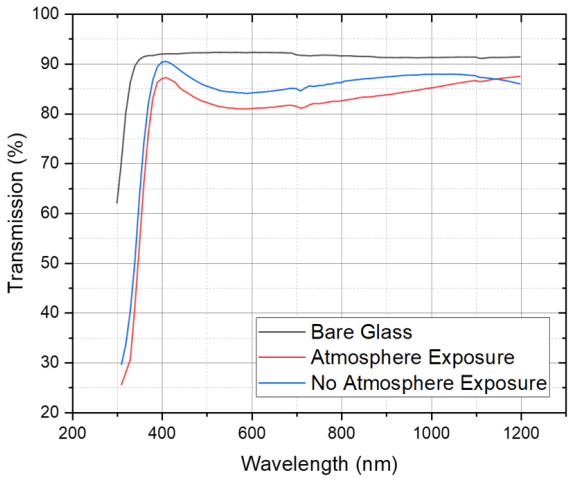


Figure 2 Transmission spectra for atmosphere exposed and no atmosphere exposed samples

Figure 2 shows the transmission spectra (measured using a PV characterization system: Bentham Instruments, PVE300) for each sample and the bare glass reference. The transmission spectrum of AZO:H with no atmosphere exposure shows increased bandgap at lower wavelengths due to the Moss-Burstein effect and decreasing transmission at higher wavelengths due to free-carrier absorption. These results clearly show that the useful Al doping concentration is significantly higher for the AZO:H with no atmosphere exposure, consistent with the sheet resistance results. The lower overall transmission of atmosphere exposed AZO:H in the visible region indicates AlO_x scattering in this layer. Therefore, the Al content in the atmosphere exposed AZO:H layer is mostly in the form of AlO_x clusters instead of useful Al dopants, which is one of the major reasons for the higher sheet resistance of this layer.

In conclusion, atmosphere exposure during AZO:H deposition shows significantly worse conductive and optical properties, mainly due to increased AlO_x cluster formation within these layers. The effect of crystallinity and the O vacancy will be further investigated via XRD and XPS measurements until the time of the conference.

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Mitigating Parasitic Absorption and Surface Recombination in TOPCon-based Bottom Cells for High Efficiency Tandem Solar Cells

Yiğit Mert Kaplan*[1], Gökhan Altıner[1], İlker Yıldız[2], Milad Ghasemi[1], Seda Kılıçkaya Ünver[1], Mustafa Büyükgüzel[1,3], Shooja Abusakha[1,3], İlkcan Erdem[1], Yunuscem Yılmaz[1], Raşit Turan[1,3,4], Hisham Nasser[1]

[1]ODTÜ-GÜNAM, Middle East Technical University, 06800, Ankara, Türkiye
[2] Central Laboratory, Middle East Technical University, 06800, Ankara, Turkey
[3]Micro and Nanotechnology Department, Middle East Technical University (METU), 06800 Ankara, Türkiye
[4]Department of Physics, Middle East Technical University (METU), 06800 Ankara, Türkiye

*mert.kaplan@odtugunam.org

Thickness reduction of the n^+ poly-Si layer has emerged as one of the most effective and readily implementable optical optimization strategies for tandem bottom cell architectures. In a monolithic two-terminal device, the doped poly-Si contact lies directly beneath the perovskite top cell and therefore acts purely as a parasitic absorber rather than contributing collected current[1]. Because the illuminated side of a bottom cell does not undergo fire-through screen printing, the thickness floor imposed by paste penetration in conventional cells no longer applies, making contacts an order of magnitude thinner than the industrial standard accessible. However, ex-situ diffusion at such thicknesses still requires optimization to achieve high passivation quality. In this study, poly-Si thicknesses of 110 nm, 80 nm, 40 nm and 10 nm were investigated, and a 10 nm ultra-thin n^+ poly-Si contact was developed by investigating *ex-situ* phosphorus diffusion conditions. Pre-deposition and drive-in temperatures were varied from 800 °C to 845 °C. To assess front-side passivation in the bottom cell architecture, two hydrogenation pathways were compared, an AlO_x sacrificial layer as hydrogen source, and aluminium-doped zinc oxide (AZO), which acts as both a hydrogen source and a recombination junction. Using the AlO_x sacrificial layer, the 10 nm n^+ poly-Si passivating contact reached 738 mV (4.5 fA/cm²) after firing, whereas the 80 nm contact was limited to 722 mV. AZO was shown to recover samples depassivated by fast firing without a capping layer, improving the implied V_{OC} from 665 mV to 713 mV. M2-sized TOPerc bottom cells fabricated with 10 nm n^+ poly-Si delivered V_{OC} values of 680–690 mV under 1-sun illumination. By PVCon 2026, UV photoelectron spectroscopy (UPS) measurement were done for investigating field effect passivation of different profiles, optical performance will have been assessed by transmission–reflection–absorption (TRA) measurements and contact resistivity by the transfer length method (TLM); full details of the ex-situ phosphorus diffusion and the hydrogenation pathways for bottom cell structures will be presented.

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PVCON2026

29-30 JUNE - 1 JULY 2026
ANKARA TÜRKİYE

SOLAR ENERGY ADOPTION AND POLICY TRANSFORMATION IN NORTH MACEDONIA

Muratcan IŞILDAK

International Balkan University, Institute of Law, Department of Balkan Studies, Skopje

Interational Balkan of Studies, Skopje

Contact: 29/02035-910617710/045/4521-9 010422259O3-2024

ABSTRACT

Introduction

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Keywords: Solar energy, Policy, North Macedonia, Energy transition

References:

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Laser-Free Wet-Chemical Patterning of BSG-Capped Poly-Si/SiO_x Passivating Contacts

Eni Muka[1] , Seda Kılıçkaya Ünver[1] , Yiğit Mert Kaplan[1] , Gökhan Altıner[1] , Agageldi Muhammetgulyyev[2] , Ayca Berfin Aydogdu[2] , Hisham Nasser[1] , Raşit Turan[1]
[1]ODTÜ-GÜNAM, Middle East Technical University, 06800, Ankara, Türkiye
[2]CW Energy Research and Development Center, Antalya, Türkiye

Motivation

Poly-Si/SiO_x: enables excellent surface passivation and carrier selectivity [1]
➔ key for high efficiencies in TOPCon and BC architectures

Conventional TOPCon: full-area front poly-Si is limited by parasitic absorption; patterned poly-fingers preserve passivation while reducing optical losses [2]

BC: only rear-side contacts; poly-Si/SiO_x for n- and p-type regions suppresses interface recombination, boosting V_{oc} values [3]

The bottleneck

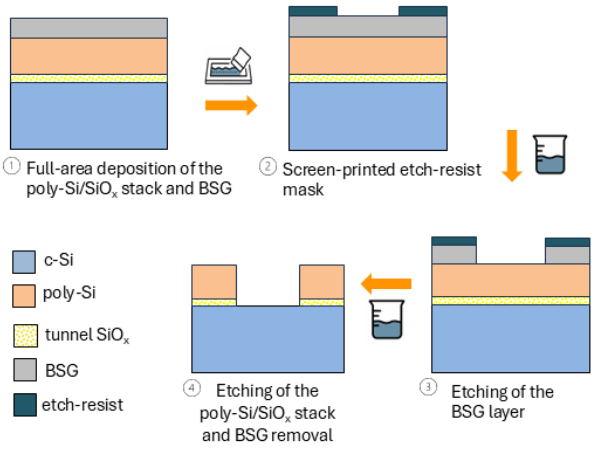
Need selectively patterned poly-Si/SiO_x without degrading passivation or damaging the ultrathin tunnel oxide [4]

Current approaches (laser ablation, laser-induced oxidation + wet removal, plasma dry etch) require costly high-precision tools and can introduce irreversible defects [5]

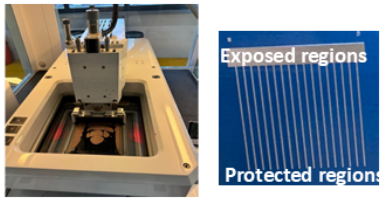
Aim: patterning route that is selective, low-damage, scalable, and compatible with industrial processing

Method

Evaluate a wet-chemical, laser-free patterning approach



Screen-Printing-Assisted Wet Etching Process for Local poly-Si/SiO_x Contacts

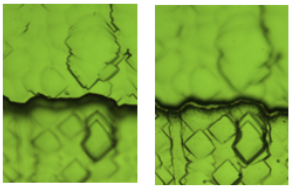


Screen-Printed Etch-Resist Pattern for Local poly-Si/SiOx Definition

Results

Visual Cue

Focus mismatch between adjacent regions indicates a vertical step created by selective etching.



Optical Microscopy of Etched and Protected poly-Si/SiO_x Regions

Electrical Test

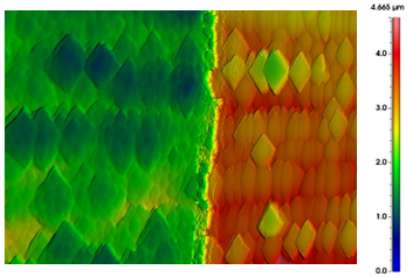
Sheet resistance separates complete and incomplete removal by orders of magnitude.

After etching measurements

Opening Completion	$R_{sh} \approx 100\ \Omega/\square$	Electrically open
Incomplete Etch	$R_{sh} = 10^3$–$10^4\ \Omega/\square$	Poly-Si/SiO_x Residues

Topography

Optical profilometry verifies a retained/etched height discontinuity.



Measured Step Height After Selective Etching

Process Optimization

Key Process Parameters for Local poly-Si/SiO_x Wet Etching

Etch-resist paste	Adhesion
	Edge definition
	Post-etch removal
Etchant Concentration	Etch rate
	Selectivity
Temperature	Etch rate
	Uniformity
BSG thickness	Selectivity
	Passivation
Surface-active additives	Surface wetting
	Reactivity
	Residues control

Conclusion

- Sequential wet etching enabled selective local removal of boron-doped poly-Si/SiO_x.
- BSG was repurposed from a diffusion byproduct into a sacrificial barrier.
- Selectivity was verified by optical contrast, R_{sh}, and profilometry.
- The optimized condition produced clean, well-defined patterned regions.
- The route is a lower-damage alternative for TOPCon and BC solar cell fabrication.

Contact Information
Eni Muka
Email: eni.muka@odtugunam.org

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TÜBİTAK Project: "Development of Local Polycrystalline Silicon for Double-Side Tunnel Oxide Passivated Contact Solar Cell (FLoRFul TOPCon)"

Phenylethylammonium-Based Bulk Modification of CsFAMA Perovskites for High-Performance Indoor Photovoltaics

Ozer Ege Tankut[1,2], Yagmur Yaren Kurnaz[1,2], Bahri Eren Uzuner[2], Zeynep Gozukara Karabag[2], Gorkem Gunbas[1,2,3], Selcuk Yerci[2,4,5], Aliekber Karabag[*2]

[1] Department of Chemistry, Middle East Technical University (METU), Ankara 06800, Turkiye
[2] Center for Solar Energy Research and Applications (ODTU-GUNAM), METU, 06800, Ankara, Türkiye
[3] Department of Polymer Science and Technology, METU, 06800, Ankara, Turkiye
[4] Micro and Nanotechnology Department, METU, 06800, Ankara, Türkiye
[5] Electrical Engineering Department, METU, 06800, Ankara, Türkiye
*Corresponding author: aliekber.karabag@odtugunam.org

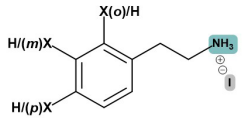
INTRODUCTION

The rapid growth of miniaturized electronics, wearable devices, wireless sensor networks, smart-home systems, and cloud-connected technologies has increased the demand for sustainable, maintenance-free, low-power energy sources. Indoor photovoltaics, particularly perovskite solar cells (PSCs), offer a promising solution due to their tunable bandgaps, strong visible-light absorption, and excellent low-light performance. Although record indoor PSC efficiencies exceed **45% under 1000 lux** and **42% under 200 lux**.[1] Since efficiency and stability are closely linked, improving both requires reducing defects inside the perovskite layer, especially at grain boundaries, buried interfaces, and top surfaces. These defects cause recombination, ion migration, charge imbalance, and degradation. Therefore, incorporating **rationally designed functional materials** directly into the perovskite bulk is a promising strategy to passivate all these defects and enhance both efficiency and operational durability of indoor PSCs.

AIM OF THE PROJECT

- Propose a synthetic pathway for **19** phenylethylammonium iodide (PEAI)-based salts (**14 mono-ammonium** and **5 di-ammonium** salts)
- Synthesize the propesed salts via practical **3-step route.**
- Confirm the molecular structures and purities of all intermediates and final targets salts by using comprehensive Nuclear Magnetic Resonance spectroscopy (**NMR**). Also, confirm the molecular masses of each targeted salt by using High-Resolution Mass Spectrometry (**HRMS**)
- After the completion of synthesis studies, all salts should be incorporated in **CsFAMA** (**Cs**: Cesium; **FA**: formamidinium; **MA**: methylammonium)-based perovskite precursor as additives

TARGETED PEAI-BASED SALTS



x-X-PEAI

x: *ortho* (o), *meta* (m), *para* (p)

X: F^-, Cl^-, Br^-

Figure 1. General illustration of *o*-, *m*-, and *p*-halogen-substituted PEAI salts

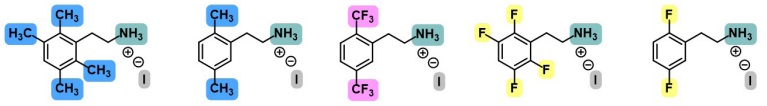


Figure 2. General illustration $(CH_3)_4$-PEAI, $(CH_3)_2$-PEAI, $(CF_3)_2$-PEAI, F_4-PEAI and F_2-PEAI salts

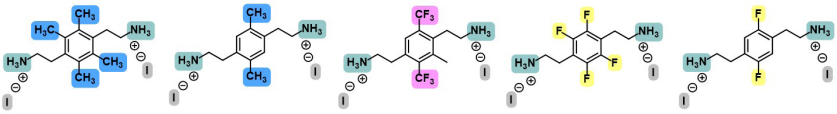
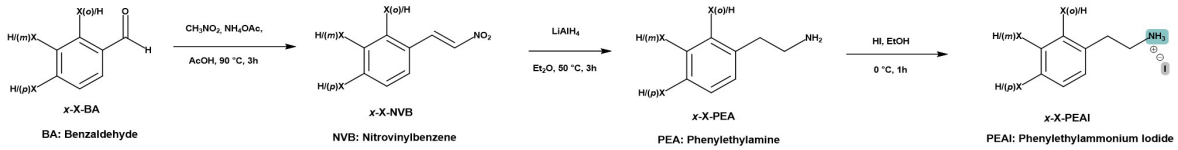


Figure 3. General illustration $(CH_3)_4$-P(EAI)$_2$, $(CH_3)_2$-P(EAI)$_2$, $(CF_3)_2$-P(EAI)$_2$, F_4-P(EAI)$_2$ and F_2-P(EAI)$_2$ salts

SYNTHETIC PATHWAY

A total of **16 target salts**, including 14 mono-ammonium salts and 2 di-ammonium salts together with 32 intermediates, were successfully synthesized through a **practical 3-step route** involving CH_3NO_2-based ***Henry (Nitroaldol) Reaction (1)***, $LiAlH_4$-based ***Reduction Reaction (2)***, and HI (57wt. H_2O)-based ***Salt-Formation Reaction (3)***.[2]



x-X-BA
BA: Benzaldehyde
x-X-NVB
NVB: Nitrovinylbenzene
x-X-PEA
PEA: Phenylethylamine
x-X-PEAI
PEAI: Phenylethylammonium Iodide

Figure 4. General synthesis pathway of ***x*-X-PEAI**-based salts from commercially sourced benzaldehyde derivatives.

RESULTS OF PEROVSKITE SOLAR CELLS

Name	V_{oc} (V)	J_{sc} (μA/cm²)	FF (%)	PCE (%)	Average PCE (%)
Reference	1.03	137.0	77.32	36.40	34.66
o-Br-PEAI	0.98	151.3	78.52	38.74	35.25
$(CH_3)_4$-PEAI	1.00	144.9	77.05	37.07	35.16
m-Br-PEAI	0.97	143.3	78.05	36.27	35.32
F_2-PEAI	1.00	140.4	77.17	35.99	35.16

Figure 5. PV parameters of top 4 performing salts compared to the control device

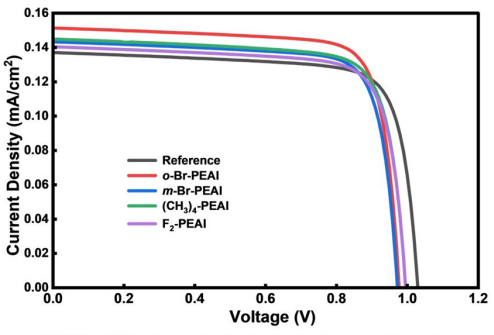


Figure 6. *J – V fitting* characteristics of top 4 performing salts compared to control device

ACKNOWLEDGMENT

This study was supported by Scientific and Technological Research Council of Türkiye (TUBITAK) under the Grant Number of **124F194**. The authors thank to TUBITAK for their supports.

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The Earth Poles: Renewable Energy with Wind and Sun

Sustainable Energy Solutions for Polar Research Stations in Antarctic and Arctic Regions

D. Kılınçoğlu[1], B. G. Akınoğlu[2], C. Baykal[3], H. C. Avcı[4], A. B. Karaveli[5]

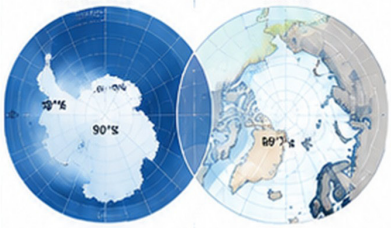
[1] Earth System Sciences, Middle East Technical University (METU), Ankara, Türkiye
[2] Department of Physics, Middle East Technical University (METU), Ankara, Türkiye
[3] Department of Physics, Middle East Technical University (METU), Ankara, Türkiye
[4] 2G Havacılık Elektronik, Hacettepe Üniversitesi
[5] TENMAK, Türkiye

MIDDLE EAST TECHNICAL UNIVERSITY METU

KEY MESSAGE

Hybrid renewable energy systems combining solar and wind power with battery storage can reliably meet the energy demands of polar research stations. Our study shows that 10–20 kW wind turbines and 100 m² high-efficiency solar panels with Li-ion batteries are sufficient to supply a 200 m² research facility in both Arctic and Antarctic conditions.

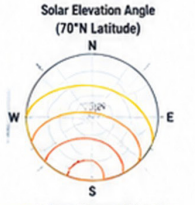
1 POLAR ENERGY CHALLENGE

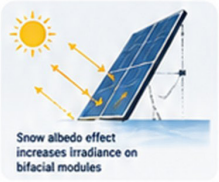


- Extreme cold and harsh conditions
- Long periods of darkness in winter
- Logistics and fuel transport limitations
- High dependence on diesel generation
- Need for reliable, clean and sustainable energy

2 SOLAR RESOURCE AT HIGH LATITUDES

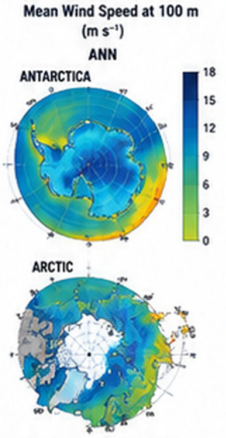
- Low solar elevation angle year-round
- Long summer daylight provides energy surplus
- High surface albedo from snow enhances bifacial PV output
- Bifacial solar modules improve energy yield by 10–30 %





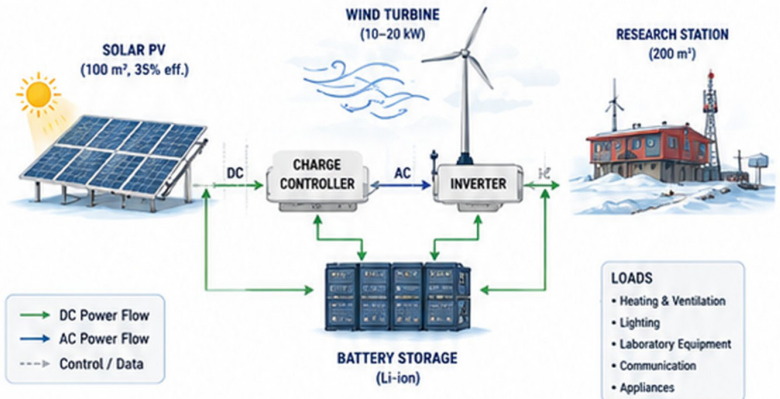
3 WIND ENERGY POTENTIAL

- Persistent katabatic winds in Antarctica
- Strong coastal and ridge-top winds in Arctic
- Small and medium turbines are ideal for research stations
- 10–20 kW class turbines offer high reliability and low maintenance



Source: ERA5 Reanalysis (1991–2020)

4 HYBRID RENEWABLE ENERGY SYSTEM



5 ENERGY SIZING RESULTS

A 200 m² research facility – annual average

SOLAR PV	100 m² bifacial modules (35% efficiency)	≈ 18–22 kWh day⁻¹
WIND TURBINE	10–20 kW class	≈ 20–25 kWh day⁻¹
BATTERY STORAGE	Li-ion battery bank (≈ 100–150 kWh)	Ensures autonomy and reliability

HYBRID SYSTEM OUTPUT
Covers the energy demand of a 200 m² research station with reliability > 95% throughout the year.

Operates in extreme cold | High system reliability | Low emissions & clean energy | Lower life-cycle costs

6 CASE STUDY & APPLICATIONS

TÜRKISH ANTARCTIC RESEARCH CAMP



- Example site: Horseshoe Island (Livingston Island)
- Renewable systems reduce fuel dependency and logistic costs
- Enables long-term, sustainable scientific activities

FUTURE ARCTIC APPLICATIONS



- High-latitude research stations and observatories
- Remote communities and monitoring systems
- Climate change and environmental studies



7 GOVERNANCE & INTERNATIONAL COOPERATION

ANTARCTICA
Antarctic Treaty System (1959)

- 5 Consultative Parties
- Peaceful use
- Freedom of scientific investigation
- Environmental protection



ARCTIC
Arctic Council (1996)

- 8 Member States
- Sustainable development
- Environmental protection
- Scientific cooperation



Peaceful cooperation, data sharing and environmental stewardship are essential for the future of polar regions.

8 KEY FINDINGS

- Hybrid solar–wind systems are technically feasible in both poles.
- Li-ion battery storage is critical for reliability and autonomy.
- Bifacial PV and small wind turbines optimize energy production.
- Renewables reduce environmental impact and operational costs.
- International cooperation ensures peaceful and sustainable progress.



CONCLUSIONS

Our review demonstrates that properly designed hybrid renewable energy systems can fully supply the energy needs of polar research stations. Solar and wind resources, when combined with battery storage, provide a clean, reliable and sustainable solution for scientific operations in Antarctica and the Arctic. These systems support long-term research, reduce carbon footprint and enhance energy independence in the most remote environments on Earth.

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[4] https://www.ats.aq/index_e.html and https://www.facebook.com/arcticcouncil/

MIDDLE EAST TECHNICAL UNIVERSITY (METU)
Earth System Sciences | Physics | Geological Engineering
Contact: dilan.kilincoglu@metu.edu.tr
Connect on LinkedIn @dilankilincoglu

SCAN ME

Impact of Geometric Design Parameters on Energy Yield and Under-Panel Light Availability in Fixed Agrivoltaic Systems: A Comparative Study of Ankara and Palermo

[Ecem ÖNEN][1] · [Vincenzo DI DIO][2] · [Talat ÖZDEN][3]
[1] University of Salerno, Italy · [2] University of Palermo, Italy · [3] METU-GÜNAM, Türkiye

BACKGROUND & MOTIVATION

- Agri-PV co-locate PV energy generation and agriculture on shared land, a growing dual land-use strategy.
- Pitch, mounting height, and tilt simultaneously control energy yield and sub-canopy PAR, a dual-objective problem.
- Ankara (continental) and Palermo (Mediterranean) provide two contrasting climatic test cases.
- A reproducible, physics-based simulation framework is needed for early-stage Agri-PV design.

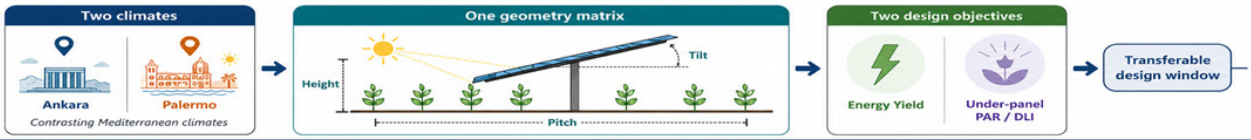
RESEARCH OBJECTIVE

Quantify how pitch, mounting height, and tilt affect PV energy yield and sub-canopy PAR in a fixed, south-facing Agri-PV, and whether a common geometric design range satisfies both objectives across two contrasting climate zones.

Key question: Does a common geometric design window satisfy both energy yield and sub-canopy light requirements across climates?

METHODOLOGY & WORKFLOW

1. **PVGIS - TMY Data** — *Ankara, TR (39.9°N, 932 m) & Palermo, IT (38.1°N, 14 m) 2005–2020 hourly*
2. **Pvlib Python - Simulation** — *Bifacial sheds, Faiman cell temp., DC PVWatts*
3. **Scenario Matrix** — *Pitch 5–10 m (0.5 m), Fixed south-facing rows, H 2.5–5 m, Tilt 20, 25, 30°*
4. **Energy Metrics** — *Specific yield, In-plane irradiance*
5. **PAR Model** — *Sub-canopy DLI, PAR values for crops*

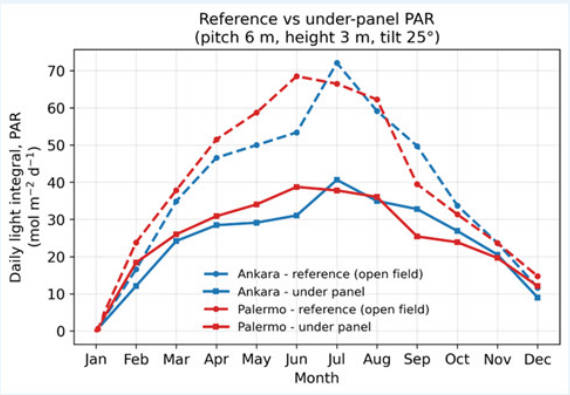


KEY RESULTS

Fixed south-facing AVS · Ankara vs. Palermo · Pitch 5–10 m · H 2.5–5 m · Tilt 20/25/30°

REFERENCE vs. UNDER-PANEL PAR

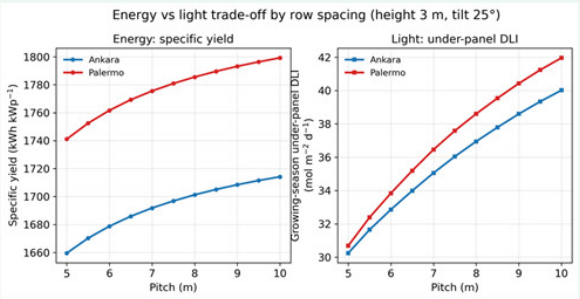
Monthly DLI (mol m⁻² d⁻¹) — pitch = 6 m, h = 3 m, tilt = 25° | Ankara (blue) vs. Palermo (red)



Palermo shows higher summer DLI than Ankara due to greater solar irradiance. Under-panel PAR at the reference configuration (pitch 6 m, h 3 m) remains above minimum thresholds for shade-tolerant crops in both climates.

ENERGY & LIGHT TRADE-OFF BY PITCH

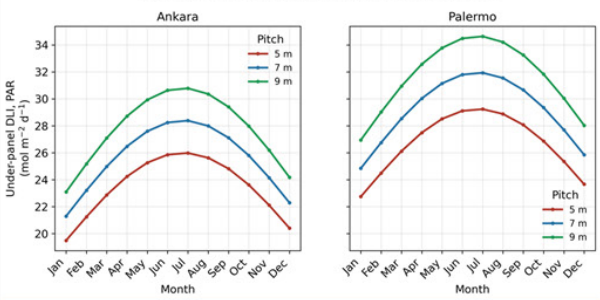
Specific yield (kWh/kWp) and growing-season DLI vs. pitch | h = 3 m, tilt = 25°



Wider pitch increases both specific energy yield and growing-season PAR. The energy–light trade-off is consistent across both climates, confirming design transferability.

SUB-CANOPY PAR BY ROW SPACING (PITCH)

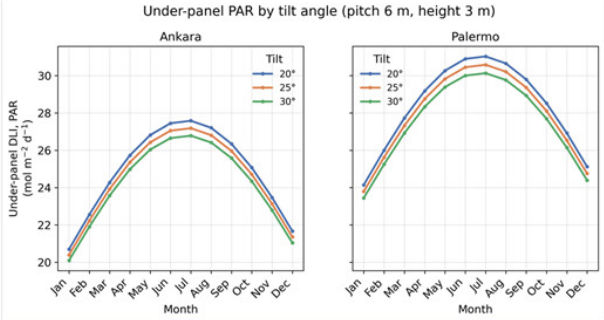
Under-panel PAR for pitch 5, 7, 9 m | h = 3 m, tilt = 25° | Ankara (left) and Palermo (right)



Pitch is the strongest geometric driver of sub-canopy PAR. Wider row spacing (5→10 m) substantially increases light interception below panels in both Ankara and Palermo.

SUB-CANOPY PAR BY TILT ANGLE

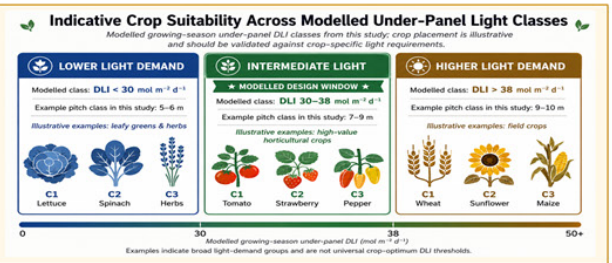
Under-panel PAR for tilt 20°, 25°, 30° | pitch = 6 m, h = 3 m | Ankara and Palermo



Tilt angle (20–30°) has a moderate, secondary influence on under-panel PAR. Both climates show parallel trends, validating cross-climate transferability of design rules.

KEY FINDING

A pitch range of 7–9 m satisfies both energy yield requirements (≥1 420 kWh/kWp) and minimum sub-canopy PAR thresholds for shade-adapted crops in Ankara and Palermo, providing a transferable geometric design window for fixed agrivoltaic systems across Mediterranean and continental European climates.



DISCUSSION

Sub-canopy light is more sensitive to pitch than to tilt or mounting height. The consistent geometric response pattern across Ankara and Palermo confirms that design rules developed at one continental-scale climate zone can transfer to a Mediterranean site, subject to location-specific calibration of absolute PAR thresholds.

Cross-climate comparison demonstrates methodology robustness. The pvlib-based simulation framework remains valid regardless of local solar resource, affirming its potential for generalisation to additional European and MENA locations.

Defining a design window rather than a point optimum is more practically useful. The pitch range 7–9 m supports both energy and agricultural objectives simultaneously, accommodating uncertainty in crop requirements and site-specific installation constraints.

CONCLUSIONS

- ✓ **Pitch is the primary driver of sub-canopy PAR in fixed agrivoltaic systems.**
- ✓ **Tilt angle (20–30°) has a moderate, secondary effect on both energy yield and agricultural light.**
- ✓ **Both Ankara and Palermo show consistent geometric response patterns, supporting cross-climate design transferability.**
- ✓ **A pitch range of 7–9 m forms a viable design window satisfying both objectives.**
- ✓ **The framework is open-source, reproducible, and transferable to other locations and climate zones.**

Future: Tracking-system extension · Crop-specific yield modelling · Additional climate zones · Regulatory framework integration

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Contact
[eonen@unisa.it]

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Sun-Position-Based Shadow Calculation for Photosynthetically Active Radiation Control in Agrivoltaic Systems

Mohammad DEROGARIAN MIANDOAB [1,2], Talat ÖZDEN [1]

[1] ODTÜ-GÜNAM The Center for Solar Energy Research and Applications/IntegratedPV Division, Ankara, Türkiye

[2] Middle East Technical University/ Electrical and Electronics Engineering, Ankara, Türkiye

[mohammad.miandoab@odtugunam.org]

Motivation and Problem Statement

Agrivoltaic systems must balance between photovoltaic energy production and crop light availability. In these systems, the panel shadow, which is continuously dependent on solar position, time, season and orientation of the panels, has a strong effect on crop level photosynthetically active radiation (PAR). Accordingly, fixed-angle or static operating strategies are not adequate for practical crop-light regulation and an adaptive panel-angle control approach is required.

Control Concept

The proposed framework uses a representative crop-side PAR measurement together with a desired PAR operating band. The MPPT angle is treated as the default energy-oriented operating point. When the measured PAR remains within the target range, the panel follows the MPPT angle. When corrective action is required, the controller evaluates the shadow condition and selects the nearest feasible panel angle relative to the MPPT reference.

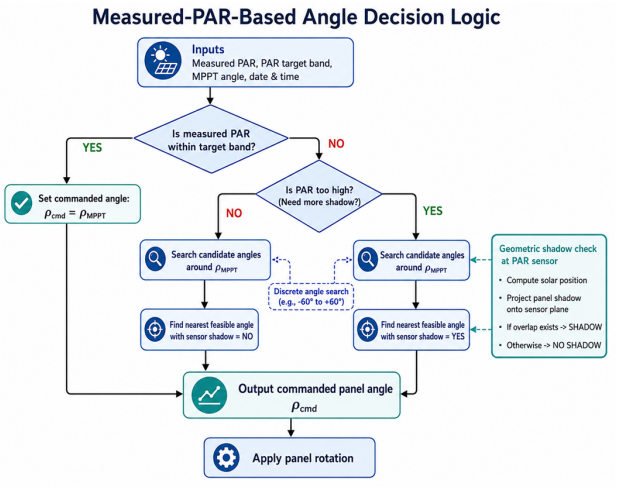


Figure 1) Measured-PAR-based control logic for panel-angle selection.

Geometric Shadow Detection Method

In the agrivoltaic farm, panel shadow is computed with a geometric model depending on sun position. For each operating instant, the PV panel geometry is rotated in three-dimensional space according to the current panel angle, and the panel vertices are projected along the solar direction on the ground plane and the sensor plane. This allows both farm scale shadow mapping and sensor level shadow detection using the overlap between the projected shadow and the PAR sensor area.

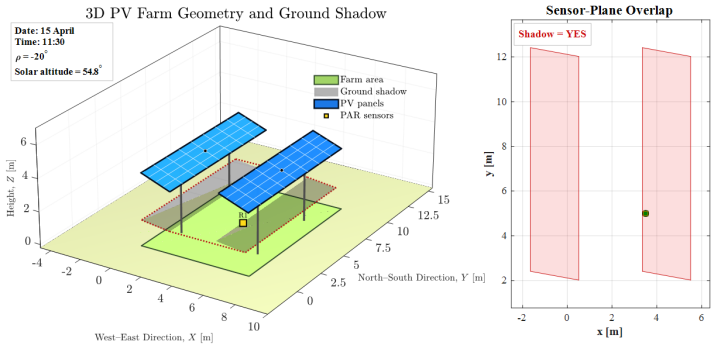


Figure 2) Geometric shadow projection and sensor-level overlap detection.

$$P_w^{k,i} = R(\rho)P_0^k + C_i$$

$$P_s^{k,i} = P_w^{k,i} + \lambda_s^{k,i} d_\odot$$

$$\lambda_s^{k,i} = \frac{z_{sens} - e_3^\top P_w^{k,i}}{e_3^\top d_\odot}$$

$$Shadow\ Status = \begin{cases} 1, & A_{int} > 0 \\ 0, & A_{int} = 0 \end{cases}$$

Optimization-Based Control Logic

- A discrete set of candidate panel angles is evaluated at each time step.
- The required shadow condition defines the feasible angles.
- The commanded angle is selected as the feasible solution closest to the MPPT reference.
- This enables PAR regulation while keeping operation close to the energy-oriented angle.

$$\Omega = \{\rho_{min}, \rho_{cmd} + \Delta\rho, \dots, \rho_{max}\}$$

$$\rho_{cmd} = \rho_{MPPT}, \quad if\ PAR_{min} <= PAR_{meas} <= PAR_{max}$$

$$\rho_{cmd} = \arg\min |\rho - \rho_{MPPT}|$$

$$\Omega_f = \begin{cases} \{\rho \in \Omega : ShadowStatus(\rho) = 1\}, PAR_{meas} > PAR_{max} \\ \{\rho \in \Omega : ShadowStatus(\rho) = 0\}, PAR_{meas} < PAR_{min} \end{cases}$$

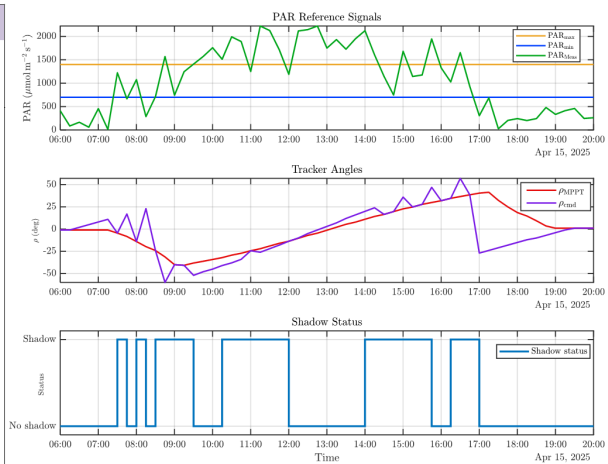


Figure 3) Simulated PAR regulation, tracker angles, and shadow status.

Conclusion & Future Work

This work presented a PAR-guided rotation-angle control approach for agrivoltaic systems. By combining measured PAR with sensor-level geometric shadow detection, the proposed method regulates crop-light conditions while preserving energy-oriented operation as much as possible.

Future work will focus on improving PAR estimation, extending the controller beyond binary shadow status, and investigating advanced decision-making methods such as fuzzy-logic-based control and shadow-area-based regulation.

Acknowledgment

This work was carried out within the S-ATP project at ODTÜ-GÜNAM under the TÜBİTAK 1004 project *Tarımda Yeşil Dönüşüm için Güneş Enerjisi (Tarım-FV)* (Project ID: 23AG020). The authors gratefully acknowledge the support of the project and ODTÜ-GÜNAM.

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INSIGHTS INTO INTERFACIAL MECHANISMS OF PEROVSKITE SOLAR CELL THROUGH ELECTROCHEMICAL IMPEDANCE SPECTROSCOPY

Mohammad Aamir[1], Sandra Winnie Angelo[1], Rajni Rohilla[2], Anubhav Raghav[2], Tabish Rasheed[1]*

[1]Department of Applied Sciences, School of Engineering and Technology, BML Munjal University, Gurugram, India

[2]Department of Applied Sciences, The NorthCap University, Gurugram, India

* Corresponding author (E-mail ID): tabish_rasheed_physics@yahoo.co.in

Abstract

In this work, lead halide perovskite solar cell containing $MAPbI_3$ as the photoactive material has been fabricated. Bias-dependent electrochemical impedance spectroscopy (EIS) measurements [1] have been performed to gain insights into the interfacial charge transport and kinetic processes. We have quantified electronic-ionic parameters such as interfacial capacitance, ionic conductivity and recombination resistances. Overall, this study provides mechanistic insights into interfacial phenomena governing device performance and stability, shedding light on pathways to design more durable perovskite solar cells.

Introduction

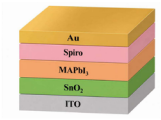


Figure 1: Schematic showing the device structure.

- Perovskite solar cells (PSCs) have emerged as a leading photovoltaic technology [2] over the past decade due to their exceptional optoelectronic properties and ease of fabrication. Power conversion efficiencies (PCEs) exceeding 25% have been achieved for single-junction devices [3]. However, stability remains the primary challenge hindering large-scale commercialization.
- Metal halide perovskites have emerged as highly promising photovoltaic materials due to their outstanding optoelectronic properties, including high absorption coefficients, tunable bandgaps, and efficient charge transport characteristics [4].
- Perovskite solar cells (PSCs) have achieved remarkable progress in power conversion efficiency; however, challenges related to defect-mediated recombination, ion migration, interfacial charge accumulation, and long-term operational stability continue to limit their practical applications [5].
- In this work, the electrical and interfacial properties of perovskite solar cells were investigated using Electrochemical impedance spectroscopy (EIS). The device configuration was ITO/SnO_2/$MAPbI_3$/Spiro-OMeTAD/Au. $MAPbI_3$ acted as the photoabsorber layer. SnO_2 and Spiro-OMeTAD served as electron and hole transport layers, respectively.
- EIS measurements were employed to elucidate the frequency-dependent charge transport behavior, interfacial charge accumulation, recombination resistance, and defect-related processes within the devices [5].
- The analysis provides deep insight into the role of interfaces, ionic effects, and transport-layer interactions in governing photovoltaic performance and stability. This study highlights the importance of understanding impedance characteristics for optimizing perovskite device architectures and developing efficient, stable next-generation solar cells.

Methodology

Complex Impedance Analysis

The frequency dependent impedance data can be represented by various mathematical expressions:

$$Z^* = Z' + jZ'' \quad \text{.....(1)}$$

where *, ′ and ′′ represents the complex, real and imaginary components of impedance, respectively.

The complex device capacitance is given as:

$$C^*(\omega) = C'(\omega) - jC''(\omega) \quad \text{.....(2)}$$

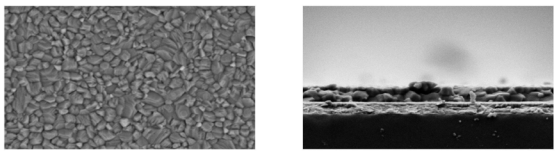
complex capacitance which were calculated using impedance data

$$C'(\omega) = -\frac{Z''}{\omega|Z(\omega)|^2} \quad \text{.....(3)}$$

$$C''(\omega) = \frac{Z'}{|Z(\omega)|^2} \quad \text{..... (4)}$$

where $|Z(\omega)|$ is the magnitude of complex impedance, and (Z') and (Z") are the real and imaginary parts of impedance, respectively.

Results



200 nm EHT 3.0 kV Mag 2.5 KX (a)

200 nm EHT 3.0 KV Mag 25 KX (b)

Figure 2: Surface electron microscope images at high magnification of $MAPbI_3$ perovskite thin film (a) top surface and (b) cross-sectional image.

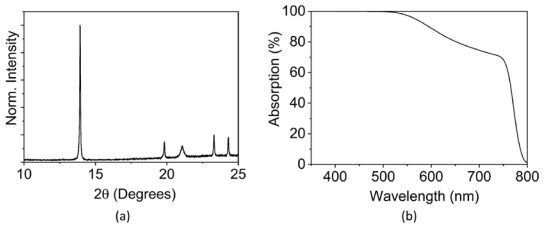


Figure 3: (a) X-ray Diffraction (XRD) plot and (b) UV-visible absorption plot of $MAPbI_3$ perovskite thin films.

Results (Continued)

Table 1: Current-voltage (I-V) characteristics of the device.

Parameter	Value
Open-circuit voltage (V_{oc})	1.05 V
Short-Circuit Current Density (J_{sc})	20.6 mA/cm²
Fill factor (FF)	71 %
Power Conversion Efficiency (PCE)	15.4 %

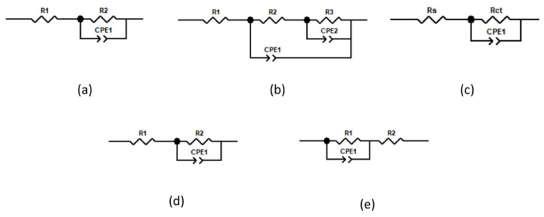


Figure 4: Circuit diagrams for Nyquist plots at (a) 0.0 V (b) 0.2 V (c) 0.4 V (d) 0.8 V and (e) 1 V.

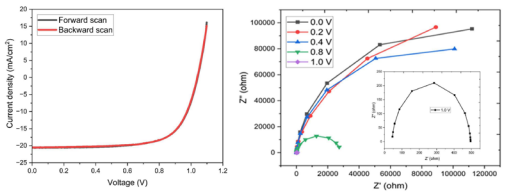


Figure 5: (a) Forward and backward scans of current density versus voltage and (b) Nyquist plots at various voltages obtained by Electrochemical impedance spectroscopy (EIS) measurements.

Important results obtained in current study are as follows:

- J–V curves show negligible hysteresis, indicating good device stability.
- High V_{oc} (~1.1 V) and current density (~20 mA cm^{-2}) suggest efficient photovoltaic performance.
- EIS results indicate reduced charge-transfer resistance at higher bias voltages.
- UV–Vis spectrum shows strong visible-light absorption with a band edge near 800 nm.
- XRD peaks confirm highly crystalline perovskite film formation.
- Sharp diffraction peaks and low impedance indicate good film quality and efficient charge transport.

Conclusion

- The perovskite solar cell achieved a **PCE of 15.4%**, indicating good photovoltaic performance.
- A high **V_{oc} (1.05 V)** and **J_{sc} (20.6 mA cm^{-2})** demonstrate efficient charge generation and collection.
- The **FF of 71%** suggests low internal losses and effective carrier transport.
- The overlap between forward and backward J–V scans indicates **negligible hysteresis** and stable device operation.
- EIS fitting reveals a **decrease in charge-transfer resistance with increasing bias voltage**, confirming improved charge transport and reduced recombination at higher voltage.

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[4] R. Kumar, B. Rakheja, N. Lamminen, et al., "Mechanistic Insights into Ionic Conduction in Lead Halide Perovskites and Perovskite-Inspired Materials," *Advanced Energy Materials* 15 (2025): https://doi.org/10.1002/aenm.202503331.

[5] J. P. Medina Flechas, D. Barrit, R. D. Patel, et al., "Characterization of ionic–electronic transport and recombination in perovskite solar cells under multi-biasing conditions," *EES Solar* (2026): https://doi.org/10.1039/D6EL00034G.

Acknowledgement

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- The encouragement and help provided by Prof. Maneek Kumar and Prof. Abhimanyu Singh Rana is gratefully acknowledged.
- Mr. Aamir is thankful to BML Munjal University for providing necessary resources and research environment for this work.

Investigation of Al-Si Rear Contact Formation for iTOPCon Solar Cells

Melisa K. Arslan[1], Seda K. Ünver[1], Aysel B. Uluşan[1], Raşit Turan[1,2], Veysel Ünsür[1,3]
[1] Center for Solar Energy Research and Application (ODTÜ-GÜNAM), Ankara, Türkiye
[2] Department of Physics, Middle East Technical University, Ankara, Türkiye
[3] Department of Electrical and Electronics Engineering, Necmettin Erbakan University, Konya, Türkiye

MOTIVATION and INTRODUCTION

- TOPCon is the dominant high-efficiency architecture in photovoltaics.
- Transition from PERC to TOPCon → increased the use of Ag pastes on both sides of the cell
- Need for cost reduction and resource sustainability
- This work, Al-Si- pastes as a low-cost rear-side substitute for industrial n-type TOPCon solar cells.

Key points:

- TOPCon → ~60% (2024) [1]
- High efficiency (>25%) but **Ag-intensive metallization** [2]
- Ag consumption ~15 mg/W (TOPCon) vs ~10 mg/W (PERC) [1]
- Need for:
  - ✓ Cost reduction
  - ✓ Resource sustainability (Ag dependency)
- **Al-Si pastes** → promising low-cost alternative
- **Challenge:** Reliable contact formation on **n^+ poly-Si/SiO_x**

EXPERIMENTAL DETAILS

- Rear-side Al-Si metallization was implemented on industrial n-type TOPCon cells to evaluate contact formation under different firing conditions.
- A comparative study with Ag reference was conducted to assess electrical and microstructural behavior.

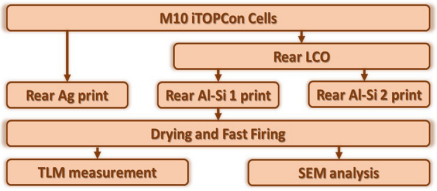


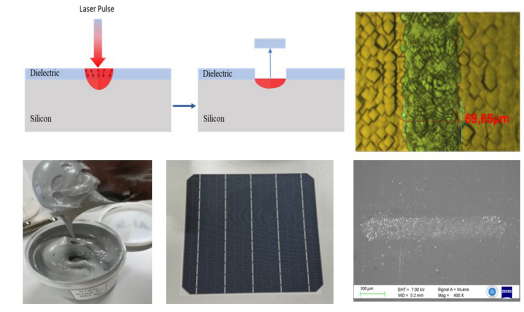
Figure 1. *Experimental flow chart.*

Process

- Substrate: **M10 n-type iTOPCon cells**
- LCO performed using 532 nm picosecond laser
- Metallization:
  - Al-Si 1 (~15% Si)
  - Al-Si 2 (~40% Si)
  - Ag reference
- Fast firing range: 660°C → 820°C (20°C increments)
- Test structure: 1 mm stripes (laser cut)

Characterization:

- **TLM** → contact & line resistivities
- **SEM & OM** → interface and surface morphology



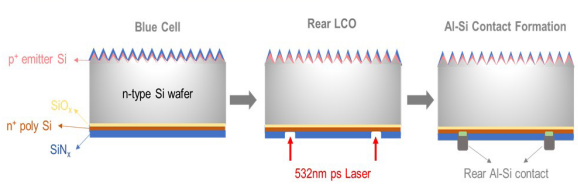


Figure 2. *Schematic representation of processes.*

RESULTS and DISCUSSION

- The impact of firing temperature on contact formation and electrical performance was systematically evaluated.
- Electrical results were correlated with microstructural evolution at the Al-Si/poly-Si interface.

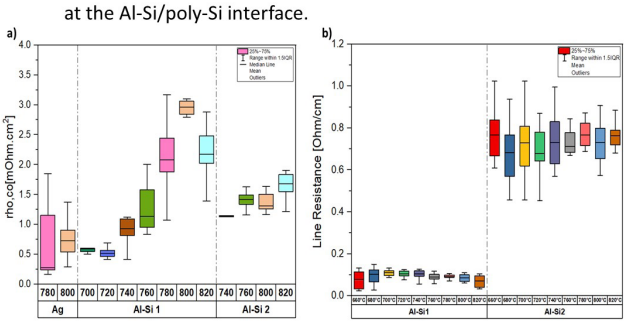


Figure 3. *a) Contact resistivity for different peak T for Ag, Al-Si, and Al-Si 2, and b) line resistivity for the Al-Si contacts.*

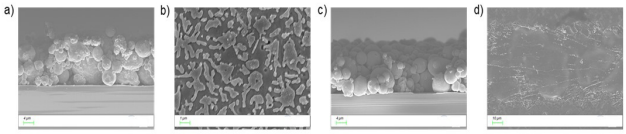


Figure 4. *Figure 3. SEM images of Al-Si 1 contacts: (a,b) 660 °C and (c,d) 800 °C, showing cross-sections (before etching) and etched surfaces revealing the Al-Si/poly-Si interface.*

Electrical Performance

- **Ag reference:** ~0.8 mΩ·cm² (780-800°C)
- **Al-Si 1 (best): ~ 0.5 mΩ·cm² @ 720°C** (lower than Ag ref)
- **Al-Si 2:** Higher resistivity (~1.5 mΩ·cm²)
- Low temperature: No proper contact (<700-740°C)
- High temperature:
  - ➢ Increased resistivity
  - ➢ Excessive diffusion
- **Line resistivity:**
  - ➢ Al-Si 1 → ~ 0.1 Ω·cm
  - ➢ Al-Si 2 → ~ 0.7 Ω·cm
  - ➢ Ag → ~ 1 Ω·cm

Microstructural Insights

- ➢ Increasing firing temperature → Deeper Al penetration + Excessive diffusion to n^+ poly-Si
- ➢ Confirms temperature-dependent interface evaluation

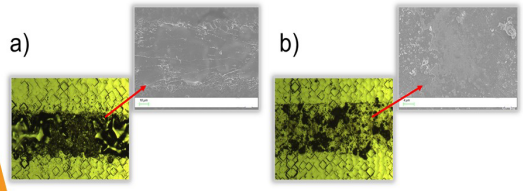


Figure 5: *a) Al-Si 1, and b) Al-Si 2 at 800°C*

CONCLUSION

- ✓ Al–Si pastes → viable alternative to Ag for TOPCon rear metallization
- ✓ Best performance (Al–Si 1):
  - $\rho_c \approx 0.5$ mΩ·cm² @ 720°C (Ag: ~0.7 mΩ·cm²)
  - Line resistance ≈ 0.1 Ω·cm (Ag: ~1 Ω·cm)
- ✓ Contact formation strongly depends on thermal budget (under/over-firing → degradation)
- ✓ Mechanism: metal penetration into poly-Si governs electrical behavior (SEM confirmed)
- ✓ Enables Ag reduction while maintaining (or improving) electrical performance in industrial TOPCon cells

Contact Person
Melisa Korkmaz Arslan
SiPV Division
Email:
melisa.arslan@odtugunam.org
Phone: +90 312 210 51 32

ACKNOWLEDGEMENT
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ODTÜ GÜNAM

PVCON 2026 PHOTOVOLTAIC CONFERENCE
5th International Conference on Photovoltaic Science and Technologies

10 nm ITO? Seriously?

Ultrathin ITO Without Fill-Factor Compromise Indoors

M. Mustafa ÇODUR, Mustafa YAŞA, Görkem GÜNBAŞ, Selçuk YERCİ

1 Why Indoor Photovoltaics ?

- **~39 billion IoT devices by 2030 need sustainable, maintenance-free power sources.**
- **Abundant indoor light enables continuous energy harvesting in homes, offices, factories, and commercial buildings.**
- **Battery replacement creates maintenance and environmental burdens.**
- **Metal-halide perovskites offer high absorption and tunable bandgaps.**

2 Progress

2017
27.4% Chen et al.
(Proof-of-concept)

2019
42.1% Li et al.
via 2D/3D heterostructure

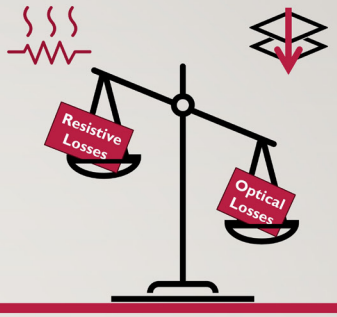
2024
44.72% Ma et al.
via some additives

today
Exceeding 45%

3 Indoor Operation Changes the Loss Landscape

One-sun
Ohmic losses dominate

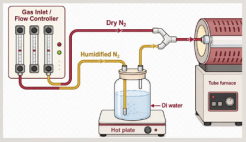
Indoor
Shunt leakage dominate



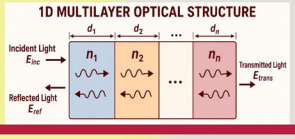
4 This Work: Thinner ITO for Indoor Perovskite Photovoltaics

Optimization of ITO resistivity
- R_{sheet} 17 Ohm/sq
- Obtaining similar resistivity for thinner films ~ 10 nm

Implementation
Implementation of the ITO with optimized thickness to the device

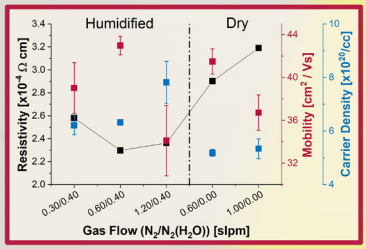


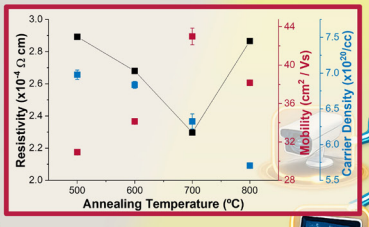
Thickness Optimization
Simulation based optimization

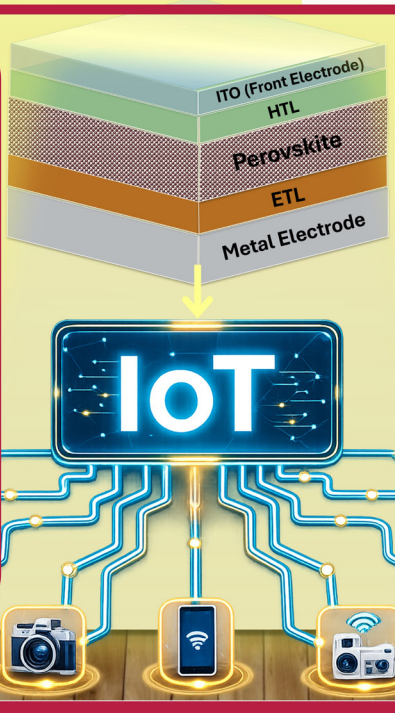


- ✓Enhanced light utilization,
- ✓Reducing Indium use

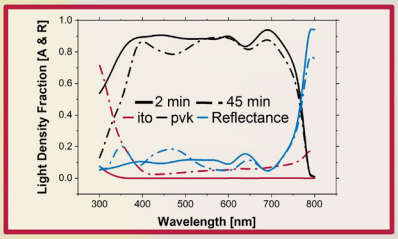
5 ITO R_{sheet} Optimization

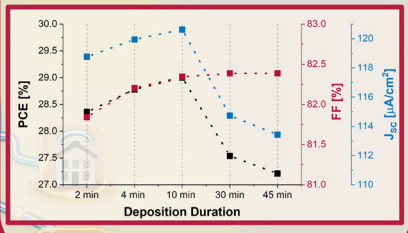






6 Device Results





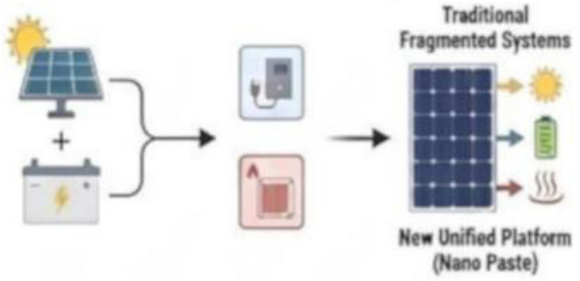
Indoor perovskite photovoltaics demand indoor-tailored optimization — ! not a one-sun blueprint !

References: *Chen et al., Adv. Funct. Mater. 2015, 25, 7064–7070 – Li et al., Adv. Mater. 2024, 36, 2306870 – Ma et al., Energy Environ. Sci., 2024,17, 1637-1644*

The 5th International Conference on Photovoltaic Science and Technologies (PVCon 2026) | Ankara, Türkiye | June 29–July 1, 2026 | Organized by METU-GÜNAM

Paradigm Shift in Integrated Energy – Printable Nano Paste Platform: Unified Solar, Storage, and Thermal Management

1. Paradigm Shift Overview



- Single Platform - Multi-Energy Solution
- Unified production, storage, and heat management
- Not just a panel, not just a battery, not just a heat system—but a smart, integrated module.

2. Challenges with Conventional Systems



Lithium Dependency: Supply chain risks, geopolitical lasues.

Supply Nations: Thermal runaway, fire hazard riska.

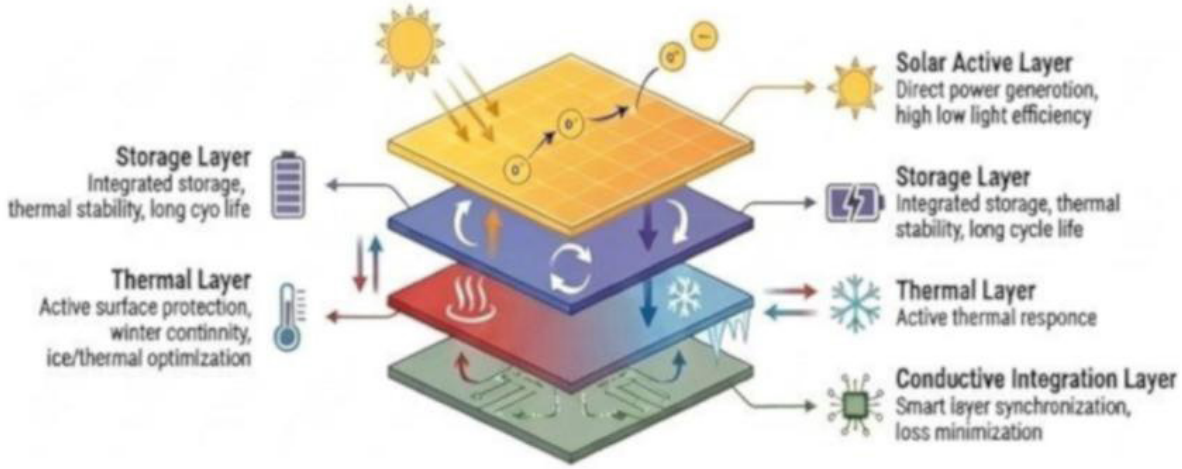
Battery Safety: Thermal runaway, fire hazard risks.

Cold Climate Inefficiency: Reduced output, damage risks.

Integration Complexity: High installation years, maintenance challenges.

Low Light Performance: Significant energy ioss in cloudy/diffuse light.

3. Integrated Solution – Printable Nano Paste Platform



4. Comparison Table

	Standard Systems (Separate Productiou/Storage/Panl)	Double Puwer Panel™ (Integrated Panel)
Installation	Rooftop Only (✓)	Rooftop + Vertical Production (✓)
Storage	External Battery (✓)	Integrated Under-Panel Storage (✓)
Thermal Management	Separate Heated Room (✓)	Integrated Protection (✓)
Production Type	Single-Side (✓)	Double/Symmstric Active Production (✓)
Efficiency Curve		

5. Performance, Testing, and Certification



- ✓ ≥500,000 charge/discharge cycles
- ✓ -40°C to +85°C operational range
- ✓ Salt, UV, humidity tests, CE, IEC, ISO certifications
- ✓ Validated for industria/iscenario use

6. Product Portfolio & Scaling



7. Strategic Advantages and Market impact



Reduced risk, higher yield | Year-round performance– even in winter | 40% more annual return in European markets | Smart energy Independence | Premium Three-in-One Pansl Architecture

METU-GÜNAM
website: odtugunam.org
email: info@odtugunam.org

Presented by Dr. Kürşad Tosun and Suniversal Ltd.

Satellite Screen Shots and Next Generation Solar Cells

Satellite-based solar-resource assessment for PV yield and feasibility

E. Akyuruk[1], S. Ener Ruşen[2], İ. Turan[3], B. G. Akınoğlu[4]

[1] METU Dept. of Physics and TENMAK, Ankara, Türkiye
[2] Karamanoğlu Mehmet Bey University, Energy Systems Engineering, Konya, Türkiye
[3] METU Dept. of Physics, METU Ankara, Türkiye
[4] METU Dept. of Physics and Earth System Science, METU Ankara, Türkiye



Source visuals: NASA MODIS satellite imagery; U.S. Department of Energy solar photovoltaic image.

ABSTRACT

Satellite imagery provides spatial information on cloud cover, surface features, albedo and climatic variability for solar irradiation estimation. This framework links satellite-derived solar-resource assessment to PV yield, intermittency and economic feasibility. Irradiation estimates are combined with module efficiency, performance ratio, temperature response and losses to estimate PV output. The resulting yield supports LCOE, revenue/profit, NPV and payback assessment under different climatic and geographic conditions.

BACKGROUND AND MOTIVATION

Motivation

- Ground-based solar radiation and sunshine-duration measurements are valuable, but their point-based coverage can miss spatial variability.
- Satellite imagery supplies repeated spatial information on cloudiness, surface features, atmospheric effects and regional climatic differences.
- Because photovoltaic production depends on local solar availability, uncertainty in irradiation estimation becomes uncertainty in yield, intermittency and feasibility.

Research Questions

- How can satellite-derived information be linked to solar-resource estimation, PV performance and economic viability?
- Which climatic and geographic variables are the main drivers of PV intermittency and regional suitability?
- How can the same assessment chain support comparison of conventional, perovskite and tandem PV technologies?



Figure 1. Satellite observation and high-resolution Earth imagery motivate remote-sensing-based solar assessment.

METHODOLOGICAL FRAMEWORK

Input — Satellite images are interpreted together with NASA POWER, ESA Earth-observation context and available surface measurements.

Irradiation — Cloud cover, surface albedo and atmospheric transparency are translated into global horizontal, direct normal and diffuse horizontal irradiation variability.

Photovoltaic Yield — Irradiation is combined with photovoltaic module efficiency, performance ratio, losses, temperature response and orientation.

Feasibility — Energy-yield estimates feed levelized cost, levelized revenue/profit, net present value and payback calculations.

Satellite-Derived Variables for Photovoltaic Assessment

Cloud cover	Cloud fields, shading effects and short-term irradiance reduction
Surface albedo	Surface reflectance and land/sea/snow context
Seasonality	Seasonal variation in annual yield and capacity factor
Latitude	Solar angle, daylight duration and regional comparison
Module properties	Module efficiency, thermal response and system losses

PHOTOVOLTAIC PERFORMANCE AND FEASIBILITY

Link to Next-Generation PV Technologies

- Advanced silicon, thin-film, perovskite and tandem solar cells aim to improve efficiency, reduce material use and expand application flexibility.
- Real deployment potential still depends on the local solar resource: irradiation level, temperature, humidity, diffuse radiation fraction and spectral conditions.
- Satellite-based resource assessment helps identify where a given photovoltaic technology may be technically suitable before detailed project design.

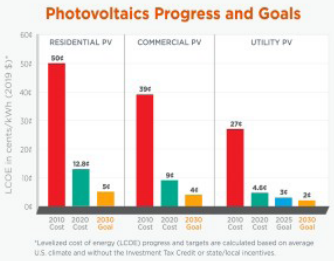


Figure 2. DOE/SETO PV LCOE progress and targets; bars show 2020 benchmark costs and 2030 goals.

Photovoltaic energy output ~ irradiation x module area x efficiency x performance ratio

Profitability
Levelized profit of energy
Resource quality and lifetime profit margin

Cost
Levelized cost of energy
Unit electricity cost from satellite-informed yield

Revenue
Levelized revenue of energy
Expected income under electricity price assumptions

Investment
Net present value / payback
Site- and technology-level investment attractiveness

EXPECTED ASSESSMENT OUTPUTS

Solar resource layer
Maps where satellite-derived irradiation is expected to be high or low, using cloud cover, surface features and seasonal patterns as inputs.

Photovoltaic yield estimate
Converts the solar resource into expected panel output by applying module efficiency, performance ratio, orientation and loss assumptions.

Intermittency profile
Identifies when useful energy output may fluctuate due to clouds, climatic seasonality and latitude-dependent daylight variation.

Feasibility indicators
Uses the yield estimate to evaluate levelized cost, revenue/profit measures, net present value and payback for renewable deployment.

CONCLUSION AND RELEVANCE

Main Contribution

- The study is framed as an assessment framework rather than a material-development study.
- It links Earth observation, irradiation modelling, PV performance and economic feasibility.
- The framework supports regional technology comparison where ground measurements are limited.

Conclusion

- Satellite imagery improves the spatial interpretation of solar-resource variability and PV intermittency.
- PV planning becomes more reliable when irradiation, losses and economic indicators are evaluated together.
- For next-generation PV technologies, local resource quality remains a site-dependent constraint.



Deployment decisions require both physical resource quality and economic feasibility.

Selected References

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Image sources: NASA MODIS Image of the Day; U.S. Department of Energy Solar Energy Technologies Office. Keywords: Satellite imagery; Solar irradiation estimation; Renewable energy; Photovoltaic systems; Climate variability; Energy economics.

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Synthesis of Low Band Gap Energy Subporphyrazine Dye Materials and Their Potential Use in Photovoltaic Solar Cells

Serap TERE[a], Uğursoy OLGUN[a,b], İlkay ŞİŞMAN[a], Mustafa GÜLFEN[a,b]

[a]*Department of Chemistry, Sakarya University, 54187, Sakarya, Turkey*
[b]*Polimer Malzeme ve Teknolojileri Araştırma Uygulama Merkezi (Polimer Tekmer), Araştırma-Geliştirme Uygulama ve Araştırma Merkezi (Sargem), Sakarya University, 54187, Sakarya, Turkey*

ABSTRACT

The organic photovoltaic solar cells (OPVs) are promising due to their simple fabrication procedure, low material cost and flexibility. In recent studies, the semiconductive conjugated organic materials as the electron donor materials blended with [6,6]-phenyl-C_{71}-butyric acid methyl ester ($PC_{71}BM$) have been investigated extensively using a single bulk heterojunction (BHJ) device structure [1-3]. The semiconductivity and solar cell material properties of many phthalocyanine and subphthalocyanine dyes have been also investigated previously [4,5]. In the present work, the synthesis, characterization and photovoltaic properties of new conjugated Al subporphyrazine dye (Al-subPz) were investigated. The Al-subPz dye shown in Figure 1 is a red color dye material with a band gap energy of 1.77 eV. Currently, we are exploring the potential technological applications of this red light emissive Al-subPz dye in different optic and electronic devices. As a result, the new Al subporphyrazine structure with imidazole rings can be considered as a promising organic solar cell dye material.

INTRODUCTION

Subporphyrazines (SubPz) are highly tunable chromophores with their intense absorption and fluorescence emissions. They are a class of cone-shaped boron(III) macrocycles and they are structural analogs to subphthalocyanines. These subporphyrazine dyes are utilized in photodynamic therapy (PDT), molecular photoswitches and organic electronics.

Many diffenet new technologies based on new organic molecules and inorganic semiconductive materials with various device configurations are desirable for the production of electricity from solar energy. The effective conversion of sun light into electricity requires strong light absorbing materials in UV-visible region and the effective transport of electrons in semiconducting active layers. For instance, perovskite solar cells (PSCs), organic photovoltaic cells (OPVs), dye sensitized solar cells (DSSCs) and thermoelectric power generators (TEGs) are commonly studied for the effective harvesting of sun light.

In our work, new type of subporphyrazine (SubPz) dye was prepared and its optical and electronic properties have been explored. Dark red color aluminum subporphyrazine (Al-SubPz) complex exhibiting strong absorption and fluorescence emission properties have been synthesized from nano Al. These new dye material have been also tested in DSSC device in order to see the light conversion performance of the molecule.

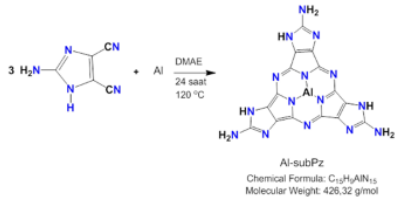


Figure-1. Synthesis of Al-subPz dye using nano Al powder.

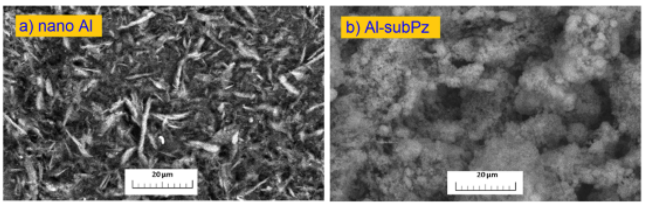


Figure-2: SEM electron microscopy images of a) nano Al particles, b) Al-subPz dye powder.

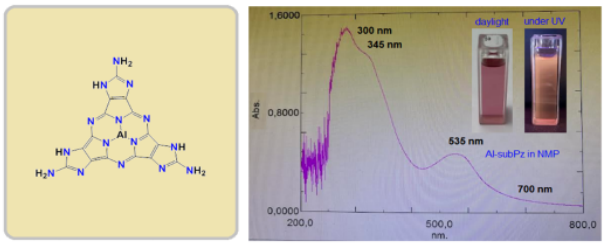


Figure-3. Flourescence Al-SubPz dye molecule and its UV-vis spectrum in NMP with flourescence emission under UV light.

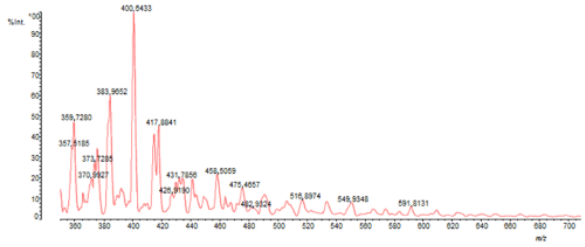


Figure-4. Maldi-Toff-MS analysis of the Al-subPz product.

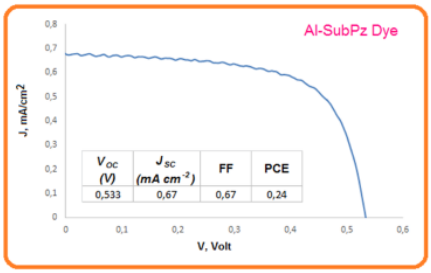


Figure-5. Measured current density-potential graph and determined performance values for the manufactured DSSC solar cell.

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*Corresponding author: serap.tere@iba.com.tr , uolgun@sakarya.edu.tr

Metal Oxide Nanoparticle-Based Photonic Glass Coatings for Structural Coloration of BIPVs

Parisa Sharif[1], Eda Cevik[2], Ilknur Ozbayrak[2], Talat Ozden[1], Sahin Coskun[3], Husnu Emrah Unalan[1,2,4], Alpan Bek[1,5]

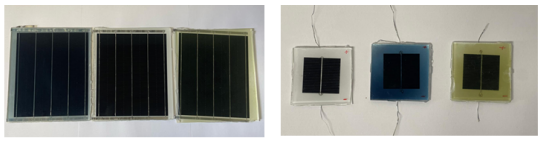
[1] The Center for Solar Energy Research and Applications (ODTU-GUNAM), Middle East Technical University (METU), 06800, Ankara, Türkiye
[2] Department of Metallurgical and Materials Engineering, Middle East Technical University (METU), 06800, Ankara, Türkiye
[3] Department of Metallurgical and Materials Engineering, Eskisehir Osmangazi University (ESOGU), 26140, Eskisehir, Türkiye
[4] Energy Storage Materials and Devices Research Center (ENDAM), Middle East Technical University (METU), 06800 Ankara, Türkiye
[5] Department of Physics, Middle East Technical University (METU), 06800, Ankara, Türkiye

e-mail: unalan@metu.edu.tr

Motivation

- Building-integrated photovoltaics (BIPVs) require effective color customization for widespread adoption in urban environments, where architectural harmony is as important as energy performance.
- In this work, we present a photonic glass–based coloration strategy using metal oxide nanoparticles (V_2O_5, MoO_3) to achieve durable colored solar panels, overcoming the limited stability of conventional dyes and pigments while maintaining minimal loss in power conversion efficiency.
- Ultrasonic spray coating is utilized as a scalable and cost-effective deposition technique for the deposition of metal oxide nanoparticles, enabling uniform large-area coatings for colored BIPV applications.
- Advances in colored BIPV technologies are expected to expand the accessible color palette, supporting the development of aesthetically versatile and architecturally integrated photovoltaic systems.

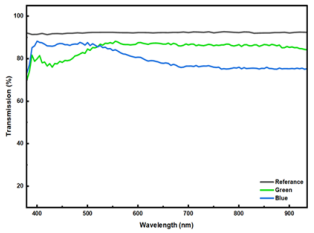
Lamination of PV Modules



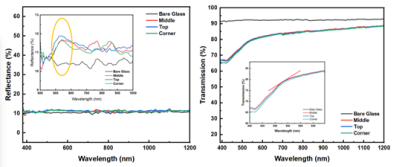
Synthesis of Metal Oxide Nanoparticles and Fabrication of Colored BIPVs



Optical Characterization



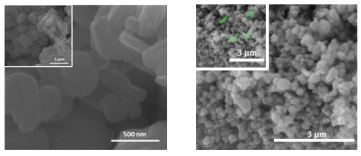
V_2O_5



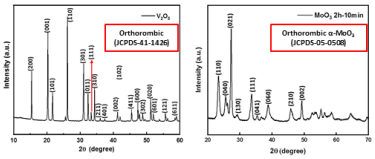
Morphological Characterization

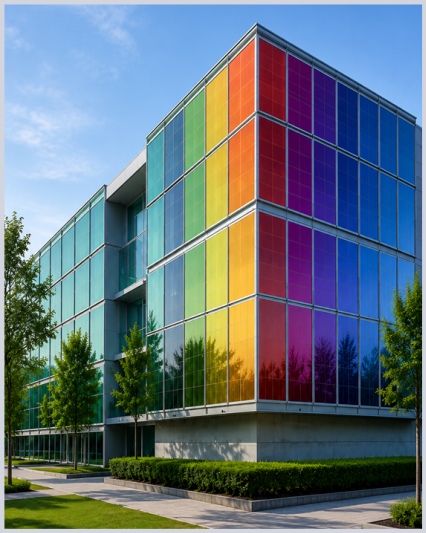
Scanning Electron Microscopy

V_2O_5 MoO_3



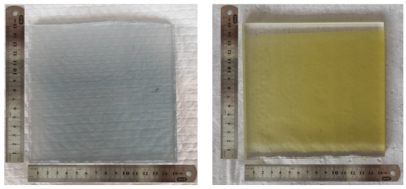
XRD Analysis



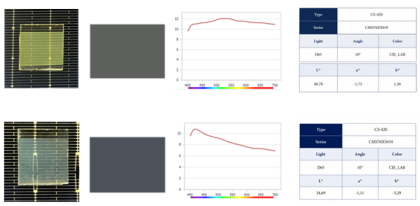


Ultrasonic Spray Deposition (15 cm x 15 cm)

MoO_3 V_2O_5



Color Analysis



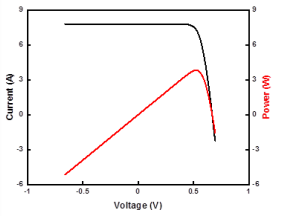
Outdoor Tests



Sample	P_{mpp}	I_{sc}	V_{oc}	I_{mpp}	V_{mpp}	FF	G_i	T_{ort}	T_{mod}
Reference	0.2	0.448	0.637	0.406	0.515	73.3	980	22.9	32.2
Green	0.1	0.276	0.622	0.27	0.51	80.3	1000	22.8	30.6
Blue	0.0	0.081	0.579	0.073	0.498	77.6	1091	22.7	32.9

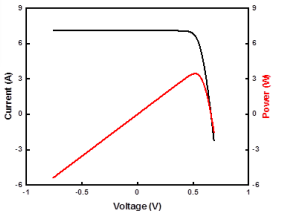
Electrical Characterization

Reference PV



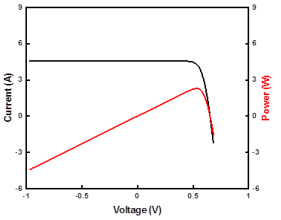
Efficiency (%): 20.202

Green PV



Efficiency (%): 18.271

Blue PV



Efficiency (%): 12.104

Conclusions

- Fully inorganic V_2O_5 and MoO_3 photonic glass coatings were demonstrated as a viable approach for durable BIPV colorization.
- Angle-independent structural coloration was achieved via Mie scattering from disordered metal oxide nanospheres.
- Ultrasonic spray coating enabled scalable and uniform deposition of photonic layers on PV cover glass.
- The V_2O_5-coated device preserved >90% of the reference PCE, whereas the MoO_3-coated device retained ~60%.
- The findings emphasize the critical role of material selection in minimizing optical losses while maintaining aesthetic functionality.
- Overall, metal oxide photonic glass coatings present a robust and scalable pathway for next-generation colored BIPV applications.

Acknowledgements

- This work was financially supported by the Scientific and Technological Research Council of Türkiye (TÜBİTAK) under Grant No 123F372.

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Contact Optimization of TOPCon Solar Cells Using Halogen Lamp and Electrical Bias

Tunçer Deniz Kurttekin*[1,3], Bülent Arıkan[1], Hande K. Cankul[1], Agageldi Muhammetgulyyev[4], Raşit Turan[1,2]
[1]Center for Solar Energy Research and Applications (ODTÜ-GÜNAM), Ankara, Türkiye
[2]Department of Physics, Middle East Technical University (METU), Ankara, Türkiye
[3]Department of Micro and Nanotechnology, Middle East Technical University (METU), Ankara, Türkiye
[4] CW Enerji, Antalya, Türkiye
*deniz.kurttekin@metu.edu.tr

Introduction

c-Si solar cells continue to dominate the photovoltaic market, and TOPCon has become one of the most promising industrial cell architectures. Although TOPCon enables low recombination through its passivating contact structure, front-side metallization remains as a critical challenge.

The contact between screen-printed Ag/Al alloy electrodes and the boron emitter can introduce high contact resistivity and metallization-induced recombination, limiting fill factor and overall device performance. Recent studies show that **Laser-Enhanced Contact Optimization (LECO)** can improve this interface by combining localized illumination with electrical bias, **enhancing metal–Si contact formation and reducing electrical losses**. However, conventional LECO relies on laser-based processing.

In this study, we investigate a simpler alternative approach using:

- halogen lamp illumination
- under electrical bias

for contact optimization in n-type TOPCon solar cells, aiming to achieve LECO-like improvements through a more accessible and potentially lower-cost process [1,2].

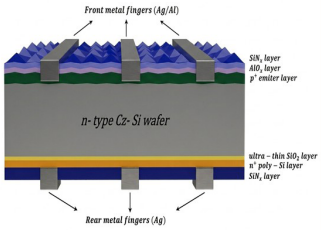


Figure 1. Schematic of the industrial TOPCon solar cell (without the LECO)

Experimental Design

Industrial n-type TOPCon samples without prior LECO treatment were prepared by cutting **9.2 cm × 2.2 cm strips** from a full-size M10R, 16 BB cell. Instead of a conventional laser-based LECO process, contact optimization was performed using **halogen lamp illumination under electrical bias**. This method was investigated as a simpler, cost-effective and more accessible alternative to industry-adopted laser based LECO.

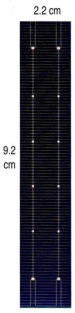


Figure 2. Treated 9.2x2.2 cm cell strips .

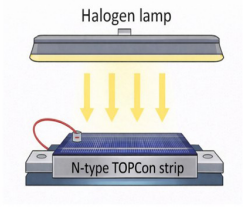


Figure 3. Schematic illustration of treatment.

Treatment Conditions		
Process Duration	Applied Voltage	Measured Current
2, 3, 4, 5 min	19V	2.6-2.8 A

The illumination intensity was measured as 3.5 suns. All **treatments** were carried out at a

- **constant 19 V**
- with processing times of **2, 3, 4, and 5 min**.

The processing of the cell strips was performed for equal durations on both the front and rear sides. A reverse bias was applied during processing on the front side, and a forward bias was applied during processing on the rear side. The resulting changes in contact quality and cell performance were analyzed by comparing the samples before and after treatment.

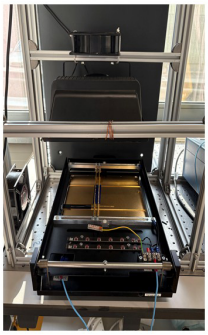


Figure 4. Experimental setup for contact optimization.

Compared with laser-based LECO, this setup offers a simpler treatment that potentially more compatible with large-scale industrial manufacturing.

Contact
Tunçer Deniz Kurttekin
ODTU-GÜNAM, Silicon Photovoltaics Division
Email: deniz.kurttekin@metu.edu.tr
Phone: +90 531 5521536

Results and Discussion

The I–V and EL analyses of a TOPCon cell processed using the conventional laser-based LECO method are presented below. These cells were produced on the same production line and were used as the reference group in the study.

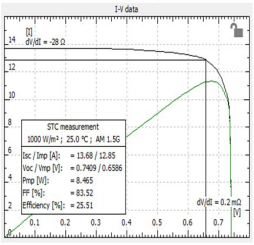


Figure 5. I-V curve of the reference full-size M10R TOPCon cell, prior to cutting.



Figure 6. EL image of a sample treated using the conventional industrial LECO process.

Dark images obtained from EL measurements before the process was applied were **significantly brightened after the process**, indicating the improvement in the contact quality. A marked improvement in the contact was also observed.

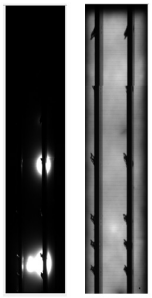


Figure 7. Before and after EL images of a 5 min front and rear-side treated sample.

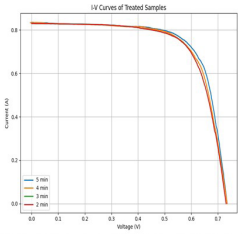


Figure 8. I-V curve of treated samples.

In addition to EL analyses, I-V measurements support the improvement in contacts. No measurable I–V response was observed before the LECO process, whereas after treatment the cells exhibited a **short-circuit current density (Jsc) of 41mA/cm²** Furthermore, measurements performed on the samples also revealed that this effect is permanent.

Table 1. Performance comparison of samples under varying treatments.

Sample	Process Duration [min]	Voc [V]	Isc[A]	FF[%]	Efficiency [%]
Cell-01	2	0.735	0.83	73.69	**22.52**
Cell-02	3	0.731	0.83	72.30	**21.90**
Cell-03	4	0.735	0.82	74.48	**22.44**
Cell-04	5	0.736	0.83	75.03	**22.94**

Among the conditions, the best overall performance was obtained for the **5 min** treated strip, reaching **Voc=0.736V, Jsc=41.0mA/cm² , FF= 75.03%** with efficiency of **22.94%**.

Conclusion

- A halogen lamp-assisted, bias-driven treatment was shown to **improve the contact quality of n-type TOPCon strips without using a laser-based LECO process**.
- The improvement was confirmed by both EL imaging and electrical measurements, with a **strong increase in Voc after treatment**.
- This approach provides a **simpler and potentially more cost-effective alternative** to conventional laser-based LECO. → corresponding to a **cost saving of** approximately **$500,000 for 1 GW** manufacturing facility.
- With further optimization, the method may have the **potential to recover or approach the factory-level efficiency** of the original cell.

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Thermal-Budget Compatibility of CIGS Processing with Silicon Bottom Cells for Alternative Thin-Film/Si Tandem Photovoltaics

Mustafa Büyükgüzel[1] , Büşra Altınsoy[1], Seda Kılıçkaya Ünver[1] , Bahri Eren Uzuner[1] , Yiğit Mert Kaplan[1], Gökhan Altıner[1] , Selçuk Yerci[1,2] , Raşit Turan[1,2] , Veysel Ünsür[1,3]

[1]ODTÜ-GÜNAM, Middle East Technical University, 06800, Ankara, Türkiye
[2]Middle East Technical University, 06800, Ankara, Türkiye
[3]Necmettin Erbakan University, 42090 Konya, Türkiye

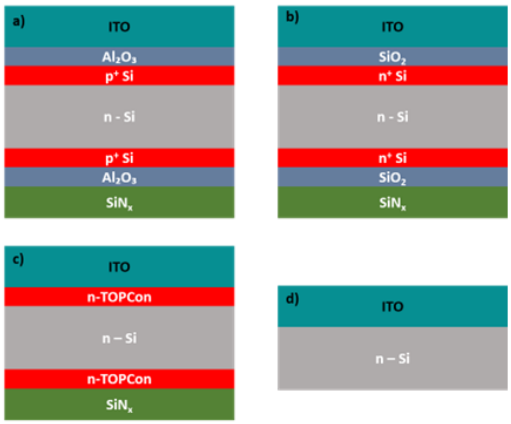
Introduction

- Tandem photovoltaics can exceed single-junction Si limits by distributing absorption across complementary bandgaps.
- CIGS is an attractive alternative top-cell candidate because of its tunable bandgap, mature thin-film processing and long-term stability.

Key Challenge: CIGS thermal processing near 500 °C – 550 °C may degrade temperature sensitive Si bottom cell properties.

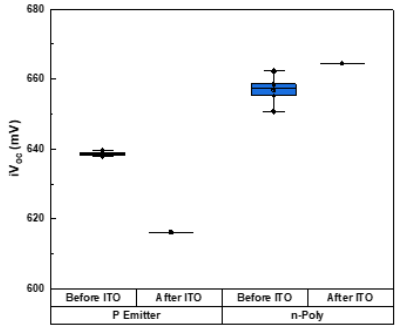
Objective: Evaluating whether Si bottom can preserve passivation, ITO conductivity and contact functionality after CIGS-related thermal exposure.

Experimental Design



- Semi-symmetric samples with different surface configurations.
- 100 nm sputtered ITO, N_2 annealing for 30 min. at selected temperatures.
- Rear side SiN_x passivation was used where applicable to maintain comparable lifetime conditions.

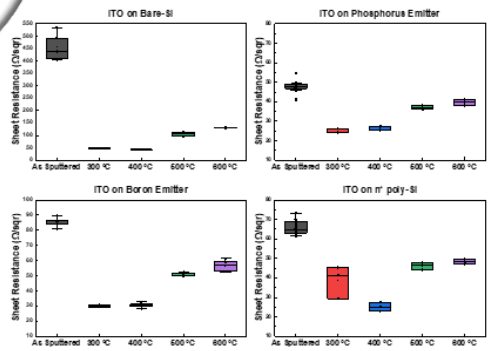
ITO Sputtering: Interface Sensitivity



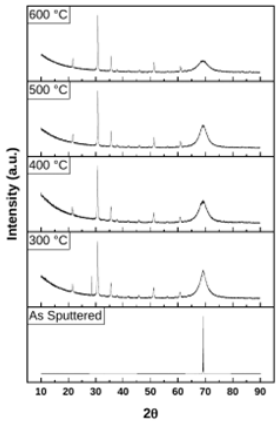
- P Emitter: 639 mV → 616 mV, consistent with sputter-induced passivation loss and increased surface recombination.
- n+ Poly Si: Remains high (664 mV), indicating stronger tolerance to ITO sputtering and better protection of the Si/ SiO_2 interface.

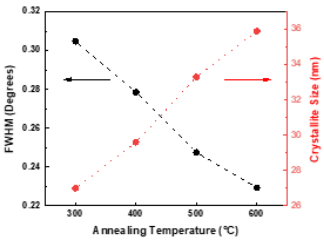
ITO Conductivity

- Highly doped surface (P, B, and n^+ poly-Si) reduces effective sheet resistance dramatically.
- The FPP response represents an electrically coupled multilayer stack, instead of isolated ITO.
- Best conductivity occurs around 300 °C – 400 °C; 500 °C – 600 °C begins to degrade transport.



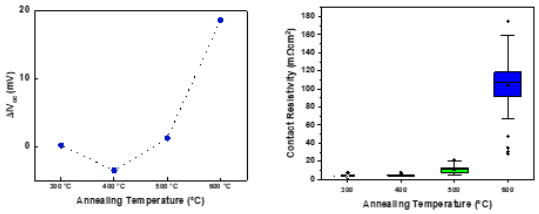
ITO Structural Evolution During Annealing





- As-sputtered ITO is weakly crystalline; annealing progressively sharpens ITO diffraction peaks.
- The (222) FWHM decreases from ~0.30° to ~0.23° while Scherrer crystallite size increases.

Passivation and Contact Stability



- **n+ Poly-Si:** 600 °C improves iV_{OC} (~+ 18.7), likely via SiN_x:H driven hydrogenation.
- **n+ Poly-Si/Ag:** Same temperature region severely degrades contact resistivity.
- Contact remains stable around 300 °C – 400 °C while passivation loss is at a minimum.

Conclusion

- n+ poly-Si passivating contacts showed higher tolerance to ITO sputtering than diffused emitters (P- or B-doped), maintaining high iV_{OC} after deposition and indicating better protection against interface damage.
- Moderate annealing at 300 °C – 400 °C provided most favorable thermal window, improving effective ITO conductivity and crystallinity while preserving Ag/n+ poly-Si contact stability.

Contact Information
Mustafa Büyükgüzel
Email: mustafa.buyukguzel@odtugunam.org

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Acknowledgement

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Optimizing Spatial ALD AlO_x for Silicon Solar Cell Edge Passivation

Furkan Eren Yılmaz[1,2], Gökhan Altıner[1], Yiğit Mert Kaplan[1], Hisham Nasser[1], Raşit Turan[1,2]

[1]ODTÜ-GÜNAM, Center for Solar Energy Research and Applications, 06800 Ankara, Türkiye

[2]Department of Physics, Middle East Technical University (METU), 06800 Ankara, Türkiye

Motivation

Efficiency Loss Link: Edge recombination is a major efficiency bottleneck in silicon solar cells.

The Cause: Wafer dicing and laser cutting expose high densities of unsatisfied silicon dangling bonds, crystal dislocations, and saw-induced defects [1].

The Challenge: Unlike front/rear surfaces, edges are geometrically challenging to coat uniformly and are typically left either untreated or treated using expensive tools dedicated to edge passivation in standard manufacturing lines.

Research Objective: Investigate edge passivation using a standard industrial spatial ALD tool that is *not* purpose-built for edges, utilizing equipment already common in high-volume PV manufacturing.

Methodology

Deposition Technique: Spatial Atomic Layer Deposition (S-ALD) of AlO_x using TMA.

Precursor Variables: Evaluated high vs. low water (H_2O) co-reactant saturation levels, and varying thicknesses.

Thermal Activation Environments:
- Inert N_2 furnace.
- Reactive, oxygen-rich ambient (hot plate).

Test Structures: Industrial half-cut TOPCon solar cells laser-cut to ~ 1x10 cm² slices to isolate and monitor edge passivation effects.

Results

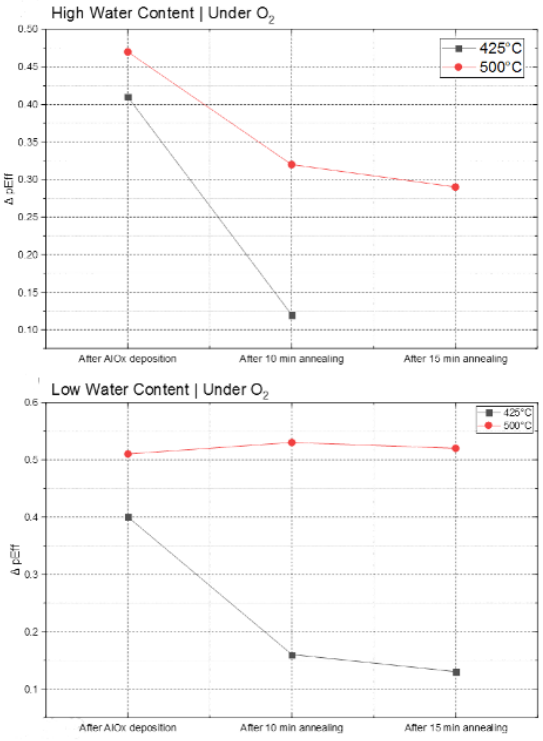


Figure 1. Δ pseudo efficiency values for AlO_x deposited with (above) high water and (below) low water content annealed under O_2

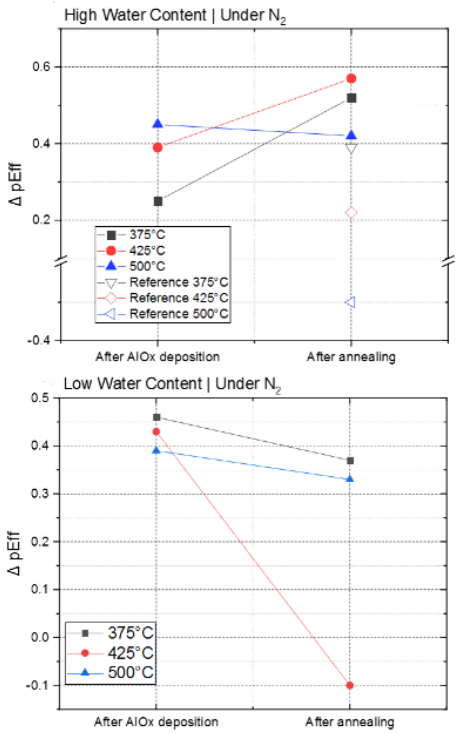


Figure 2. Δ pseudo efficiency values for AlO_x deposited with (above) high water and (below) low water content annealed under N_2

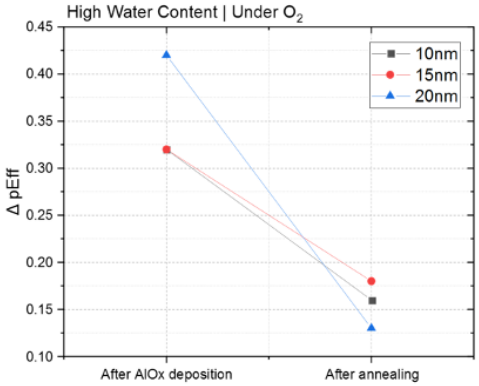


Figure 3. Δ pseudo efficiency values for AlO_x for varying thicknesses deposited with high water content and annealed under O_2

Samples	V_{oc} [mV]	pFF [%]	pEff [%]
Initial	713.00	77.92	22.22
After Deposition	715.17	79.02	22.61
After Annealing (425°C)	719.50	79.18	22.79

Table 1. Best-performing cell (high water content, annealed under N_2) parameters (average of measurements from six different points)

Conclusion

Feasibility: Demonstrated effective edge passivation using a standard spatial ALD tool that was not dedicated for edge passivation.

Key Requirement: Passivation quality depends heavily on deliberately pairing precursor water saturation levels with the correct thermal activation environment.

Inert N_2 Ambient: High-water films achieved an optimal +0.57%$_{abs}$ ΔpEff increase at 425°C. Low-water films degraded due to less dense AlO_x triggering premature H_2 effusion [2].

Reactive O_2 Ambient: Low-water films were successfully rescued at 500°C via external O_2 diffusion, growing a damage-consuming interfacial SiO_x layer and maximizing negative fixed charge density (Q_f) [3].

Contact Information
Furkan Eren Yılmaz
Email: furkan.yilmaz_06@metu.edu.tr

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Pushing the Efficiency Limits of Inverted Perovskite Solar Cells through Organic Salt Passivation

Gül Simge Özdemir[1,2,5], Sude Çebi[2,3,5], Figen Varlıoğlu Yaylalı[2], Mustafa Yaşa[2], Selçuk Yerci[1,2,4], Görkem Günbaş[1,2,3]

[1] Middle East Technical University/Department of Micro and Nanotechnology, Ankara, Türkiye

[2] ODTU-GUNAM/ Division of Materials Development and Recycling, Ankara, Türkiye

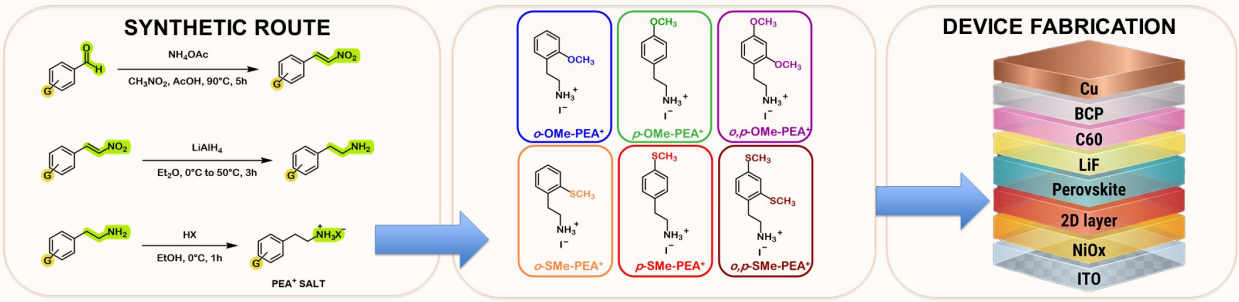
[3] Middle East Technical University/Department of Chemistry, Ankara, Türkiye

[4] Middle East Technical University/Department of Electrical and Electronics Engineering, Ankara, Türkiye

[5] Equally contributed

INTRODUCTION & METHODOLOGY

Inverted (p–i–n) perovskite solar cells (PSCs) have emerged as highly promising photovoltaic devices due to their high power conversion efficiency, low-temperature processability, and compatibility with tandem solar cell architectures. However, a key bottleneck currently limiting rapid improvements in PSC efficiency is insufficient long-term operational stability under real-world conditions. Conventional passivation often fails to efficiently reduce degradation caused by intrinsic defects and specific interfacial chemical vulnerabilities. Interfacial passivation using organic ammonium salts has become an effective strategy to suppress defect-assisted recombination and improve charge extraction. Inspired by our detailed molecular findings on phenylethylammonium (PEA) derivatives, this work suggests a targeted Interface Engineering strategy using a modification approach for inverted PSCs. The main scientific goal is twofold: first, to elucidate the molecular design principles and validate a simple, safe, and scalable synthetic route (nitration → reduction → salt formation) for PEA candidates, with emphasis on the effects of functional-group positions. Secondly, this work focuses on improving the buried interface (HTL/Perovskite). This molecular-level passivation aims to reduce defect pathways and strengthen structural resilience under prolonged operational stress, thereby advancing the development of durable PSC technology. Crucially, the sulfur atom in the -SMe group acts as a soft Lewis base, forming strong coordinate bonds with undercoordinated Pb^{2+} defects while simultaneously facilitating beneficial interactions with the NiOx hole transport layer due to its chalcophilic nature. This dual-sided coordination effectively bridges the interface, suppressing non-radiative recombination, improving charge extraction kinetics, and significantly enhancing the structural and operational stability of the device.



RESULTS & DISCUSSION

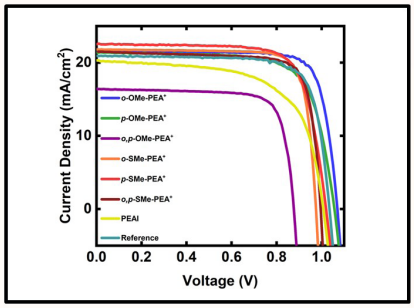


Figure 1. J-V curves of passivated devices and reference device.

Table 1. J-V curve results of passivated devices with PEAI and Synthesized salts.

SAMPLE	V_{OC} (V)	J_{SC} (mA/cm^2)	FF (%)	PCE (%)
o-OMe-PEA$^+$	1.05	21.48	80.35	18.19
p-OMe-PEA$^+$	1.05	21.37	81.61	18.38
o,p-OMe-PEA$^+$	0.94	16.45	46.01	7.110
o-SMe-PEA$^+$	1.02	21.81	80.61	18.08
p-SMe-PEA$^+$	1.01	22.52	75.18	17.08
o,p-SMe-PEA$^+$	1.05	21.49	80.54	18.34
PEAI	1.01	20.30	63.74	13.04
Reference	1.04	20.94	77.68	16.99

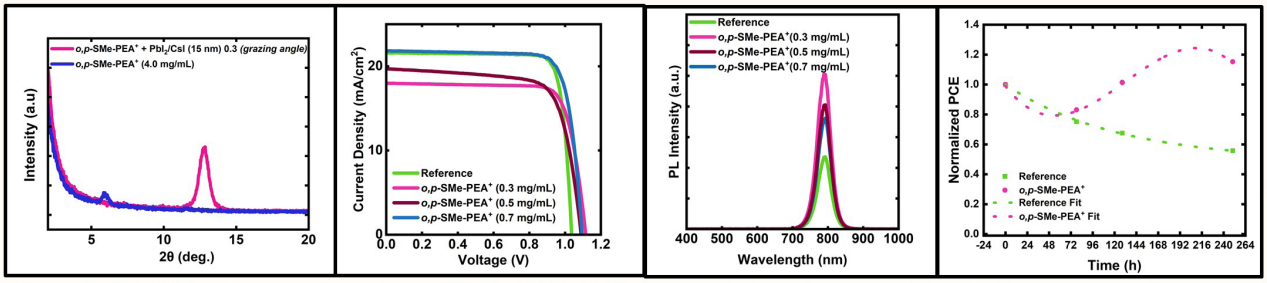


Figure 2. a) XRD for the champion salt, *o,p*-SMe-PEA$^+$ **b)** J-V Curve, **c)** Photoluminescence Intensity (PL) results for the concentration study, **d)** 250-hour preliminary stability tests of the devices with the best-salt.

CONCLUSION & FUTURE WORK

Various organic salts were synthesized for interface passivation in p-i-n PSCs, and all salts were screened in detail to observe their potential effects. As a result of the screenings, *o,p*-SMe-PEA$^+$ salt was determined to be the champion passivation material showing the highest performance for interface engineering. In optimization studies performed with different concentrations (0.3, 0.5, and 0.7 mg/mL) of the champion salt, significant improvements were obtained in the current density-voltage (J-V) characteristics of the cells compared to the reference device. PL analyses showed that the optimized concentrations successfully passivated surface defects of the 2D layer with increasing emission intensity and minimized non-radiative recombination. In addition, low-angle (grazing angle) X-ray diffraction (XRD) measurements confirmed the structural orientation of the 2D layer formed by the applied salt and the increase in crystal quality. Initial 250-hour preliminary stability tests of the devices revealed that the passivated cell maintained its normalized power conversion efficiency significantly better than the reference cell. Future studies will complete comprehensive 1000-hour aging tests to fully prove the long-term durability and commercial potential of this optimized passivation strategy.

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[2] ACS Energy Lett. 2023, 8, 11, 4563–4571.

ACKNOWLEDGEMENTS

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Techno-Economic-Environmental Comparison of Lithium-Ion and Sodium-Ion Battery Storage Systems for a 2 MW PV Power Plant

Ezgi USLAN DOĞAN, Yağmur BUDAK, Ömer Faruk TUNÇBİLEK
TENMAK Clean Energy Research Institute (TEMEN), Ankara

Abstract

This study presents a techno-economic-environmental assessment of a 2 MW grid-connected solar power plant in Kahramankazan district of Ankara considering lithium-ion and sodium-ion energy storage systems as alternative configurations. The hourly load profile, regional meteorological data, LCOE of hybrid system and environmental impacts were analyzed. Comparative evaluations were conducted based on key performance indicators.

Introduction

Lithium-Ion (Li-ion) Batteries



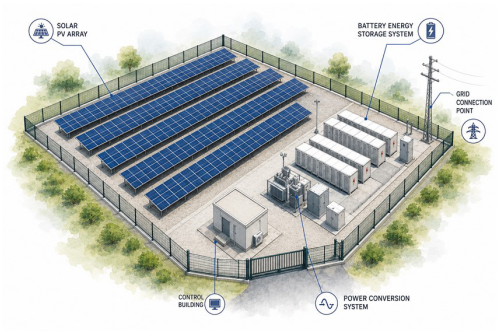
These batteries are the most widely used technology in grid-scale energy storage due to their high energy density, long cycle life, and millisecond response time.

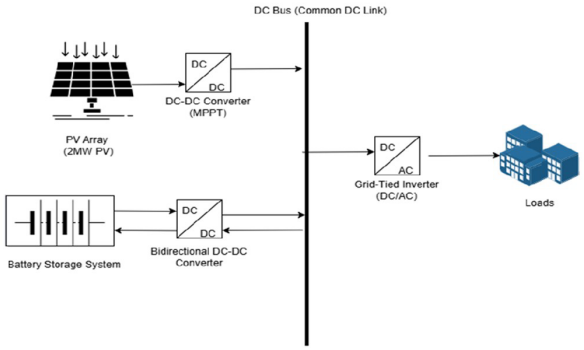
Sodium-Ion Batteries

Thanks to the cost advantage provided by the abundance of raw materials and their ability to offer high capacity, they are a strong alternative for large-scale grid applications.

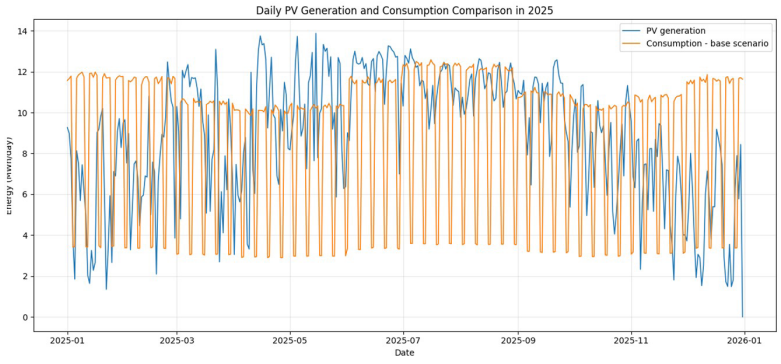


System Design





Design Parameters & Power- Load Curve



LCOE

Economic Metric	PV + Lithium-Ion (90% Efficiency)	PV + Sodium-Ion (Mid - 92% Efficiency)
Initial CAPEX	$1,968,390	$1,901,590
Hybrid LCOE	$58.54 / MWh	$54.23 / MWh
Project NPV (25-Years)	$1,825,400	$1,984,150
Discounted Payback Period	5.9 Years	5.2 Years

Environmental Impact

	PV + Lithium-Ion Battery	PV + Sodium-Ion Battery
Net Electricty Production	3171.99 MWh/year	3188.25 MWh/year
Avoided CO_2 Emissions	1395.68 tCO2/year	1402.83 tCO2/year
Life-Cycle (Embedded) Carbon Emissions	3246.66 tCO_2-eq	3146.66 tCO_2-eq
Carbon Payback Period	2.53 years	2.44 years

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From Ice Sheet Dynamics to Energy Economics: A Review of Physical and Mineralogical Controls on Greenland Instability

Linking Subglacial Processes to Arctic Infrastructure Risk and the Levelized Cost of Energy (LCOE)

Dilan Kılınçoğlu[1] · Bülent G. Akınoğlu[1,2] · Abdullah Buğrahan Karaveli[1,3] · İsmail Ömer Yılmaz[4]

[1] Earth System Sciences, Middle East Technical University (METU), Ankara, Türkiye
[2] Department of Physics, Middle East Technical University (METU), Ankara, Türkiye
[3] TENMAK, Türkiye
[4] Department of Geological Engineering, Middle East Technical University (METU), Ankara, Türkiye

MIDDLE EAST TECHNICAL UNIVERSITY METU

KEY MESSAGE

Greenland Ice Sheet (GrIS) instability emerges from the interaction of thermodynamic forcing, mechanical constraints, and subglacial mineralogical processes. These physical changes translate into significant socio-economic risks for Arctic energy infrastructure through permafrost degradation and sea-level rise, driving up the Levelized Cost of Energy (LCOE).

1. ARCTIC AMPLIFICATION

The Arctic is warming nearly 4 times faster than the global average since 1979.



~4x FASTER WARMING

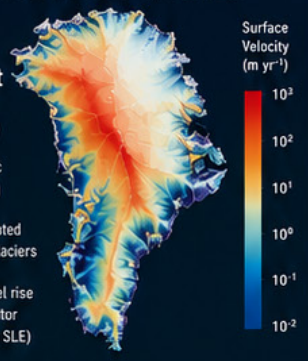
- Loss of sea ice & snow cover reduces surface albedo
- More solar energy absorbed by ocean & land
- Atmospheric and oceanic feedbacks amplify warming

Source: Rantanen et al., 2022

2. GREENLAND ICE SHEET RESPONSE

Mass loss from the Greenland Ice Sheet has accelerated over the last three decades.

3,902 Gt ice loss (1992–2018)



- Dynamic thinning
- Accelerated outlet glaciers
- Sea-level rise contributor (~7.4 m SLE)

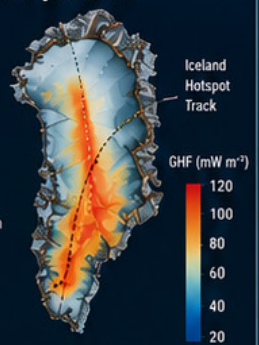
Source: IMBIE Team, Shepherd et al., 2020

3. THERMODYNAMIC DRIVER

Geothermal Heat Flux (GHF)

Internal heat from the Earth is a primary control on basal melting and ice flow.

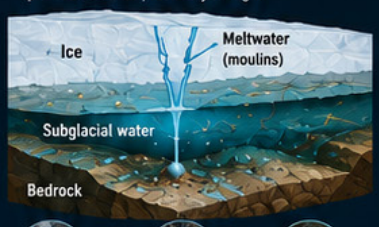
- Iceland hotspot track runs NW-SE across Greenland
- Elevated GHF (up to 100+ mW m⁻²) induces basal melt
- Reduces basal friction and ice viscosity, enhancing sliding



Source: Martos et al., 2018; Rogozhina et al., 2016

4. MINERALOGICAL PROCESSES

Subglacial geochemical activity is more pronounced than previously thought.





Reaction-induced dissolution of bedrock minerals | Synthesis of clay minerals (smectite, illite) | Formation of low-silica melts at low T

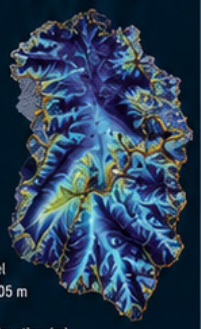
These processes alter basal hydrology, sediment rheology and may influence long-term ice dynamics.

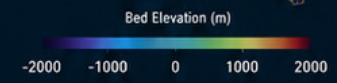
Sources: Crompton et al., 2015; Graly & Rezvanbebbahani, 2022

5. MECHANICAL CONTROLS

Bed topography governs ice flow, grounding line retreat and Marine Ice Sheet Instability (MISI).

- BedMachine v3 (150 m resolution)
- Deep fjords and over-deepened valleys
- Retrograde bed slopes promote unstable retreat
- Greenland's sea level potential: 7.42 ± 0.05 m

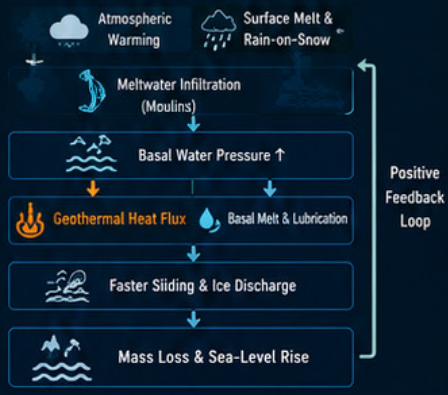




Source: Morlighem et al., 2017

6. COUPLED FEEDBACKS

Instability arises from the coupling of atmospheric, thermodynamic and mechanical processes.

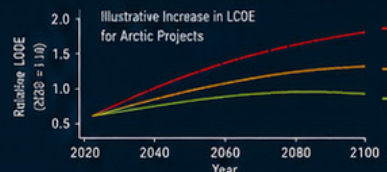


7. IMPLICATIONS FOR ARCTIC ENERGY SYSTEMS

Physical changes increase hazards and costs for energy infrastructure.



Permafrost Degradation	Coastal & River Flooding	Infrastructure Damage	Energy System Vulnerability	Higher LCOE
Thawing weakens foundations and pipelines, causing subsidence.	Sea-level rise and storm surge threaten facilities and ports.	Roads, rails and power lines face increasing failure risk.	Disruptions increase operational costs and uncertainty.	Capital and O&M costs rise, leading to higher LCOE for Arctic projects.



Key Takeaway

Neglecting cryospheric and geochemical changes leads to underestimated risks and substantial economic burdens.

8. CONCEPTUAL FRAMEWORK

A multi-criteria approach to assess physical instability and economic impacts on energy systems.

1. **Physical Attribution** — Weigh the influence of GHF, topography, climate forcing and geochemical processes using AHP (Analytic Hierarchy Process).
2. **Spatial Risk Mapping** — Overlay instability hotspots with energy infrastructure, permafrost and SLR flood hazard maps (GIS).
3. **Economic Integration** — Estimate infrastructure damage, adaptation costs and adjust LCOE for 2050–2100 scenarios.
4. **Decision Support** — Provide Arctic stakeholders with actionable risk assessments for resilient energy planning.

CONCLUSIONS

- Greenland instability is controlled by the coupling of thermodynamic forcing, mechanics and subglacial mineralogical processes.
- Geothermal heat and geochemical reactions at the bed influence basal conditions and long-term ice dynamics.
- These physical changes pose significant risks to Arctic energy infrastructure through permafrost degradation and sea-level rise.
- Integrating geophysical knowledge with economic assessment is essential to reduce uncertainties and support resilient energy development.

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MIDDLE EAST TECHNICAL UNIVERSITY (METU)
Earth System Sciences | Physics | Geological Engineering

Contact: dilan.kilincoglu@metu.edu.tr

Connect on LinkedIn @dilankilincoglu

SCAN ME

Comparative Analysis of Light Distribution in Agrivoltaic Systems Fixed vs. Tracking Systems Based on Multi-Site PPFD Measurements in Türkiye

Ömer Yalçın · Dr. Duygu Kuzyaka · Doç. Dr. Talat Özden
ODTÜ-GÜNAM · Center of Solar Energy Research and Applications

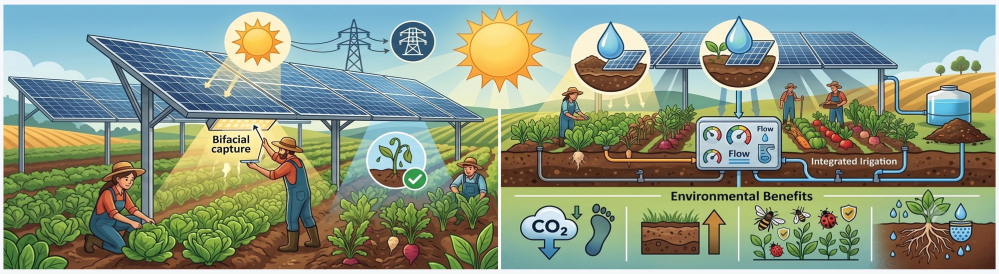
INTRODUCTION

Energy Production
Solar electricity from PV panels above agricultural land
Bifacial panels capture reflected light from crop panel below

Crop Growth
Partial shading reduces water stress in high-irradiance zones
Shade-tolerant crops thrive beneath fixed-tilt panels

Resource Efficiency
Same land for food + energy (Land Equivalent Ratio > 1.0)
Reduced water evaporation and improved microclimate

Research Question: How does structural design (fixed vs. tracking) affect the spatial and temporal homogeneity of light available to crops?



PILOT SITES

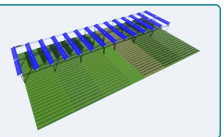




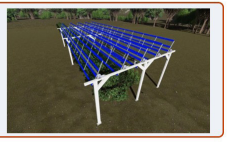


Study Sites & Design

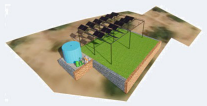
Ayaş
Ankara · 800-1000m
Single-axis tracking ±80° E-W
90 kWp · 224 panels · 1,613 m²



Erciyes
Kayseri · 1000-1100m
Single-axis tracking ±80° E-W
Bifacial 250W · 120 panels · 30 kWp

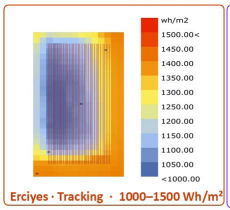


Taşarası
Balıkesir · 490-500m
Fixed-tilt 21° · E-W oriented
14 kWp · 24 panels · 143 m²

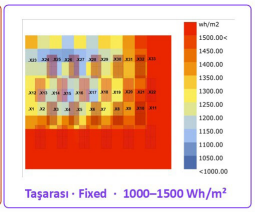


Light Distribution Modeling

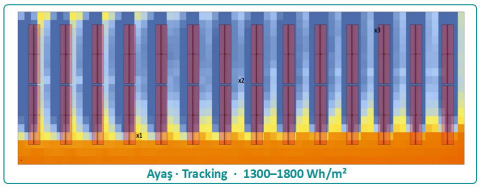
Rhinoceros + Ladybug Simulation
Joint development with METU Dept. of Architecture



Erciyes · Tracking · 1000–1500 Wh/m²



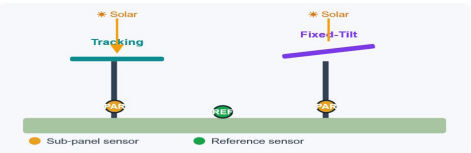
Taşarası · Fixed · 1000–1500 Wh/m²



Ayaş · Tracking · 1300–1800 Wh/m²

Field PPFD Measurements

PAR Sensors at Crop Canopy Height

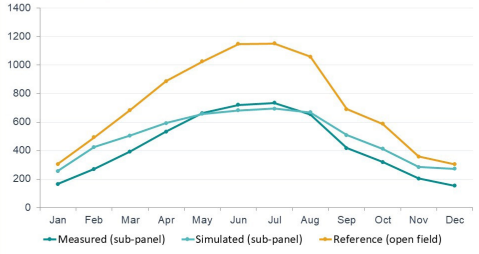


- Sensor: Quantum (PAR) sensors
- Sampling: 15-min intervals, full annual cycle
- Points: Sub-panel + open-field reference pairs
- Sites: Ayaş (Ankara) · Erciyes (Kayseri) · Taşarası (Balıkesir)

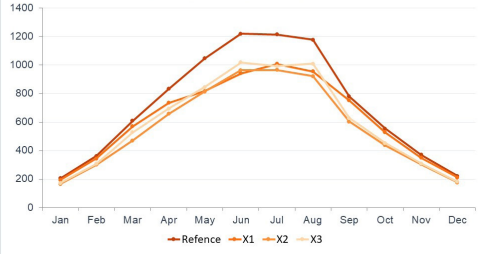
Annual PPFD measured across 3 climatic zones — simultaneous paired readings throughout the year.

RESULTS

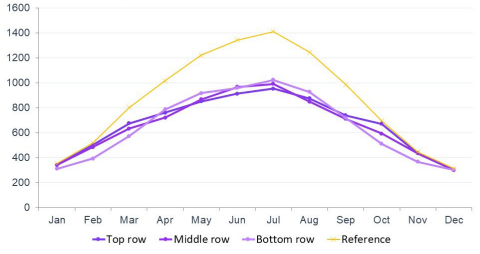
Ayaş — Tracking System
Daily avg. PPFD (µmol/m²s) · Sub-panel vs. Simulation vs. Reference



Erciyes — Tracking System
Daily avg. PPFD (µmol/m²s) · Sensor positions X0–X3



Taşarası — Fixed-Tilt System
Monthly avg. PPFD (µmol/m²s) · Top / Middle / Bottom rows



AYAŞ MEASURED VS SIMULATED



CONCLUSIONS

01 Tracking → High PPFD Homogeneity
Single-axis tracking redistributes shading throughout the day, yielding sub-panel PPFD near open-field levels (800–1,600 µmol/m²s) with low spatial variation. Ideal for light-demanding crops.

02 Fixed-Tilt → Characterizable Shadow Bands
Stationary panels create predictable shadow patterns. Annual avg. sub-panel PPFD reaches 76% of reference — well-suited for shade-tolerant leafy crops planned around known shadow bands.

03 Design Dominates Climate
Multi-site data confirms structural design choice is the primary driver of sub-panel light quality across Türkiye's diverse climatic regions — more decisive than local irradiance differences.

Supported by TÜBİTAK 1004 (S-ATP, No: 23AG020) · Ankara Kalkınma Ajansı (Ayaş TarımGES, TR51/21/KIRSAL/0018) · FrontAg Nexus (Taşarası) · HORIZON-WIDERA-2022 SolarHub (No: 101086110)
Light distribution algorithm: Dilara Güney & Prof. Dr. İpek Gürsel Dino (METU Architecture)

omer.yalcin@odtugunam.org | ODTÜ-GÜNAM, Ankara | PVCon 2026

Sakarya University
FACULTY OF ENGINEERING · ELECTRICAL & ELECTRONICS ENG.

PVCON 2026
GRADUATION PROJECT · JUNE 2026

Autonomous Photovoltaic Panel Cleaning Robot

Design and prototype development of a low-cost, **ESP32-based autonomous system** for small-to-medium solar installations

Vahit Cem Bozkaya · **Can Burak Turcan** Advisor — Assoc. Prof. Dr. Ceyda Aksoy Tırmıkçı

100%	≈80 min	~25 s	3.4 kg·cm
Core-function success in prototype testing	Runtime per 11.1 V 3S LiPo charge	Per long-edge cleaning pass	Drive torque (need ≈2 kg·cm)

01 — PROBLEM & MOTIVATION

Dust quietly erodes every panel's output

Accumulated dust, sand and particulate fouling on PV surfaces reduce light absorption and degrade efficiency. Field studies report power losses of **15–30%** in high-soiling environments. Manual cleaning is labor-intensive, inconsistent, and increasingly impractical as installations scale.

15–30%
YIELD LOST TO SOILING

A prior data-driven study on the Sakarya University M6 rooftop array measured **15–20%** loss when uncleaned, and **10–12%** recoverable gain via a cleaning schedule.
That work answered *when* — this answers *how*.

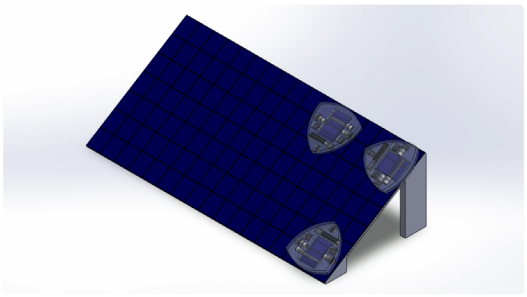


FIG. 1 Robot executing an autonomous cleaning traverse on a tilted PV array (CAD).

02 — SYSTEM DESIGN

A Reuleaux-triangle robot from accessible parts

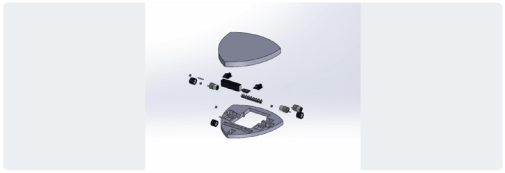


FIG. 2 Exploded view — 3D-printed Reuleaux chassis, motors, helical brush, board & battery.

01 **3D-printed Reuleaux chassis** — compact footprint, inherent directionality
02 **2× JGB37 geared DC motors** + passive front wheel — differential drive
03 **Helical bristle brush** — own 12 V 200 RPM motor, continuous contact
04 **ESP32-WROOM-32 + 2× L298N** — central control & motor drivers
05 **2× HC-SR04 + 11.1 V 3S LiPo** — edge sensing & onboard power

INTERNAL LAYOUT

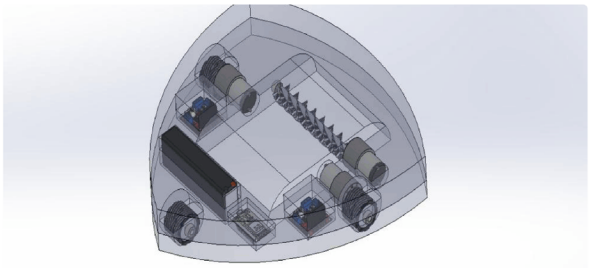


FIG. 3 Transparent assembled view — rear-corner drive motors, helical brush, control board & battery packed within the Reuleaux shell.

03 — AUTONOMOUS OPERATION

Boustrophedon coverage with ultrasonic edge sensing

STEP 01 **Power on** — 3 s start delay → STEP 02 **Brush ON** — Continuous run → STEP 03 **Read sensors** — Front + rear HC-SR04 → DECISION **Edge < 8 cm?** — else keep cleaning ↺ → U-TURN **90° · lane · 90°** — Reverse direction, repeat

EDGE RANGING
$d = (t \times 0.0343) / 2$
Time-of-flight distance, per HC-SR04 echo.

SAFETY
Rear < 4 cm → stop
Emergency forward move to avoid back-edge fall.

DRIVE SPEED vs PWM DUTY

9.1	18.2	27.3	36.4
25%	50%	75%	100%

cm/s · cleaning runs at **25% (9.1 cm/s)** for uniform contact.

04 — VALIDATION & RESULTS

All three core functions verified

A weighted evaluation across five criteria returned **100% overall success**. The prototype proves autonomous motion, continuous brushing, and sensor-based edge detection on representative panel surfaces.

100%	100%	100%
Edge detection	Software integration	Mechanical integrity
weight 30%	weight 25%	weight 20%

LIMITATION → NEXT L298N BJT drivers introduce a **~2–3 V drop**, reducing usable torque. Planned revision: **MOSFET driver (TB6612FNG)** + 4S battery for full drive headroom.

35°	0.42 m/s
Critical tilt; stable across 15–35° panels	Brush tangential speed, uniform contact

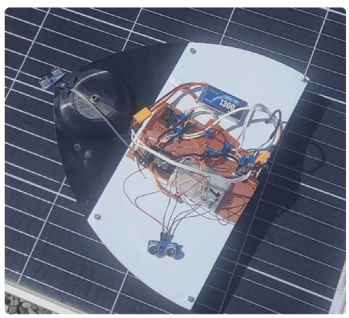


FIG. 4 Functional prototype tested outdoors on a PV panel — ESP32 control board, dual L298N drivers, HC-SR04 sensors and 11.1 V LiPo.

05 — TOWARD FULL AUTONOMY

A four-layer roadmap to field scale

The prototype establishes Layer 1. Subsequent layers add perception, fluid cleaning and cloud-coordinated decision-making.

LAYER 1 ✓ BUILT	LAYER 2	LAYER 3	LAYER 4
Motion	**Sensing**	**Cleaning**	**Decision**
ESP32 · L298N · differential drive · 11.1 V LiPo	HC-SR04 · OV2640 camera + OpenCV · GPS u-blox + IMU fusion	Water spray — 12 V pump · MOSFET PWM · injector nozzle + brush	Python optimization · MQTT/WiFi · autonomous solar recharging

A coherent, low-cost autonomous PV-cleaning platform realized from commercially accessible components — a validated hardware and firmware foundation for scalable solar maintenance.

KEYWORDS Renewable Energy · PV Cleaning · Solar Panel Maintenance · Autonomous Cleaning Robot · PV Efficiency Optimization

turcancanburak@gmail.com · cembozkaya10@gmail.com

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Sakarya University · EEE
June 2026

THE EFFECT OF ENCAPSULANT MATERIALS AND EDGE SEALING ON POTENTIAL INDUCED DEGRADATION IN PV MODULES

Utku Akbas and Abdulkerim Gok*

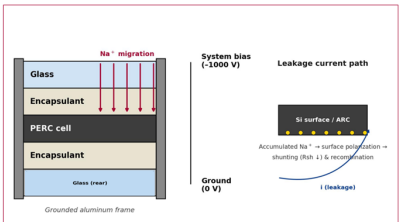
Gebze Technical University (GTU), Department of Materials Science and Engineering, Gebze/Kocaeli, 41400, Turkey

Corresponding Author: Abdulkerim Gok | e-mail: agok@gtu.edu.tr

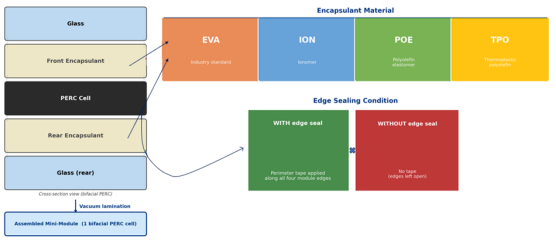
INTRODUCTION AND MOTIVATION

Potential induced degradation (PID) is a major reliability concern for PV modules operated at high system voltages under elevated temperature and humidity.

- Under negative system bias, Na^+ ions migrate from the glass through the encapsulant to the cell surface, leading to surface polarization, leakage currents, and shunting (PID-s).
- The encapsulant is the primary ionic barrier between the glass and the cell, so its volume resistivity and moisture permeability strongly influence PID susceptibility.
- Polyolefin-based encapsulants (POE, TPO) and ionomers have been reported in the literature to offer higher volume resistivity than standard EVA, motivating their evaluation as PID-resistant alternatives.
- In this work, one-cell PERC mini-modules were fabricated with four encapsulant materials — EVA, ionomer, TPO, and POE — to directly compare their PID behavior.
- Each module, with different encapsulant materials, was constructed with and without edge sealing to assess whether edge-seal tape mitigates lateral moisture ingress.
- Modules were tested at 85°C (dry) for 96 hours under -1000 V bias and characterized by IV curve tracing and electroluminescence (EL) imaging before and after stress.



MINI-MODULE FABRICATION

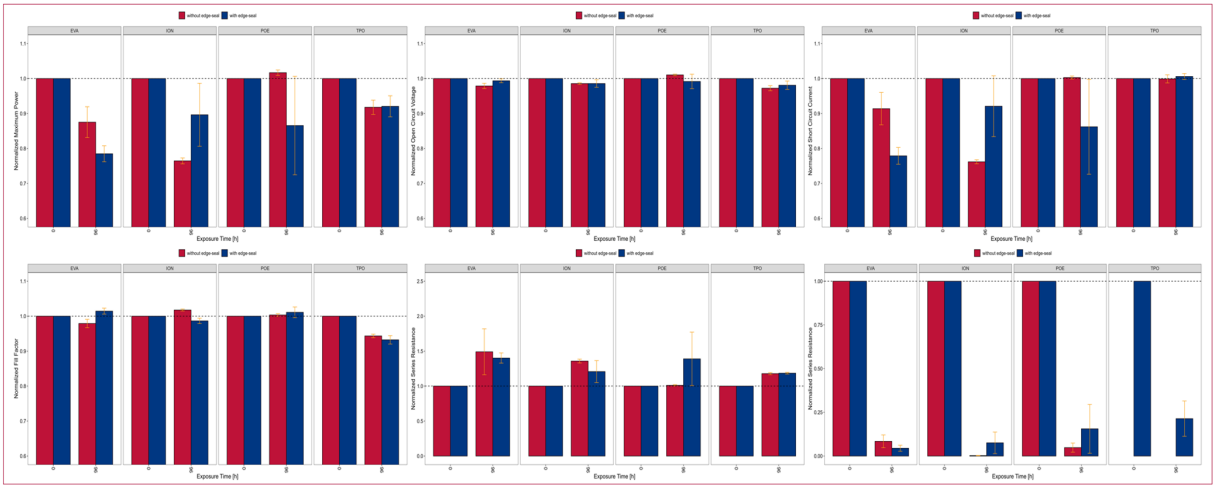


PID TEST METHOD & CHARACTERIZATION

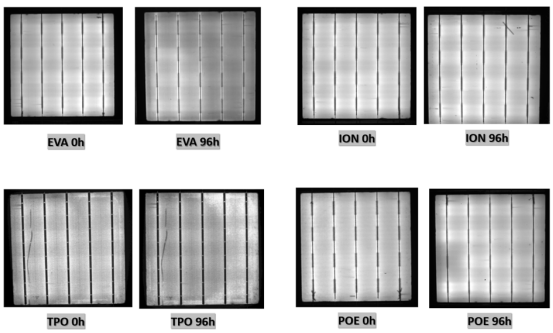
PID stress testing and characterization were carried out as follows:

- Each encapsulant material was tested in duplicate, both with and without edge sealing.
- IV curve tracing was performed before (0 h) and after (96 h) stress, extracting P_m, V_{oc}, I_{sc}, FF, series resistance (R_s), and shunt resistance (R_{sh}).
- EL imaging at 0 h and 96 h was used to visualize shunting and dark-area growth, complementing the averaged electrical parameters.

Material	ΔP_m	ΔV_{oc}	ΔI_{sc}	ΔFF	ΔR_s	ΔR_{sh}
EVA	-12.5%	-2.1%	-8.6%	-2.1%	+49.1%	-91.6%
ION	-23.6%	-1.4%	-23.8%	+1.8%	+35.8%	-99.7%
POE	+1.7%	+1.0%	+0.3%	+0.3%	+1.1%	-95.2%
TPO	-8.2%	-2.8%	-0.1%	-5.7%	+17.8%	N/A*



ELECTROLUMINESCENCE IMAGES



ELECTRICAL CHARACTERIZATION (0 H → 96 H)

- **Shunt resistance (R_{sh}) collapses dramatically across all materials** (down 85–99% in EVA, ionomer and POE), confirming shunting as the dominant PID mechanism rather than series-resistance growth.
- Power output (P_m) loss ranks: ionomer (−23.6%) > EVA (−12.5%) > TPO (−8.2%) > POE (+1.7%, essentially stable), identifying POE as the most PID-resistant encapsulant tested.
- EVA shows the largest series resistance increase (R_s +49%), suggesting an additional metallization/contact-degradation contribution on top of shunting.
- The effect of edge sealing on P_m retention is material-dependent: it improves outcomes for ionomer and TPO but worsens them for EVA and POE — edge-seal tape is not a universal PID mitigation.

V_{oc} and FF remain comparatively stable for all materials, confirming that PID-induced power loss here is driven primarily by shunting rather than junction-level degradation.

SUMMARY AND OUTLOOK

- POE and TPO outperform EVA in PID resistance, while ionomer shows the largest power loss despite its high nominal volume resistivity.
- Across all materials, shunt resistance collapse is the dominant degradation signature, consistent with PID-s (shunting-type) behavior rather than polarization or corrosion mechanisms.
- Edge sealing is not a one-size-fits-all solution. It helps ionomer and TPO but worsens outcomes for EVA and POE, so its use should be tailored to the specific encapsulant.

This work is conducted as part of the Solar-Era.NET project: PV40+ and supported by the funding from The Scientific and Technological Research Council of Turkey (TUBITAK) under the Grant No: 120N520.

Characterization of Sputtered Metal Oxides as an Electron Selective Contacts for Flexible Gallium Arsenide Solar Cells

Hazal Zaimler[1*], Burcu Arpapay[2,3], Mustafa Kulakcı[2,4]

[1]Department of Physics, Institute of Graduate Education, Eskişehir Technical University, [2]Nanoboyut Research Laboratory, Department of Physics, Eskişehir Technical University, [3]Department of Advanced Technologies, Institute of Graduate Education, Eskişehir Technical University, [4]Institute of Earth and Space Sciences, Eskişehir Technical University

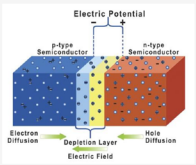
E-mail: hazalzaimler@gmail.com

ABSTRACT

ZnO and TiO_2 thin films were deposited on glass and GaAs substrate using RF magnetron sputtering and evaluated as candidates for electron selective contacts in flexible GaAs solar cell. Structural, optical, and electrical properties were investigated under different annealing conditions. ZnO exhibited high optical transparency, improved crystallinity, and lower resistivity after N_2 annealing, indicating greater potential as the primary electron transporting layer. TiO_2 demonstrated favorable transparency and wide-bandgap selectivity, but also exhibited higher resistivity and substrate-dependent crystallization. These results suggest that ZnO/TiO_2 based ESC structures may enable simplified flexible GaAs solar cell architectures.

MOTIVATION: TOWARD FLEXIBLE AND LOW COMPLEXITY GaAs SOLAR CELLS

Conventional PN Junction



Electron Selective Contact Aproach

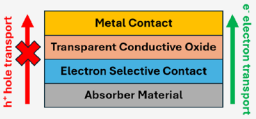
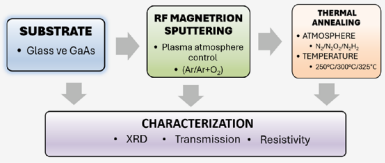


Figure 1. Schematic comparison of a conventional GaAs p-n junction and the electron-selective contact approach

- Carrier separation by built-in electric field
- Requires doped epitaxial layers
- Complex and costly epitaxial growth and fabrication

- Carrier selectivity through band alignment
- Reduced fabrication complexity
- Potentially lower parasitic absorption

EXPERIMANTAL METHODOLOGY



TiO_2 CHARACTERIZATION RESULTS:

Structural Properties

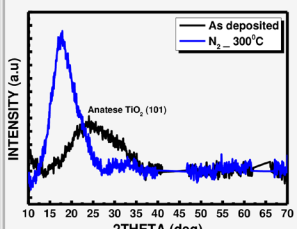


Figure 3. XRD patterns of TiO_2 thin films deposited on Glass before and after annealing under N_2 atmosphere conditions

- On glass, the as-deposited TiO_2 film showed an anatase-related peak near 25.3°, corresponding to the anatase (101) reflection
- Annealing did not systematically sharpen the anatase peak; several annealed films exhibited weak or amorphous-like diffraction features.
- N_2 annealing at 300 °C produced a broadened low-angle feature, suggesting residual stress or structural disorder.
- On GaAs, anatase formation was not clearly resolved and substrate/interface-related effects became more dominant.

Optical and electrical characterization

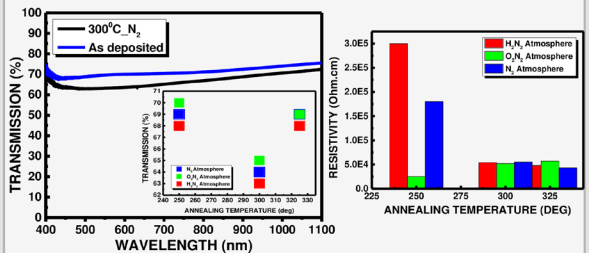


Figure 4. Optical transmittance and electrical behavior of TiO_2 thin films, indicating its potential role as a selectivity-supporting/hole-blocking oxide.

- TiO_2 showed moderate visible region transmittance, but any atmosphere at 250°C-325°Cdid not provide a simultaneous optical electrical improvement. requires further optimization before GaAs integration.
- TiO_2 showed higher resistvity compared and lower transmission with ZnO

ELECTRON SELECTIVE CONTACT DESIGN AND MATERIAL SELECTION

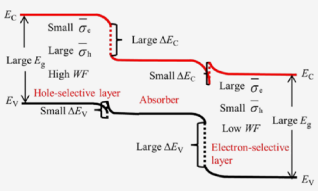


Figure 2. Design guidelines for carrier-selective contacts, emphasizing band alignment, optical transparency, and electrical conductivity[1].

Material Roles

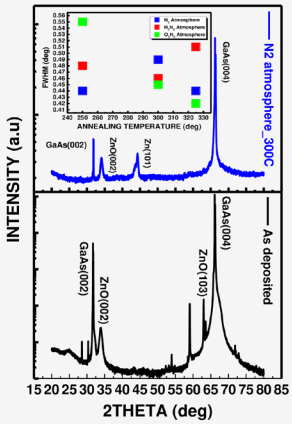
Band Alignment
Favorable electron extraction, easy electron transport and bloking hole
- ZnO higher band gap(3.3eV) easy electron trasnport
- TiO_2high bandgap(3.2eV)hole bloking layer

Optical Transmission
Reduced parasitic absorption, optical transperancy
- ZnO high transperancy about %80-90

Electrical Conductivity
Efficient electron transport
- ZnO lower resistivity about 10E-2 ohm.cm

ZnO CHARACTERIZATION RESULTS:

Structural Properties



Structural characterization of ZnO/GaAs

- XRD patterns of ZnO thin films deposited on GaAs before and after annealing. The appearance of characteristic ZnO diffraction peaks indicates crystalline ZnO formation.
- FWHM values were used to compare the structural evolution under different annealing conditions.
- ZnO films show (002) highly oriented wurtzide structure.
- Annealing at 300 °C under an N_2 atmosphere enhanced the ZnO(002) peak, and the obtained FWHM value, when evaluated together with the resistivity and optical transmittance results, provided the most favorable structural, electrical, optical balance.

Figure 5. XRD patterns of ZnO thin films deposited on GaAs before and after annealing under N2 atmosprhere condition and FWHM values under different conditions.

Optical and electrical characterization

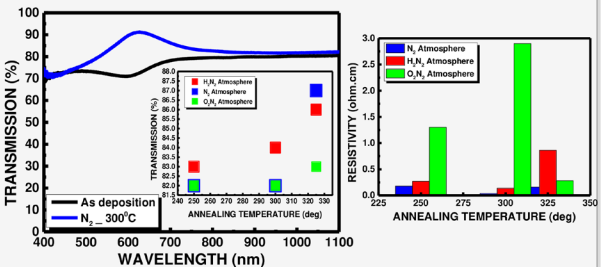


Figure 6. Optical transmittance and electrical resistivity behavior of ZnO thin films under different annealing atmospheres and temperatures.

- N_2 annealing yielded the lowest resistivity around 300 °C.
- Oxidizing atmosphere generally increased resistivity.
- The optimum condition could be find balance conductivity and transparency with N_2 atmosphere annealing

CONCLUSION

ZnO showed the most favorable balance between crystallinity, optical transparency, and conductivity. N_2 annealing at 300 °C revealed the ZnO(002) peak and provided favorable low-resistivity behavior while maintaining optical transmittance. TiO_2 showed anatase-related formation on glass; however, its annealing response, stress behavior, and GaAs interface compatibility require further optimization. Therefore, ZnO is considered the main electron-transporting oxide, while TiO_2 may serve as a selectivity-supporting/hole-blocking layer in a complementary ESC architecture.

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ACKNOWLEDGEMENTS

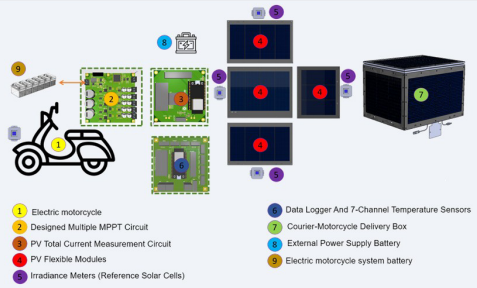
This work was supported by the Scientific and Technological Research Council of Türkiye (TÜBİTAK) under project number 124F405, and by Eskişehir Technical University under Scientific Research Project (BAP) number 25ADP085.

VIPV System Design, Development and Performance Tests for an Electric Courier Motorcycle

Ahmet Hamdi Aksoy[1/2], Yunus Çay[1], Talat Özden[1], Ahmet Necati Özsezen[2]
[1] ODTÜ-GÜNAM, Middle East Technical University, Ankara · [2] Automotive Engineering Dept., Kocaeli University, Kocaeli · Türkiye
ahmet.aksoy@odtugunam.org

INTRODUCTION

In this study, an integrated system based on shingled cell technology is developed within the framework of Light Vehicle Integrated Photovoltaic (VIPV) applications to extend the range of an electric motorcycle.



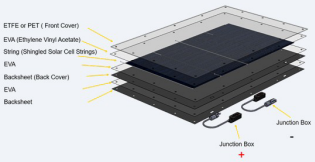
1. Electric motorcycle
2. Designed Multiple MPPT Circuit
3. PV Total Current Measurement Circuit
4. PV Flexible Modules
5. Irradiance Meters (Reference Solar Cells)
6. Data Logger And 7-Channel Temperature Sensors
7. Courier-Motorcycle Delivery Box
8. External Power Supply Battery
9. Electric motorcycle system battery

METHODOLOGY

1. Solar Module Integration

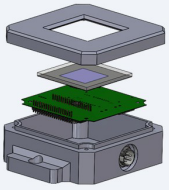
- Shingled Cell Technology: PERC M2 cells laser-cut into strips and bonded with Electrically Conductive Adhesive (ECA).
- Flexible PV Integration: Four ETFE-based flexible shingled panels integrated onto the top, rear, right, and left surfaces of the delivery box.

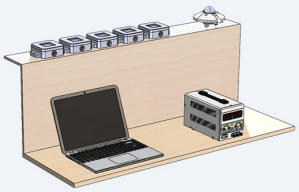
Surface	Right Side	Top	Left Side	Rear
Short Circuit Current I_{sc} (A)	1.69	1.68	1.61	1.71
Short Circuit Voltage V_{oc} (V)	33.93	38.6	33.68	25.16
Rated Power P_{max} (W)	43.85	49.92	41.81	32.33
Rated Current I_{mpp} (A)	1.58	1.53	1.51	1.58
Rated Voltage V_{mpp} (V)	27.77	32.65	27.72	20.48
FF (%)	76.42	76.96	77.11	75.14
PV module Efficiency (%)	19.45	19.61	18.55	19.12
Surface Area (m^2)	0.2205	0.257	0.2205	0.1659
Front Material	ETFE	ETFE	PET	ETFE

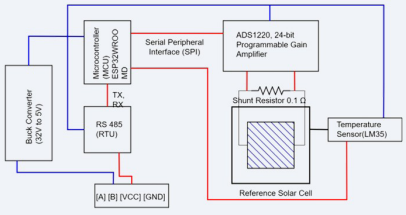


2. Sensor & Calibration System

- Irradiance Measurement: Reference PERC-cell irradiance sensors integrated with a 24-bit ADS1220 ADC and ESP32 MCU.
- Communication Interface: Data transmission handled via a robust RS485/Modbus protocol.
- Outdoor Calibration: Sensors calibrated outdoors against a secondary standard SMP11 pyranometer ($R^2 > 0.997$).





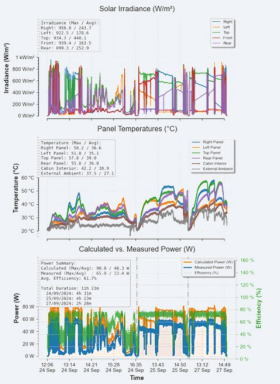


KEY RESULTS

- Cumulative harvest of 364.9 Wh → +20.3% battery State-of-Charge and +14.2 km of grid-independent range.
- Top surface dominant: 448 W/m² (45.1% of

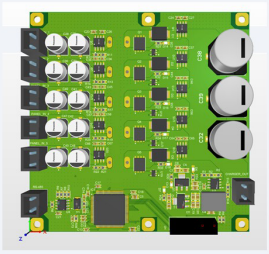
Courier Box Surface	Average Irradiance (W/m²)	Distribution Share	Technical Remark
Top	448	45.1%	Highest exposure due to horizontal sky view.
Rear	253	18.3%	Moderate exposure, often influenced by the rider's shadow.
Right	244	21.9%	Significant lateral irradiance was captured during the route.
Left	179	14.7%	Lowest exposure, likely due to shading or route orientation.
Total	**1124**	**100%**	

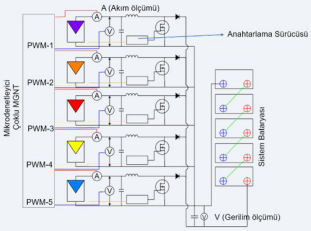
- Total PV array 167 Wp across 4 shingled panels (49.9 / 43.9 / 41.8 / 32.3 W).
- Independent MMPPT per surface suppresses mismatch losses from heterogeneous irradiance.
- ETFE front-sheet outperformed the equivalent PET panel under fluctuating conditions.



3. Power Electronics & Control

- Custom MMPPT Charger: Development of an STM32-based 5-channel Multi-Maximum Power Point Tracking charger.
- Independent Boost Converters: Dedicated boost converter per surface utilizing the Perturb & Observe (P&O) algorithm.
- Battery Charging: Charging of 72 V main battery pack.





4. Field Testing & Data Logging

- Urban Route Testing: Field tested over a 20 km urban route in Ankara, Turkey under real-world driving and parking conditions.
- Synchronous Data Logging: Real-time, synchronized logging of electrical, irradiance, and thermal performance data.



CONCLUSIONS

A multi-surface VIPV system on an electric delivery motorcycle delivered +20.3% SoC (~11.4 hours) and +14.2 km of grid-free range from 364.9 Wh harvested, at 61.8% cycle efficiency. Shingled cells and multi-channel MPPT proved decisive for compact, multi-oriented integration. Future work targets wide-bandgap (GaN/SiC) power stages for higher switching frequency and further efficiency gains.

ACKNOWLEDGEMENTS

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Advanced Photoluminescence Imaging of Perovskites via Pixel-Wise k-factor Mapping

Muhammed Çoban | **Assoc. Prof. Selçuk Yerci** | **Cem Maden**
METU | **Department of Physics**

Overview. While metal-halide perovskites show immense potential for next-generation photovoltaics, their commercial efficiency is often limited by localized non-radiative recombination. In this work, we present a high-resolution spatial diagnostic technique using pixel-wise optical ideality factor (k-factor) mapping derived from photoluminescence (PL) imaging. By analyzing the power-law dependence of PL emission on excitation intensity ($I_{PL} \propto I_{exc}^{k}$), we can spatially isolate underlying recombination-generation mechanisms. This approach successfully maps the material quality across the film, allowing us to visually distinguish regions of ideal band-to-band radiative emission ($k \approx 1$) from severely degraded areas dominated by trap-assisted Shockley-Read-Hall (SRH) losses ($k \approx 2$).

Why Perovskites?

- **Silicon Efficiency Plateau:** Widely used silicon cells are rapidly approaching their practical and fundamental Shockley-Queisser limit ($\approx 33\%$).
- **Unprecedented Progress:** Perovskite power conversion efficiency (PCE) has skyrocketed from 3.8% to over 26% in less than two decades.
- **Exceptional Physics:** They combine a high optical absorption coefficient with an easily tunable bandgap and extraordinary defect tolerance.

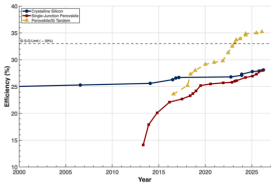


Figure 1: Evolution of Efficiency in Solar Cells[1]

Introduction

The **k-factor** (also known as **optical ideality factor**) is a parameter that provides insight about the **optoelectronic quality** of perovskite modules. The main purpose of this study is to extract the k-factor for every individual pixel across a photoluminescence (PL) image and form the k-map. This mapping allows us to visually and understand **local defects**, **structural dislocations**, and **non-uniformities**, helping us understand the underlying recombination-generation mechanisms within the perovskite lattices.

- **The Physical Relationship:** The k-factor is a proportionality constant that form a relation between the incoming excitation light intensity and the measured photoluminescence signal.
- **Quantifying Efficiency:** By investigating this relationship, it is possible to determine the k-factor and it quantifies the local radiative efficiency of the material.
- **Underlying Mechanisms:** To understand the k-factor, the recombination-generation (RG) mechanisms of the perovskites must be investigated.

Recombination - Generation Mechanism

To evaluate the k-factor map, we isolate the three mechanisms:

Band-to-band: Direct annihilation of electron and hole. This results with a photon ($R \propto n^2$).

SRH (Trap): Defect-state non-radiative. The energy lost as heat ($R \propto n$).

Auger: Three-particle non-radiative. (Can be ignored) ($R \propto n^3$).

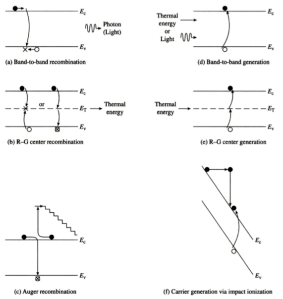


Figure 2: Recombination Mechanisms in Perovskites [2]

Background & Derivation

At steady-state, the generation rate (G) proportional to the laser intensity (I_{exc}) equals the total recombination rate[3]:

$$G \propto I_{exc} = \underbrace{An}_{\text{SRH}} + \underbrace{Bn^2}_{\text{B2B}} + \underbrace{Cn^3}_{\text{Auger}}$$

The measured photoluminescence signal (I_{PL}) is strictly proportional to the radiative fraction of this recombination process:

$$I_{PL} \propto R_{rad} = Bn^2 \quad \Longrightarrow \quad n \propto \sqrt{I_{PL}}$$

By substituting the carrier density back into the generation mechanism, the generalized relationship emerges as **a power law**:

$$I_{PL} \propto I_{exc}^{\mathbf{k}}$$

The k-factor is obtained **for every individual pixel** as the **slope of the logarithmic fit**:

$$\log(I_{PL}) = \mathbf{k} \cdot \log(I_{exc}) + \text{constant}$$

The Radiative Limit ($k \approx 1$)

State: Pristine Film → Radiative Dominant ($G \approx Bn^2$)

$I_{exc} \propto n^2$ & $I_{PL} \propto n^2$

$$\Longrightarrow \mathbf{I_{PL} \propto I_{exc}^{1}}$$

Meaning: High-quality lattice → Ideal emission → Minimal traps.

The SRH / Trap Limit ($k \approx 2$)

State: Defective Film → SRH Dominant ($G \approx An$)

m

$I_{exc} \propto n$ & $I_{PL} \propto n^2$

$$\Longrightarrow \mathbf{I_{PL} \propto I_{exc}^{2}}$$

Meaning: Degraded material → High trap density → Structural losses.

Mapping Workflow: Measure I_{exc} & I_{PL} → Calculate k-factor → Generate **k-map**.

Experimental Setup & Methodology

The optical imaging system is custom-built to precisely correlate the excitation intensity (I_{exc}) with the resulting spatial photoluminescence (I_{PL}).

- **Excitation Source:** Blue LED with active GPU-fan to provide thermal stability during measurement.
- **Spatial Detection:** Blackfly camera (BFLY-PGE-09S2M) to capture PL signal.
- **Optical Isolation:** Long-pass filter placed to block reflected blue light and isolate the PL signal.
- **System Automation:** MATLAB interface synchronizing the LED current steps with camera acquisition.

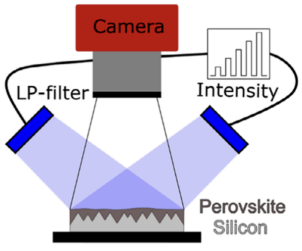


Figure 3: Schematic of the Experimental Setup[4]

Power Calibration

To provide accurate k-factor extraction, the non-linear output of the excitation LED should be corrected.

- **Reference Measurement:** A calibrated photodiode placed at the sample plane to measure true incoming light intensity.
- **Optical Mapping:** Light intensity is recorded across the full sweep (0.2 A to 0.9 A).
- **Interpolation Table:** Using this data, an interpolation table has been formed to ensure I_{exc} reflects true photon flux, removing non-linearities, and thermal instabilities.

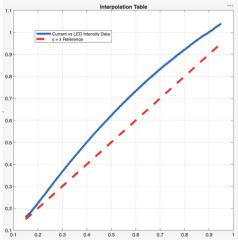


Figure 4: Current vs Intensity Interpolation Data

Data Acquisition & Processing

To translate the theoretical k-factor derivation into a physical spatial map, we developed a customized, pixel-by-pixel image processing workflow using MATLAB.

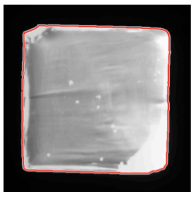


Figure 5: PL Emission Image for a Radiative Sample

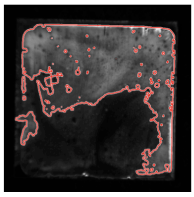


Figure 6: PL Emission Image for a Trap-State Sample

- **Calibration:** Optimize camera gain and exposure time to maximize dynamic range and prevent saturation.
- **Excitation Sweep:** Current sweep from 0.9 A to 0.2 A to capture PL images with different I_{exc} values.
- **Power Correction:** Map raw drive current to true optical power (I_{exc}) using an interpolation table.
- **Data Extraction:** Isolate the brightness value (I_{PL}) for every (x, y) pixel across the image using the camera measurement.
- **Pixel-Wise Fitting:** Calculate local k-factor slopes using best fit line on $\ln(I_{PL})$ vs. $\ln(I_{exc})$ graphs.

Results & Conclusion

By extracting the k-factor for every pixel, we have successfully mapped the quality of perovskite modules.

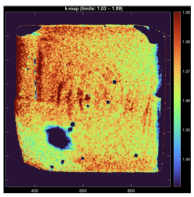


Figure 7: Radiative State Sample k-map

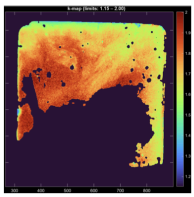


Figure 8: Trap State Sample k-map

- **High-Quality Module ($k \approx 1.03$):** The mean k-factor is near 1.03, proving the sample is dominated by ideal, radiative recombinations.
- **Trap-State Module ($k \approx 1.70$):** The mean k-factor shifts toward 2.0, instantly exposing a high density of non-radiative defects and poor material quality.
- **Impact:** This pixel-wise mapping technique provides a fast, reliable, and non-destructive way to investigate dynamics of a perovskite module, allowing researchers to visually determine efficiency losses.

Future Outlook

- **Machine Learning Integration:** We aim to train predictive models by using these spatial k-maps with physical structural parameters, specifically PbI_2 film thickness and surface roughness.
- **Process Optimization:** This dataset will act as a feedback loop for the manufacturing process, allowing for fine-tuning of the parameters for the manufacturing of the samples and commercial scale modules

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LEAD-FREE • SUSTAINABLE

Design and Optimization of Current-Matched Lead-Free Two-Terminal Perovskite Tandem Solar Cells

N. S. Bozkurt[1,2], **A. Arslan**[2,3], **A. Yildiz**[1,2]

[1] *Department of Energy Systems Engineering, Faculty of Engineering and Natural Sciences, Ankara Yildirim Beyazit University, Ankara 06010, Türkiye*

[2] *The Center for Third Generation Solar Cells Research and Applications (SOLAR 3.0), Ankara Yildirim Beyazit University, Ankara 06010, Türkiye*

[3] *Department of Electronics and Automation, Technical Sciences Vocational School, Ankara Yildirim Beyazit University, Ankara 06010, Türkiye*

MOTIVATION & AIM

Wide-bandgap lead-free tin-based mixed-halide perovskite materials enable high open-circuit voltages and compatible bandgaps for tandem architectures. In this work, a fully lead-free monolithic two-terminal (2T) tandem solar cell consisting of a $CsSnIBr_2$ perovskite top cell and a silicon heterojunction (SHJ) bottom cell is designed and optimized using SCAPS-1D to achieve current matching and maximize overall efficiency.

OPTIMIZED PERFORMANCE (AM1.5G, 1000 W/m², 300 K)

V_{OC}	J_{SC}	FF	PCE
1.78 V	18.8 mA/cm²	81.5 %	27.3 %
Open-circuit voltage	Short-circuit current	Fill factor	Power conversion efficiency

$$PCE = (V_{OC} \times J_{SC} \times FF) / P_{in} \times 100 \quad | \quad P_{in} = 100\ mW/cm^2$$

- $J_{SC,tandem} \approx \min(J_{SC,top}, J_{SC,bottom}) = 18.8\ mA/cm^2$ (current matched)
- $V_{OC,tandem} \approx V_{OC,top} + V_{OC,bottom} = 1.03 + 0.75 = 1.78\ V$

TANDEM DEVICE ARCHITECTURE (2T)

	Layer	Material	Thickness
TOP CELL (Perovskite)	FTO (Front TCO)	FTO	500 nm
	SnO_2 (ETL)	SnO_2	20 nm
	$CsSnIBr_2$ ($E_g \approx 1.65$ eV)	$CsSnIBr_2$	600 nm
	NiO_x (HTL)	NiO_x	20 nm
INTERCONNECT (ITO)	ITO (Recombination Layer)	ITO	80 nm
BOTTOM CELL (SHJ)	a-Si(p⁺) (Emitter)	a-Si	10 nm
	a-Si(i) (Intrinsic)	a-Si	5 nm
	c-Si (n-type, SHJ Wafer)	c-Si	150 µm
	a-Si(i) (Intrinsic)	a-Si	5 nm
	a-Si(n⁺) (Emitter)	a-Si	10 nm
	Ag (Back Contact)	Ag	200 nm

TOP ABSORBER: $CsSnIBr_2$ (Lead-Free Tin-Based Mixed-Halide Perovskite)

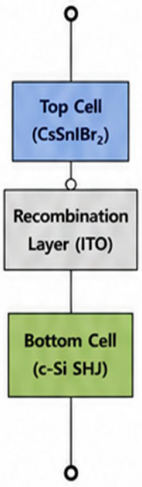
- Bandgap (E_g) ≈ 1.65 eV
- High V_{OC} potential
- Cut-off wavelength ≈ 752 nm
- Improved bandgap compatibility with c-Si bottom cell
- Suitable for tandem applications

CURRENT MATCHING PRINCIPLE

Tandem Cell (2T)
$J_{SC} \approx 18.8\ mA/cm^2$
$V_{OC} = 1.78\ V$

Top Cell ($CsSnIBr_2$)
$J_{SC} \approx 18.8\ mA/cm^2$
$V_{OC} = 1.03\ V$

Bottom Cell (c-Si SHJ)
$J_{SC} \approx 18.8\ mA/cm^2$
$V_{OC} = 0.75\ V$



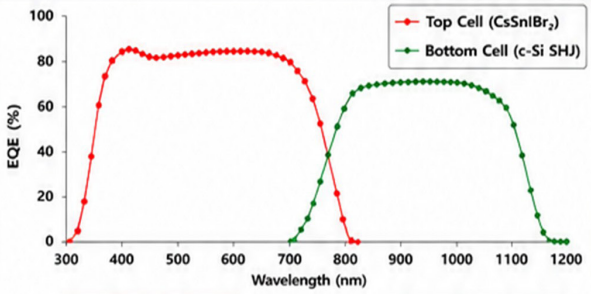
In a two-terminal (2T) tandem configuration, the sub-cells are connected in series.

- The overall current is limited by the lower J_{SC} of the sub-cells (current matched).
- The open-circuit voltage is the sum of the sub-cell voltages.

$$J_{tandem} = J_{bottom} = 18.8\ mA/cm^2$$

$$V_{tandem} = V_{top} + V_{bottom} = 1.78\ V$$

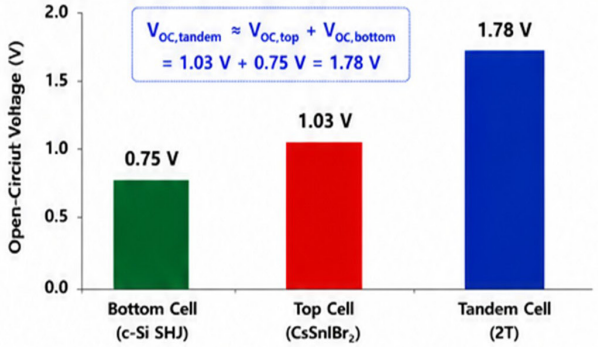
EXTERNAL QUANTUM EFFICIENCY (EQE)



Top Cell ($CsSnIBr_2$)
$E_g \approx 1.65$ eV
Cut-off ≈ 752 nm

Bottom Cell (c-Si SHJ)
$E_g \approx 1.12$ eV
Cut-off ≈ 1100 nm

OPEN-CIRCUIT VOLTAGE (V_{OC}) COMPARISON



$V_{OC,tandem} \approx V_{OC,top} + V_{OC,bottom}$
$= 1.03\ V + 0.75\ V = 1.78\ V$

KEY FEATURES

- Fully lead-free monolithic 2T tandem architecture
- High open-circuit voltage (1.78 V)
- Current matched at $J_{SC} \approx 18.8\ mA/cm^2$
- High fill factor (81.5%)
- High efficiency (27.3%) by SCAPS-1D optimization
- Compatible bandgap and minimal optical losses
- Promising for next-generation sustainable photovoltaics

CONCLUSION

A fully lead-free two-terminal tandem solar cell combining a wide-bandgap tin-based mixed-halide perovskite ($CsSnIBr_2$) top cell with a silicon heterojunction bottom cell is designed and optimized by SCAPS-1D. Through current matching and thickness tuning, a high efficiency of 27.3% is achieved with V_{OC} = 1.78 V, J_{SC} = 18.8 mA/cm² and FF = 81.5%. These results demonstrate the strong potential of lead-free tandem architectures for next-generation, high-efficiency and sustainable photovoltaic technologies.

nsbozkurt@aybu.edu.tr

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Design and Optimization of Current-Matched Lead-Free Two-Terminal Perovskite Tandem Solar Cells

A. Arslan[1,2] N. S. Bozkurt[2,3] A. Yildiz[2,3]

[1] *Dept. of Electronics and Automation, Technical Sciences Vocational School, Ankara Yildirim Beyazit University*

[2] *Dept. of Energy Systems Engineering, Faculty of Engineering and Natural Sciences, Ankara Yildirim Beyazit University*

[3] *Center for Third Generation Solar Cells Research and Applications (SOLAR 3.0), Ankara Yildirim Beyazit University*

MOTIVATION & AIM

Perovskite materials with tunable bandgaps are highly promising to exceed the **Shockley-Queisser limit** of conventional Si solar cells. Monolithic **two-terminal (2T) tandem solar cells** with lead-free perovskite top cells and c-Si bottom cells are investigated and optimized using SCAPS-1D simulation.

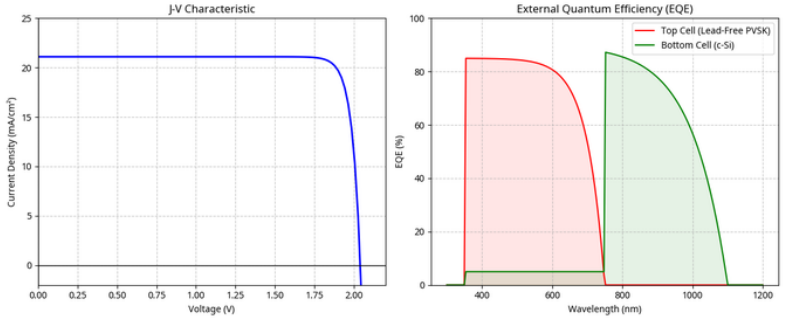
OPTIMIZED PERFORMANCE PARAMETERS

V_{OC}	J_{SC}	FF	PCE
1.92 V	**20.8** mA/cm²	**72.5** %	**28.95** %
Open-circuit voltage	Short-circuit current	Fill factor	Power conversion eff.

TANDEM DEVICE ARCHITECTURE

ARC	**Top Contact / Anti-Reflection Coating** Light entry — minimizes reflection losses	
PVSK	**Top Sub-Cell Absorber** Lead-free perovskite — tunable E_g	***$FASn(I_{0.75}Br_{0.25})_3$*** Formamidinium Tin Iodide Bromide
ETL	**Electron Transport Layer** Electron extraction	***SnO_2*** Tin Oxide
TCO	**Transparent Conductive Oxide** Tunnel / interconnect junction	***ITO*** Indium Tin Oxide
HTL	**Hole Transport Layer** Hole extraction — interface engineering	***Spiro-OMeTAD*** Spirobifluorene derivative
c-Si	**Bottom Sub-Cell Absorber** Complementary NIR absorption	***c-Si*** Crystalline Silicon
BC	**Back Contact** Current collection	***Ag / Al*** Silver or Aluminium

SIMULATION RESULTS



CONCLUSION

Current matching and carrier-recombination minimization via bandgap and thickness tuning yield a PCE of **28.95%**. These results provide critical guidance for fabricating **high-efficiency, stable, and eco-friendly** next-generation tandem solar cells.

Tandem Solar Cells · Perovskite · c-Si · SCAPS-1D · Lead-free · Current Matching

✉ aykutarslan@aybu.edu.tr

Ankara Yildirim Beyazit University
SOLAR 3.0 Research Center, Ankara

ROOM TEMPERATURE, ANNEAL-FREE RF MAGNETRON SPUTTERED SnO_x ELECTRON TRANSPORT LAYERS FOR PLANAR PEROVSKITE SOLAR CELLS

Busra Ileri[1], Aliekber Karabag[1] , Wanhai Wang[2] , Weihua Tang[2] , Gorkem Gunbas[1,3,4], Selcuk Yerci[1,5,6]

[1]ODTU GUNAM, Middle East Technical University, Çankaya, Ankara 06800, Türkiye
[2]Xiamen University, Xiamen 361005, China
[3]Department of Chemistry, Middle East Technical University, Cankaya, Ankara 06800, Türkiye
[4]Polymer Science And Technology Department, Middle East Technical University, Cankaya, Ankara, 06800, Türkiye
[5]Department of Electrical Electronics Engineering, Middle East Technical Technical University, Cankaya, Ankara, 06800, Türkiye
[6]Micro and Nanotechnology Department, METU, 06800, Ankara, Türkiye

Introduction

High-quality, cost-effective, and efficient electron transport layers (ETLs) are crucial for enhancing the stability and scalability of perovskite solar cells (PSCs). Tin oxide (SnO_x) is the most widely used ETL material in PSCs due to its suitable band alignment, high transparency, and excellent electron mobility. Various deposition methods, such as spin-coating, chemical bath deposition, and magnetron sputtering, have been used to fabricate SnO_x films. [1]

Why SnO_x by sputtering?

- **INDUSTRIAL & SCALABLE** — *High-throughput, well-established deposition technology*
- **HIGH-QUALITY FILMS** — *Uniform, dense, low defect and pinhole-free*
- **SOLVENT-FREE PROCESS** — *Environmental friendly*

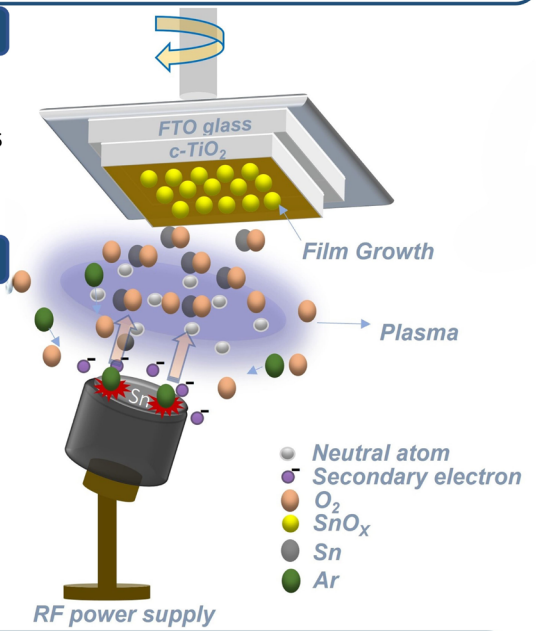
OUR APPROACH

- **RF Power** 50 W (optimized)
- **Oxygen Ratio** 100 % O_2 (optimized)
- **Process Pressure** 6 mTorr (optimized)
- **Thickness** 12.8 nm (ultra-thin)
- **Annealing** Room Temperature



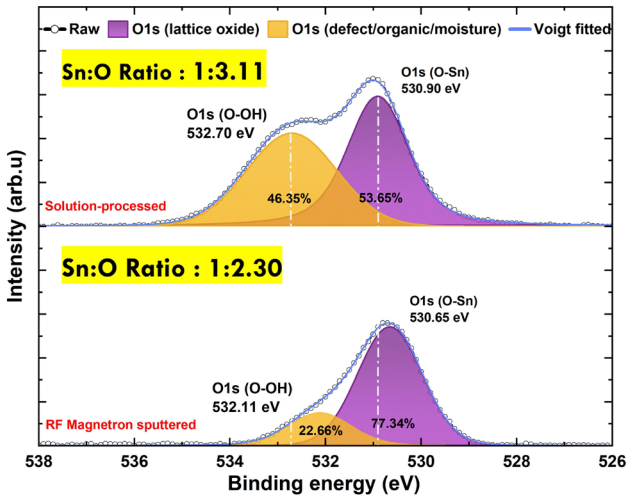
KEY ADVANTAGE

✔Ultra-thin, anneal-free SnO_x via Sn target for planar PSCs.



RESULTS

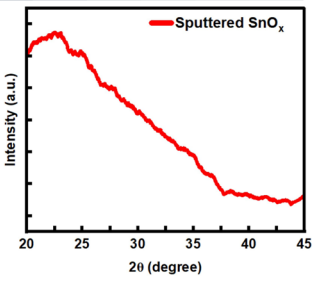
- Hydroxyl content of the SnO_x layer investigated by **XPS**.



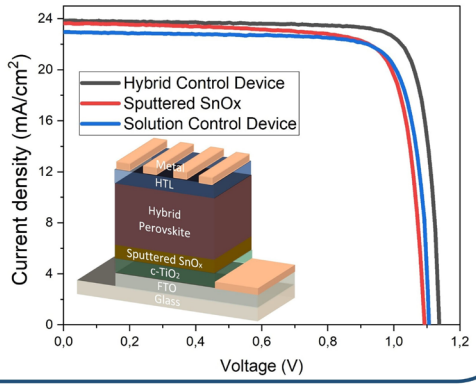
- A PSC device fabricated by our SnO_x layer & its performance compared with the conventional control devices of our team.

Device	V_{OC} (V)	J_{SC} (mA/cm²)	FF (%)	PCE(%)
Sputtered SnO_x	1.09	23.63	79.35	20.50
Hybrid Control Device	1.14	23.74	83.32	22.55
Solution Control Device	1.10	23.00	81.16	20.53

- The bandgap of the SnO_x measured as 1.61 eV by **PL**, while **XRD** result revealed that the phase of "*anneal-free*" film is developed as amorphous structure.



- Performance comparison of the PSC devices clearly show that the anneal-free and amorphous SnO_x could compete with its competitors known through literature.



Conclusion

- Anneal-free, ultra-thin (~12.8 nm) SnO_x ETLs were successfully fabricated from a metallic Sn target via RF magnetron sputtering, with deposition parameters (RF power, Ar:O_2 ratio, process pressure, and thickness) systematically optimized for high-performance device integration.
- The optimized planar PSC device achieved a high PCE of 20.50% (V_{OC} : 1.09 V, J_{SC} = 23.63 mA/cm², FF = 79.35%).
- X-ray photoelectron spectroscopy (XPS) analyses revealed that, compared to solution-processed SnO_x, the sputtered-SnO_x had over 50% lower hydroxyl content and a Sn:O ratio of 1:2.30, indicating minimised surface defects.
- These results demonstrate that thin, anneal-free, vacuum-based SnO_x provides a robust ETL approach for highly efficient, flexible, and scalable PSCs. This method is suitable for industrial applications.

References

[1] Z. Peng, L. Jin, Z. Zuo, Q. Qi, S. Hou, Y. Fu, and D. Zou, "Isolating the Oxygen Adsorption Defects on Sputtered Tin Oxide for Efficient Perovskite Solar Cells," ACS Applied Materials & Interfaces, vol. 15, no. 19, 2023.

Acknowledgements

This study was supported by Scientific and Technological Research Council of Türkiye (TUBITAK) under the Grant Number of 124N957. The authors thank to TUBITAK for their supports. The authors also thank ODTU-GUNAM for access to synthesis, characterization, and cell fabrication facilities.

Anthranilic Acid-Functionalized UiO-66-NH_2 Interfaces for Improved Crystallinity and Charge Transport in Perovskite Solar Cells

Dilek ÇIRAK, Selin YILMAZ YILDIRIM, Burak GÜLTEKİN

dilekcirak89@gmail.com

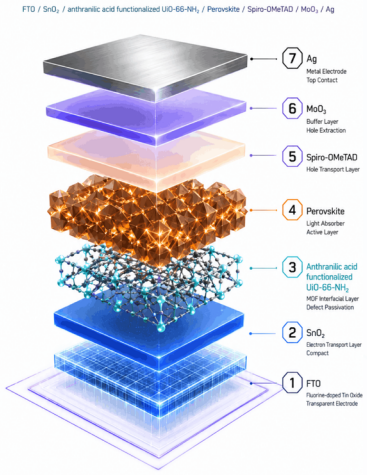


Figure 1. Schematic illustration of the perovskite solar-cell architecture

Abstract

Metal–organic frameworks (MOFs) are promising interfacial materials for perovskite solar cells due to their tunable porosity and chemical functionality. Here, UiO-66-NH_2 was functionalized with anthranilic acid and inserted between SnO_2 and the perovskite absorber. FTIR and powder XRD confirmed successful functionalization and preservation of the MOF framework. The functionalized MOF improved perovskite crystallinity, interfacial charge transfer, short-circuit current density, and power conversion efficiency. These results demonstrate its potential as an effective interfacial material for high-performance perovskite solar cells.

Results

X-ray diffraction (XRD)

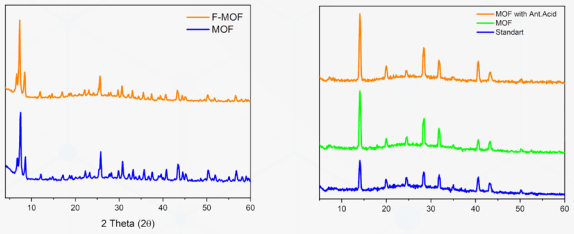


Figure 2. XRD patterns of pristine and anthranilic acid-functionalized UiO-66-NH_2 powders (left) and standard, MOF-based, and functionalized MOF-based perovskite thin films (right).

FTIR Spectroscopy

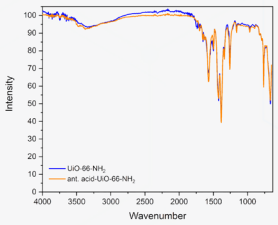


Figure 3. FTIR spectra of pristine UiO-66-NH_2 and anthranilic acid-functionalized UiO-66-NH_2.

IPCE

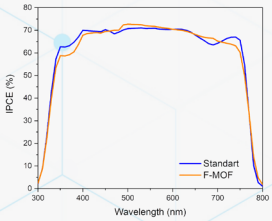


Figure 4. IPCE spectra of standard and anthranilic acid-functionalized MOF-based perovskite solar cells.

J-V Parameters

FTO/SnO_2/Perovskite/Spiro-OMeTAD/MoO_3/Ag
FTO/SnO_2/Functional-MOF/Perovskite/Spiro-OMeTAD/MoO_3/Ag

	Jsc	Voc	FF	PCE
Standart-F	23,5	1080	64,15	16,28
Standart-R	23,3	1070	64,51	16,09
MOF-F	25,4	1070	60,29	16,45
MOF-R	25,3	1070	62,83	17,07

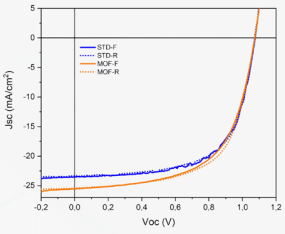


Figure 3. J–V characteristics and photovoltaic parameters of standard and functionalized MOF-based perovskite solar cells measured under forward and reverse scan.

Conclusion

- Anthranilic acid functionalization was achieved without disrupting the UiO-66-NH_2 crystalline framework.
- FTIR and powder XRD confirmed chemical modification and structural preservation.
- The functionalized MOF interlayer improved perovskite crystallinity and film quality.
- Devices containing the functionalized MOF showed higher short-circuit current density and improved power conversion efficiency.
- Performance enhancement was mainly attributed to improved photocurrent generation and interfacial properties.

Acknowledgement

I would like to acknowledge the Presidency of the Republic of Türkiye, Department of Strategy and Budget, for supporting the infrastructure and providing some of the consumables used in this study. I also gratefully acknowledge the Ege University Office of Scientific Research Projects (Project No: 32665) for providing financial support for the fabrication of solar cells and the supply of consumables. I also acknowledges the TÜBİTAK 2211-C Scholarship Program for its financial support.*

Ege University · Solar Energy Institute

Evka 3, 119/1. Sk. No:1, 35100 Bornova/İzmir

https://eusolar.ege.edu.tr/

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ALD-Engineered Al_2O_3 Interfacial Layers for Enhanced Perovskite Solar Cell Performance

Selin Yılmaz Yıldırım, Dilek Çırak,Burak Kahraman ,Burak Gültekin

Ege University, İzmir, Türkiye

Introduction

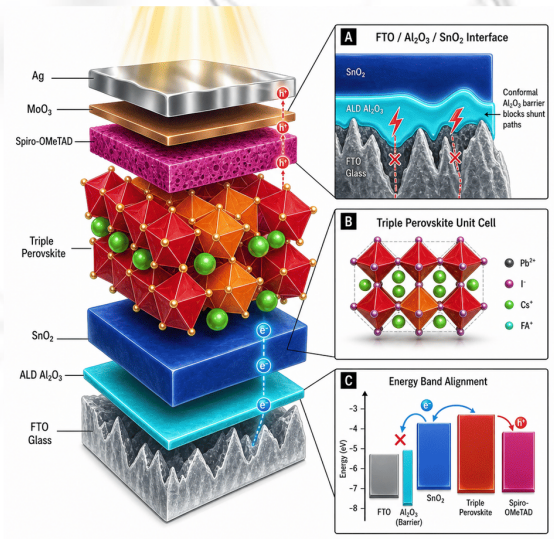


Figure 1. Schematic illustration of n-i-p perovskite solar cell architecture.

Methods

- **Architecture:** FTO / ALD-Al_2O_3 / SnO_2 / Triple Perovskite / Spiro-OMeTAD / MoO_3 / Ag
- **Thickness Tuning:** ALD cycles were precisely controlled to yield Al_2O_3 layers of **2, 5, 6, and 8 nm**, optimizing the electron tunneling mechanism.

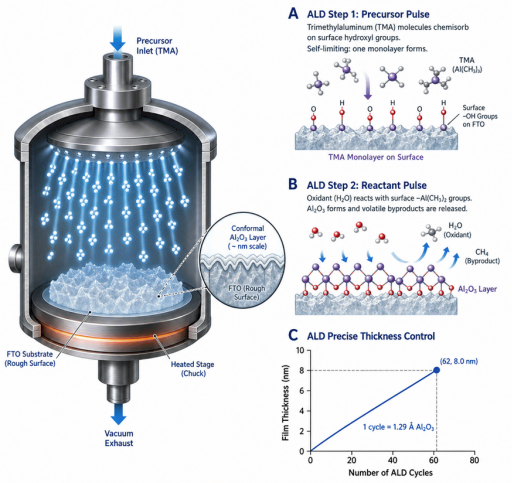
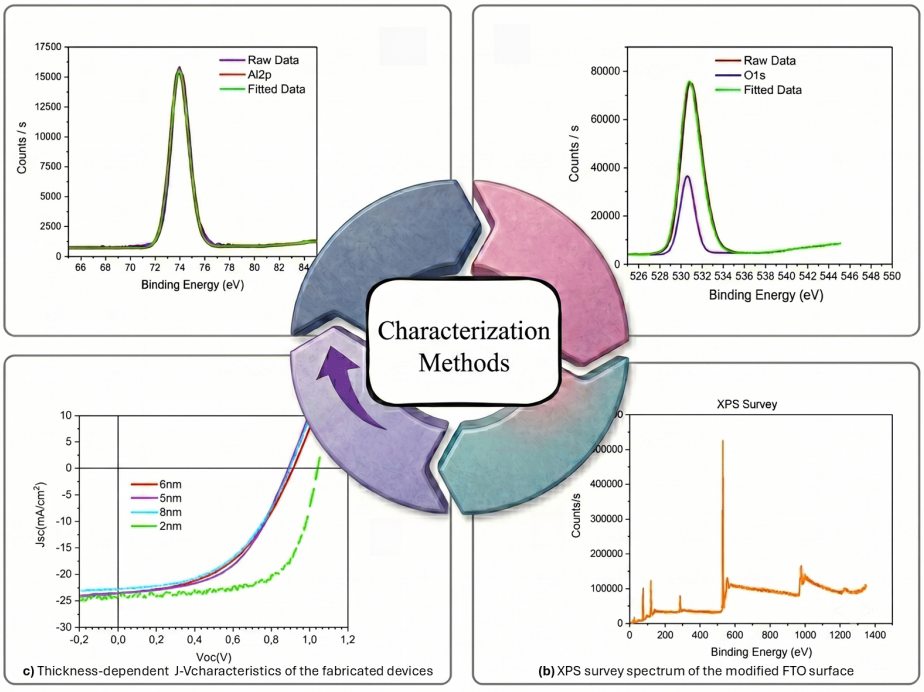


Figure 2. Figure 2. ALD fabrication protocol for Al_2O_3 interface engineering: Mechanistic details and thickness calibration curve..

- **Motivation:** Interfacial recombination significantly limits perovskite solar cell (PSC) efficiency.
- **Approach:** Atomic Layer Deposition (ALD) was employed to grow ultrathin, highly conformal Al_2O_3 interlayers between the FTO substrate and the SnO_2 ETL.
- **Impact:** The Al_2O_3 layer provides excellent surface passivation, blocks shunt paths, and optimizes charge extraction dynamics.

Results and Discussion

(a) High-resolution XPS spectra of Al2p and O1s core levels. .



c) Thickness-dependent J-Vcharacteristics of the fabricated devices

(b) XPS survey spectrum of the modified FTO surface

	Jsc	Voc	FF	PCE
2 nm ALD	22,8	1010	65	14,42
5 nm ALD	23,3	890	53	10,89
6 nm ALD	23,3	910	50,01	10,33
8 nm ALD	22,7	900	49,39	10,10

Name	Start BE	Peak BE	End BE	Height CPS	FWHM eV	Area (P) CPS.eV	Area (N) TPP-2M	Atomic %
Al 2p	80	74,06	68,4	82287,03	2,78	249761,83	5755,3	34,08
C 1s	298	284,56	279	42275,77	1,63	161078,45	2258,36	12,05
Sn 3d	500	484,08	479	1666,54	0	11213,48	7,21	2,38
O 1s	544,41	531,02	525,66	453415,67	3,16	1547468,52	8819,99	52,49

Conclusion

Surface Planarization: ALD-grown Al_2O_3 layers effectively modulate the FTO surface morphology by filling structural voids, leading to a significant reduction in surface roughness and providing a superior template for subsequent perovskite crystallization.

•Interfacial Charge Transfer: The integration of the SnO_2 layer onto the passivated substrate optimizes the energy band alignment, facilitating efficient electron extraction while utilizing the ultra-thin Al_2O_3 layer to modulate charge transport via **quantum tunneling**.

ACKNOWLEDGEMENT

I would like to acknowledge the Presidency of the Republic of Türkiye, Department of Strategy and Budget, for supporting the infrastructure and providing some of the consumables used in this study.

DFT-Generated Theoretical Framework for the Predictive Screening of Self-Assembled Monolayers

Feyza Güler[1], Cem Maden[1,2], Hande Toffoli[1,3]

[1]Department of Physics, Middle East Technical University, Ankara, Türkiye
[2]ODTU-GUNAM, Middle East Technical University, Ankara, Türkiye
[3]Department of Micro and Nanotechnology, Middle East Technical University, Ankara, Türkiye

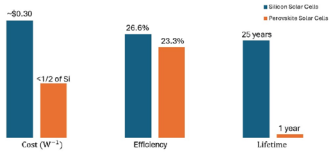
ABSTRACT

Perovskite Solar Cells (PSCs) show great promise for next-generation photovoltaics, but interfacial recombination and long-term instability remain significant barriers. This work combines high-throughput DFT calculations on 98 SAM candidates with Random Forest machine learning to build a physics-informed screening framework. Incorporating quantum mechanical descriptors (HOMO, LUMO, dipole moment) substantially improved predictive accuracy for PCE, and four high-potential SAM candidates were identified for experimental follow-up.

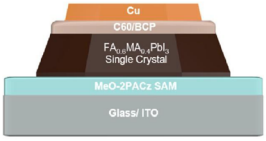
INTRODUCTION

Motivation & Approach

PSCs offer low fabrication costs and tunable bandgaps, but uncoordinated interface defects cause non-radiative recombination and rapid degradation — particularly in p-i-n inverted architectures. SAMs passivate these defects, yet experimental trial-and-error screening of large candidate libraries is slow and resource-intensive. This work builds a data-driven pipeline that combines structural cheminformatics with DFT quantum mechanical calculations to rationally identify the most promising SAM candidates.



The comparison of Perovskite and Silicon Solar Cells



PSC Device Structure

THEORY

Density Functional Theory

DFT avoids solving the many-body Schrödinger equation directly by using the electron density n(**r**) as the fundamental variable. The Kohn-Sham equations reduce the problem to a set of single-particle equations:

$$\left[-\tfrac{1}{2}\nabla^2 + V_{ext}(\mathbf{r}) + \int \frac{n(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|}d\mathbf{r}' + V_{XC}(\mathbf{r})\right]\phi_i = \varepsilon_i\phi_i$$

The eigenvalues ε_i yield the molecular orbital energies governing energy level alignment at the SAM/perovskite interface. The electronic band gap is then obtained as:

$$E_g = E_{LUMO} - E_{HOMO}$$

Calculations performed using the ORCA software package.

Interfacial Energy Alignment

In p-i-n inverted PSCs, SAMs act as the Hole Transport Layer (HTL). Two conditions must be satisfied simultaneously:

- **HOMO ↔ VBM alignment:** the SAM's HOMO must sit close to the perovskite Valence Band Maximum to drive efficient hole extraction.
- **LUMO ↔ CBM offset:** the SAM's LUMO must remain above the Conduction Band Minimum to block electrons and suppress interfacial recombination.

Dipole moments (extracted in Debyes from the DFT electron density) further modulate the effective work function at the interface.

METHODOLOGY

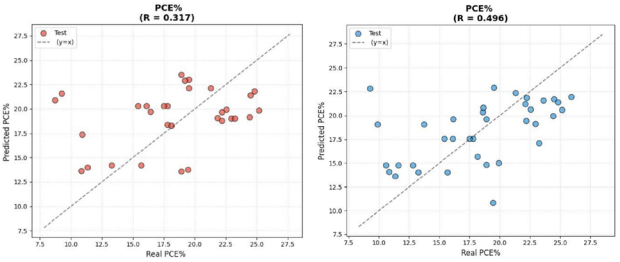
Computational & ML Framework

The structural dataset was compiled from a literature review of 30+ publications. SMILES strings were generated for each molecule and passed to RDKit to compute 217 molecular descriptors. DFT geometry optimizations were then run for 98 candidates to extract HOMO and LUMO eigenvalues and dipole moments, which were added to the feature set.
A *Random Forest Regression* model was trained on an 80/20 split. To prevent data leakage and isolate SAM-specific contributions from absorber-layer effects, a group shuffle splitting strategy was applied — samples were grouped by perovskite composition ($MAPbI_3$, $FAPbBr_3$, $FASnI_3$), so the model was forced to generalize across absorber types rather than memorize them.

RESULTS

Improvement in Predictive Accuracy

Adding DFT-derived electronic features improved performance across all four photovoltaic metrics. The largest gain was in PCE — consistent with PCE being sensitive to precise energy level alignment.



J_{sc}	V_{oc}	FF	PCE
$R = 0.724$	$R = 0.520$	$R = 0.447$	$R = 0.496$

Key Feature Importances (PCE)

Feature importance analysis revealed a clear hierarchy of physical parameters governing PCE variance.

Feature	Category	Importance	%
$MAPbI_3$	Absorber composition		26.9%
$FASnI_3$	Absorber composition		5.8%
EState_VSA6	Structural descriptor		5.4%
HOMO	DFT quantum feature		2.7%
SPS (packing)	Structural descriptor		2.6%

Composite Scoring Methodology

To objectively rank candidates, a weighted Descriptor Score was defined:
Relative PCE (50%): predicted PCE normalized within each perovskite subset, isolating the SAM's passivation contribution from absorber effects.
Structural Quality (30%): aggregated score from topological and surface charge descriptors (EState_VSA6, SPS).
HOMO Alignment (20%): proximity of the computed HOMO to the ideal VBM, penalizing large hole-extraction barriers.

SAM ID	PCE (%)	HOMO (eV)	Score
ADAI	15.90	−5.14	0.87
Br-2EPT	22.44	−5.31	0.85
EADR03	21.20	−5.34	0.84
PATPA	24.49	−5.41	0.83

All four candidates exhibit HOMO levels in the −5.1 to −5.4 eV range, indicating favorable alignment with the perovskite VBM.

SUMMARY

This project established a data-driven framework for screening SAM candidates for Perovskite Solar Cells. By augmenting structural descriptors with DFT-calculated HOMO/LUMO levels and molecular dipole moments, the Random Forest model achieved substantially improved predictive accuracy — especially for PCE. Statistical analysis confirmed that hydrogen bond donor count strongly correlates with Fill Factor, while HOMO alignment governs voltage-dependent behavior.

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[2] B. Dong et al., Nat. Energy 10, 342–353 (2025)

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OPTIMAZING SELF-ASSEMBLED MONOLAYER DEPOSITION VIA MACHINE LEARNING FOR ENHANCED P–I–N PEROVSKITE SOLAR CELLS

Gulay Zeynep Gunel[1], Sevdiye Basak Turgut [1], Burak Kahraman[1] Ceylan Zafer[1]

[1] Solar Energy Institute /Energy Technology, Izmir, Turkey.

zeynepgunel94@gmail.com

BACKGROUND & MOTIVATION

Self-assembled monolayers (SAMs) are promising interfacial layers for enhancing charge extraction and reducing recombination losses in perovskite solar cells. However, SAM performance strongly depends on molecular structure and processing conditions. Here, machine learning-assisted Bayesian optimization was used to systematically optimize Br-TATPAC SAM deposition parameters, including solvent composition, concentration, coating method, and post-deposition washing conditions.

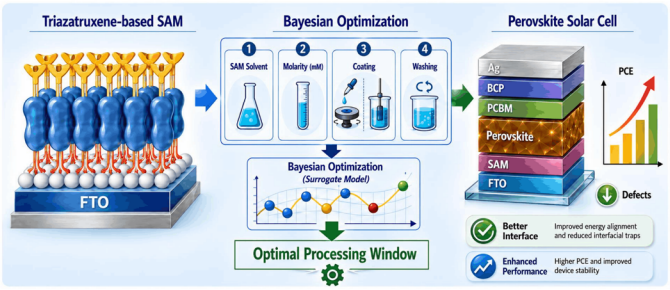


Figure 1. Schematic illustration of the triazatruxene-based SAM, Bayesian optimization workflow, and inverted p–i–n perovskite solar cell architecture.

SYNTESIS OF TRIAZATRUXENE BASED SAM

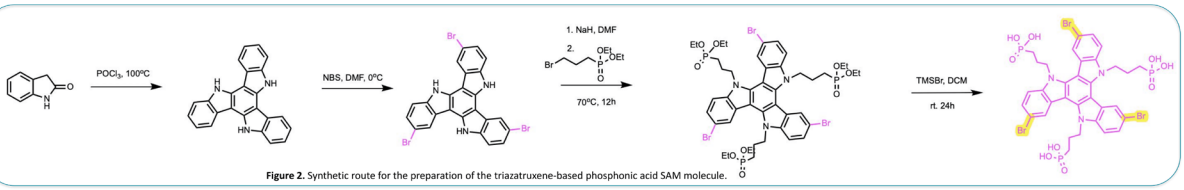


Figure 2. Synthetic route for the preparation of the triazatruxene-based phosphonic acid SAM molecule.

MACHINE LEARNING OPTIMIZATION

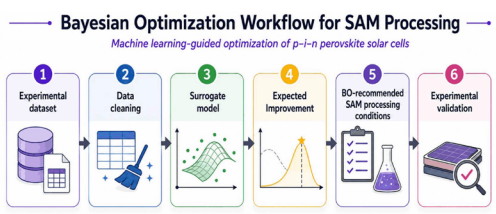


Figure 3. Workflow of Bayesian optimization employed for SAM process optimization, including experimental iterations, surrogate model prediction, and candidate selection.

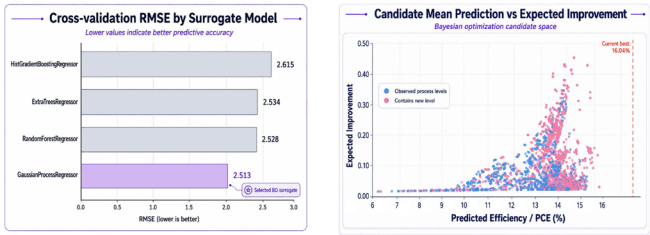
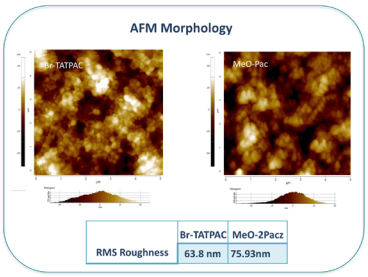


Figure 4. Cross-validation RMSE comparison of different surrogate models used in the Bayesian optimization framework. Lower RMSE values indicate higher predictive accuracy. Candidate mean prediction versus expected improvement obtained from the Bayesian optimization search space.

THIN FILM CHARACTERIZATION



	Br-TATPAC	MeO-2Pacz
RMS Roughness	63.8 nm	75.93nm

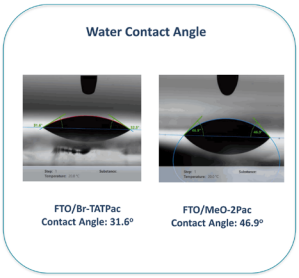


Figure 4. AFM images of perovskite films deposited on SAM-modified FTO substrates. Water contact-angle measurements of SAM-modified FTO substrates.

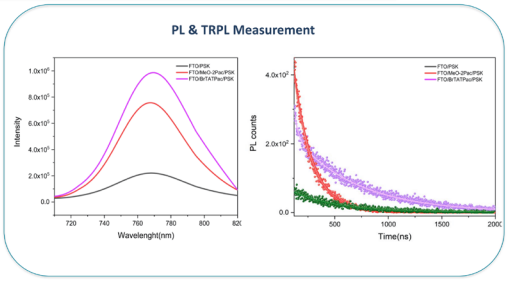


Figure 5. Steady-state PL and TRPL analyses of perovskite films on bare FTO, MeO-PACz, and Br-TATPac substrates. Br-TATPac shows the strongest PL emission and the longest carrier lifetime (~526 ns), indicating effective defect passivation and reduced non-radiative recombination.

DEVICE PERFORMANCE & RESULTS

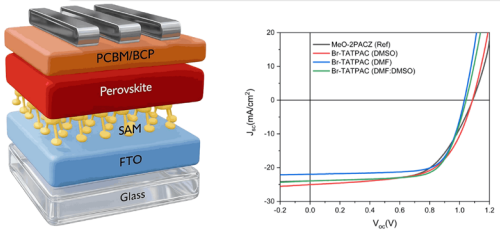


Figure 6. Device architecture and photovoltaic performance of SAM-based p–i–n perovskite solar cells. J–V characteristics and extracted photovoltaic parameters demonstrate the effect of solvent-dependent Br-TATPAC deposition conditions.

	J_{sc}(mA/cm²)	Voc (mV)	FF(%)	PCE(%)
MeO-2PACz	23.8	1090	62	16.1
Br-TATPAC (DMSO)	24	1090	63	16.7
Br-TATPAC (DMF)	21.9	1030	71.7	16.2
Br-TATPAC (DMF:DMSO)	23.8	1040	70	17.2

- Optimized Br-TATPAC SAM deposition conditions improved the photovoltaic performance of p–i–n perovskite solar cells.
- The mixed DMF solvent system achieved the best overall performance, with a maximum PCE of 17.2%.
- Spectroscopic analyses indicated improved charge extraction and reduced recombination losses.
- Surface characterization revealed enhanced film morphology and interface quality.
- Bayesian optimization accelerated the SAM process-development workflow.

ACKNOWLEDGEMENT

This work was supported by Ege University Scientific Research Projects (BAP), TÜBİTAK 2211-C National PhD Scholarship Program, TÜBİTAK China–Türkiye Bilateral Cooperation Project (Project No: 225N068), and the Presidency of the Republic of Türkiye, Department of Strategy and Budget (Project No: 16-DPT-002).

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Metal Oxide/GaAs Heterojunctions for Flexible Solar Cells: Fabrication and Characterization

Hazal Zaimler[1*], Burcu Arpapay[2,3], Mustafa Kulakcı[2,4]

[1]Department of Physics, Institute of Graduate Education, Eskişehir Technical University, [2]Nanoboyut Research Laboratory, Department of Physics, Eskişehir Technical University, [3]Department of Advanced Technologies, Institute of Graduate Education, Eskişehir Technical University, [4]Institute of Earth and Space Sciences, Eskişehir Technical University

E-mail: hazalzaimler@gmail.com

ABSTRACT

In this study, non-epitaxial ZnO and TiO_2 electron-selective contacts were integrated into GaAs heterojunction solar cells to evaluate their potential for flexible III-V photovoltaic devices. Flexible GaAs/ESC hybrid cells were fabricated using an inverted epitaxial structure, polyimide carrier bonding, epitaxial lift-off, sputtered metal oxide contact deposition, and front grid metallization. The photovoltaic performance was characterized under AM1.5G illumination. ZnO-contacted substrate-based devices showed the highest efficiency of 2.44%, while flexible ZnO and TiO_2 devices yielded similar efficiencies around 1.4%. The results demonstrate the feasibility of GaAs/metal oxide hybrid cells, although low Voc values indicate that interface-related losses remain the main performance limitation.

MOTIVATION: NON EPITAXIAL CONTACT FOR FLEXIBLE GaAs SOLAR CELL

Electron Selective Contact Aproach

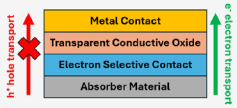


Figure 1 Non-epitaxial metal oxide contact approach for GaAs solar cells.:

Flexible GaAs with Non-Epitaxy ESC

- Carrier selectivity through band alignment
- ZnO/TiO_2 enable electron extraction
- Wide-bandgap oxides block hole transport
- Reduced short wavelength parasitic absorption compared with conventional epitaxial window layers
- Compatible with flexible thin-film GaAs processing

GaAs/METAL OXIDE HETEROJUNCTION DESIGN

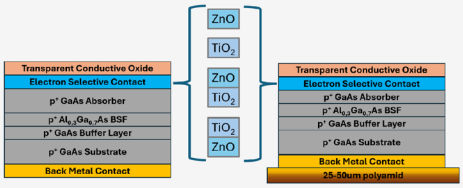


Figure 2. Schematic cross-sectional design of substrate-based and flexible GaAs/metal oxide heterojunction solar cells using ZnO, TiO_2, and ZnO/TiO_2 and TiO_2/ZnO based electron-selective contact configurations.

SIMULATION AND LITERATURE BENCHMARKS

SIMULATED STRUCTURE	PCE(%)
TiO_2 ESC	29,29
ZnO ESC	27,21
TiO_2/ZnO ESC	28,77
ZnO/TiO_2 ESC	26,57
p-n GaAs reference	20,64

Table 1. Simulated photovoltaic performance of GaAs/metal oxide ESC heterojunction structures and the conventional p-n GaAs reference cell calculated without antireflective coating.

CELL STRUCTURE	ESC METAL OXIDE	EFFICIENCY (%)
InP/TiO_2/ITO	TiO_2	%19,2
InP/Ta_2O_5/ITO	Ta_2O_5	%19,1
InP/ZnO/ITO	ZnO	%18,1
GaAs/ZnO/TiO_2/ITO	ZnO/TiO_2	%21,2
GaAs/ZnO/AZO	ZnO	%1,39

Table 2. Reported photovoltaic efficiencies of III-V solar cells using metal oxide electron-selective contacts, highlighting the potential of oxide-based carrier-selective contact architectures for high-performance III-V photovoltaics

Simulation results suggest that metal oxide ESC-based GaAs heterojunctions can theoretically outperform the conventional p–n GaAs reference, while literature reports confirm the potential of oxide-based carrier-selective contacts in III–V solar cells.

FABRICATION OF FLEXIBLE GaAs/ESC HYBRID SOLAR CELLS

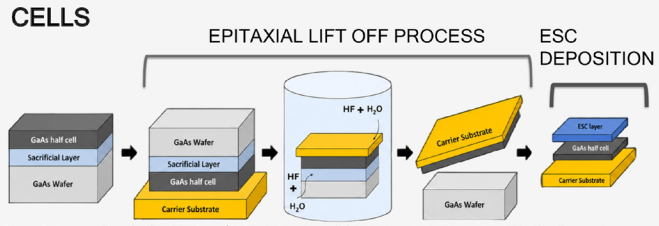


Figure 3. Process flow for flexible GaAs/ESC hybrid solar cell fabrication, including epitaxial half-cell growth, epitaxial lift-off, ESC deposition.

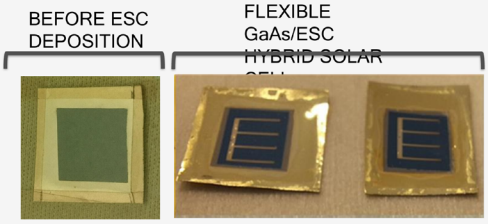


Figure 4. Photograph of the GaAs half-cell structure before metal oxide electron-selective contact deposition and front contact formation.

PHOTOVOLTAIC PERFORMANCE

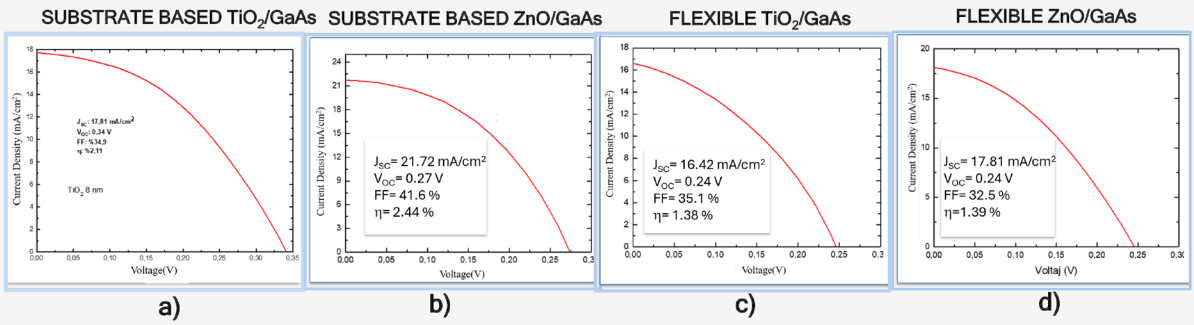


Figure 5. a), b), c), d) Photovoltaic performance of substrate-based and flexible GaAs/ESC hybrid solar cells using ZnO and TiO_2 electron-selective contacts.

CONCLUSION

GaAs/metal oxide heterojunction solar cells were demonstrated as a feasible non-epitaxial approach for flexible III-V photovoltaics. Simulation results indicate that TiO_2, ZnO, and bilayer ESC structures can outperform the conventional p-n GaAs reference by combining electron-selective transport with reduced short-wavelength optical losses. The fabricated substrate-based and flexible devices confirm the process compatibility of sputtered metal oxide contacts with GaAs half-cell structures. Nevertheless, the gap between simulated and experimental performance, especially the low Voc and FF, shows that interface recombination and contact losses remain the main limitations. Future work will focus on GaAs/ESC interface optimization, oxide thickness control, and post-deposition treatments to improve carrier selectivity and device efficiency.

PVCON 2026 PHOTOVOLTAIC CONFERENCE
Sith International Conference on Photovoltaic Science and Technologies

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2. Pham, D. P., Lee, S., & Yi, J. (2021). Potential high efficiency of GaAs solar cell with heterojunction carrier selective contact layers. Physica B: Condensed Matter, 611, 412856.

ACKNOWLEDGEMENTS

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Solar Energy Ecosystem in Greece: Opportunities and Challenges

Nihad Mammadli (METU), Selin Piravadili (TÜBİTAK) , Pinar Derin-Güre (METU, ODTÜ-GÜNAM), Evangelos Rikos (CRES), George Karagianis (CERTH)

Introduction

Greece has emerged as a top European performer in solar energy deployment, fundamentally transforming its energy sector. Renewable energy sources, dominated by photovoltaic (PV) and solar thermal technologies, now cover over 50% of domestic electricity demand. Despite massive installed PV capacity, the energy cannot be fully utilized due to stagnant domestic demand and severe grid capacity constraints. This research analyzes stakeholder perspectives to identify structural bottlenecks and propose actionable pathways to stabilize and expand the Greek solar ecosystem.

Research Gap

Despite academic focus on Greece's rapid acceleration in raw photovoltaic (PV) installation, a critical research gap remains regarding the socio-technical and structural bottlenecks of an oversupplied ecosystem. This study addresses these critical gaps by capturing perspectives across industry, academia, and energy communities.

Methodology

Data was gathered through semi-structured interviews to capture diverse, high-level perspectives across the Greek energy sector. The transcripts were analyzed using qualitative thematic analysis to extract recurring structural, economic, and social patterns.

Table 1. *Methological Details*

Methodology Component	Details
Sample Size	13 semi-structured interviews.
Participant Profiles	Industry (5), Academia & Research (5), Energy Communities (2), Public Sector (1).
Analysis	Inductive thematic analysis focusing on grid infrastructure, regulatory frameworks, and technological adoption.

Key Findings - Opportunities

Geographical Advantages: Greece possesses world-class solar irradiation and wind resources, providing an exceptional natural baseline for continuous renewable expansion.

Solar Thermal Leadership: The country benefits from a highly mature solar thermal manufacturing legacy, exporting over 60% of its production and dominating the residential domestic hot water market.

Agrivoltaics (Agri-PV) Expansion: New legal frameworks enable dual land use, allowing simultaneous agricultural cultivation and energy generation while protecting crops and saving water.

Energy Communities: Distributed generation and collective self-consumption models offer a pathway to increase local social acceptance and energy democracy.

"*Greece renewable energy potential is arguably its most valuable natural resource.*" — **Respondent 9**

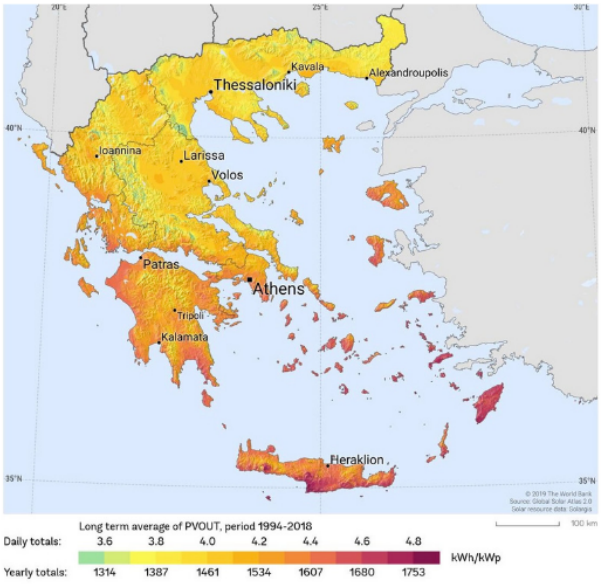


Figure 1. *Photovoltaic Power Potential Map of Greece*
Source: World Bank Group, n.d.

Key Findings - Challenges

Grid Congestion and Curtailment: An oversupply of midday PV generation exceeds both domestic demand and current grid capacity, leading to heavy energy curtailments and negative wholesale prices.

Bureaucratic Delays: Fragmented licensing procedures across multiple agencies (e.g., environmental, archaeological) create administrative complexity and prolong project approvals for years.

Energy Storage Deficit: The ecosystem severely lacks large-scale battery and thermal storage infrastructure needed to balance intermittent solar production.

Social Resistance & Land-Use Conflicts: Large-scale solar and wind installations frequently face opposition from local communities due to perceived landscape degradation and competition for high-productivity agricultural land.

"*Honestly, the biggest issue is bureaucracy and complexity. It takes too long to move from idea to implementation, and there are too many steps and authorities that are involved.*" — **Respondent 10**

Discussion and Policy Recommendations

Prioritize Energy Storage: Shift national policy and financial incentives away from pure PV capacity expansion and strictly toward battery and thermal storage integration.

Digitalize Permitting Systems: Implement a centralized, digital "one-stop-shop" to streamline multi-agency approvals and drastically reduce licensing waiting periods

Foster Hybridization and Agri-PV: Provide targeted subsidies and technical guidelines to promote integrated solutions, such as coupling PV with heat pumps, and scaling Agri-PV to support farmer

Accelerate Grid Infrastructure Upgrades: Enhance domestic grid capacity and cross-border interconnections to safely absorb, manage, and export surplus renewable generation.

Interview Questions

References

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101086110.

Self-Assembled Monolayer Engineering for High-Performance p–i–n Perovskite Solar Cells with Varying Bandgaps

Elif Sude Camkiran[1,2], Nisa Ferlibas[1,2], Bahri Eren Uzuner[2], Zeynep Gozukara Karabag[2], Gorkem Gunbas[1,2,3,4], Selcuk Yerci[1,2,5], Aliekber Karabag[*2] , Wanhai Wang[6] , Weihua Tang[3]

[1]Micro and Nanotechnology Department, METU, [2]Center for Solar Energy Research and Applications (ODTU-GUNAM), [3]Department of Chemistry, METU, [4]Polymer Science And Technology Department, [5]Electrical Engineering Department, METU, [6]Xiamen University (XU)

*Corresponding author: aliekber.karabag@odtugunam.org

Introduction

The performance of inverted (p–i–n) perovskite solar cells is strongly influenced by the interface between the hole-transport layer and the perovskite absorber. Interfacial defects and non-uniform contact can increase non-radiative recombination and limit charge extraction. [1]

Self-assembled monolayers (SAMs) provide a molecular-scale approach for modifying this interface. In this study, the carbazole-based novel SAM was introduced between NiO_x and CsFAMA perovskite.

Objectives

- Optimize the concentration of novel SAM on NiO_x.
- Examine its influence on surface wettability.
- Evaluate its effect on photovoltaic performance.
- Test the optimized concentration with different CsFAMA compositions and bandgaps.

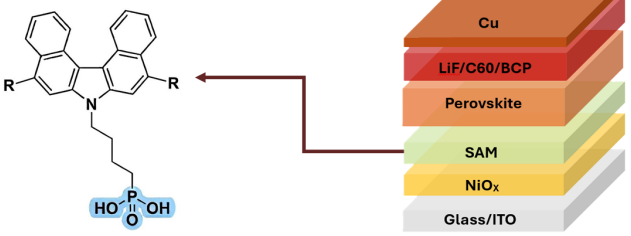
Methodology

Novel SAM solutions with concentrations of **0.3, 0.5, 0.8, 1.0, and 1.2 mg mL^{-1}** were deposited onto ITO/NiO_x substrates.

After deposition of the CsFAMA perovskite absorber, the LiF/C_{60}/BCP electron-transport layer and Cu electrode were deposited to complete the p–i–n devices.

Characterization

- Current density–voltage measurements were used to determine V_{OC}, J_{SC}, *FF* and PCE.
- Contact-angle measurements were performed to evaluate the surface modification produced by novel SAM.
- Devices containing **0.8 mg mL^{-1} Novel SAM** were subsequently tested with different perovskite precursor compositions



Results

Novel SAM Concentration Optimization

Bandgap : 1.61 eV

Device	V_{OC} (V)	J_{SC} (mA/cm^2)	FF (%)	PCE (%) (Avg.)
Reference	1.02	23.12	80.89	19.15 (17.85)
Novel SAM 0.3 mg/mL	1.15	23.67	82.68	22.51 (21.45)
Novel SAM 0.5 mg/mL	1.16	22.71	84.05	22.10 (21.30)
Novel SAM 0.8 mg/mL	1.14	23.86	82.77	22.58 (21.70)
Novel SAM 1.0 mg/mL	1.17	23.27	80.43	21.82 (21.17)
Novel SAM 1.2 mg/mL	1.15	23.28	79.64	21.31 (20.93)

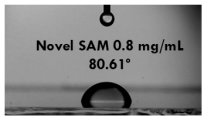
Bandgap : 1.67 eV

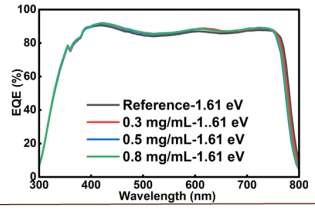
Device	V_{OC} (V)	J_{SC} (mA/cm^2)	FF (%)	PCE (%) (Avg.)
Reference	1.08	19.37	80.43	16.78 (15.66)
Novel SAM 0.8 mg/mL	1.18	20.03	82.80	19.52 (18.52)

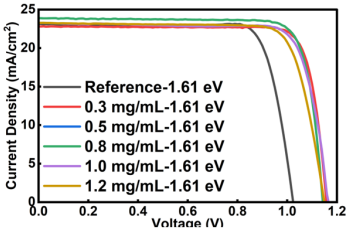
Bandgap : 1.72 eV

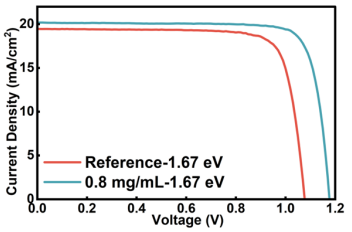
Device	V_{OC} (V)	J_{SC} (mA/cm^2)	FF (%)	PCE (%) (Avg.)
Reference	1.12	17.92	76.53	15.38 (14.32)
Novel SAM 0.8 mg/mL	1.19	18.37	80.30	17.56 (16.80)

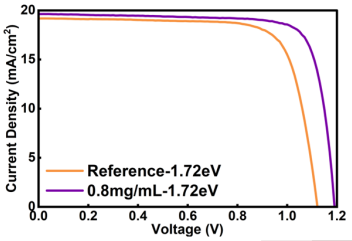












Conclusion

- The incorporation of novel SAM effectively modified the NiO_x surface, as demonstrated by the increase in contact angle from 39.70° to 80.61°.
- Concentration-dependent optimization identified 0.8 mg/mL as the optimum condition, increasing the best power conversion efficiency from 19.15% for the reference device to 22.58%. The optimized novel SAM layer also enhanced the performance of devices containing different perovskite compositions and bandgaps. For the 1.72 eV composition, the PCE increased from 15.38% to 17.56%, whereas for the 1.67 eV composition it increased from 16.78% to 19.52%.
- These improvements were mainly accompanied by increases in open-circuit voltage and fill factor, indicating that the novel SAM provides beneficial interfacial modification between NiO_x and the perovskite absorber.

References

[1] Hu, H., et.al.(2025). Self-assembled monolayer engineering improves the sensitivity and response speed of high-performance perovskite photodetectors. Journal of Materials Chemistry C, 13(24), 12169–12178.

Acknowledgements

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ODTÜ METU

ReSolarize

PVCON 2026 PHOTOVOLTAIC CONFERENCE
5th International Conference on Photovoltaic Science and Technologies

A Multi-Stream Circular Recovery Framework for High-Purity Photovoltaic Material Upcycling

Dijan Asarkaya , Seray Özgen , Neva Kızak
Department of Mechanical Engineering, Middle East Technical University, Ankara, Türkiye
Department of Environmental Engineering, Hacettepe University, Ankara, Türkiye
Department of Political Science and Public Administration; and Economics, Middle East Technical University, Ankara,Türkiye
Email: dijan.asarkaya@metu.edu.tr

1.THE CHALLENGES AND OUR SOLUTIONS

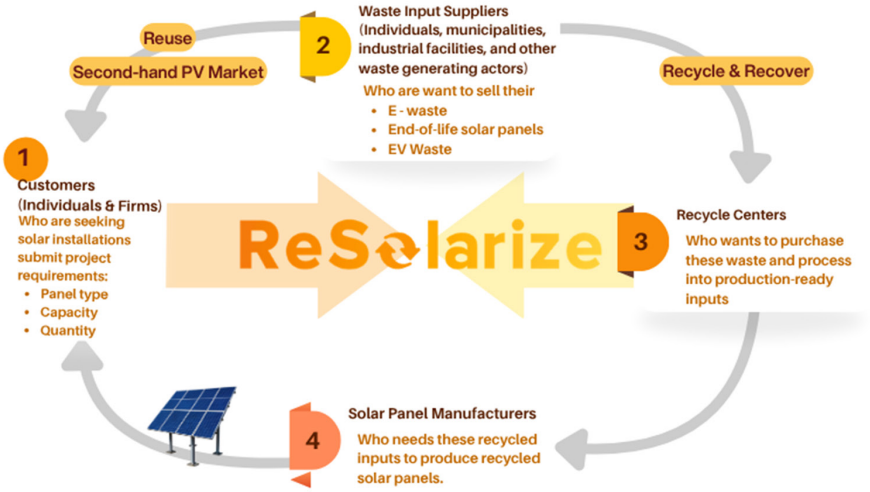
Dependence on
Unsustainable Supply Chains
- Threatens strategic autonomy and economic security

High Cost of
Critical Raw Materials
- Creates raw material volatility
- Builds entry barrier for vulnerable groups

10 million
tons of end-of-life panels by 2050 in the US
- Growing disposal challenge in solar energy



- B2B Digital Marketplace
- A bridge to recover and reuse critical raw materials
- More resilient and sustainable solar supply chains
- Democratization of solar energy ecosystem



2.TECHNICAL PARTS



- SOLAR PANELS (PV WASTE)
- E-WASTE (Silver,Copper)
- EV BATTERIES (Copper, Aluminum, Nickel)

Challenges
- The problem of Grinding
- Loss of Optical Integrity
- Conventional "Downcycling"
- The Silicon Gap

Hot Knife Delamination: Preserving 91% Transmitance

Pyrolysis: Vaporizes EVA without oxidizing silicon cells.

Alternative Green Way: Wet Gravity Separation

NaCl solution: 73% less Carbon Dioxide emisions

3.REVENUE STREAM & PRICING

1% of Transactions
Access For All:
SMEs, early-stage startups and women-led initiatives

5% of Transactions
Corporate

- Waste-input Transactions
  Individuals, companies, municipalities and other entities
- Recycled Materials Transactions
  Recycle Centers
- Solar Panel Sale Transaction
  Solar panel manufacturers

Impact-weighted pricing based on Just Transition & Gender Equality

4.SOCIO - ECONOMIC IMPACTS

Democratizing access to clean energy
Recycled solar panels are 40-60% cheaper than conventional panels.

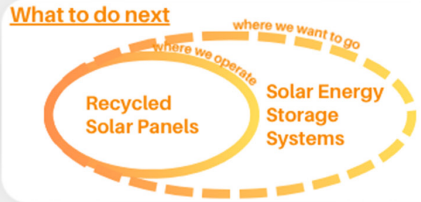
Green job creation & just transition
Provides reskilling pathways for workers in recycling and clean tech.

Strengthening strategic autonomy
Converts e-waste, EV waste, and end-of-life PV panels into domestic raw materials.

Turning citizens into active participants
Behavioral change and long-term social ownership of the energy transition.

CO_2 Environmental benefit
Integrated model prevents 2,158 kg CO2 equivalent per ton of PV wastage processed.

What to do next



Our Website



Extended Field Performance Analysis of Three Different Photovoltaic Technologies Over a 14-Year Period Under Semi-Arid Climate Conditions

Ahmet Hekim, Ahmet Hamdi Aksoy, Doç. Dr. Talat Özden
Center of Solar Energy Research and Applications (ODTÜ-GÜNAM), Ankara, Türkiye
ahmet.hekim@odtugunam.org

■ INTRODUCTION

This study evaluates the long-term PR degradation of mono-Si, µc-Si/a-Si, and CdTe PV systems using nearly 14 years of outdoor field data from Central Anatolia. Filtered energy data were analyzed within the IEC 61724 framework, and regression-based methods were used to compare technology-dependent degradation trends under semi-arid climate conditions.



Fig. 1. Mono-Si, micro-crystalline based amorphous silicon and CdTe grid connected PV systems.

■ METHODOLOGY

The PV output and irradiance data were quality-controlled and monthly normalized before analysis. Missing or invalid daily values were marked as NaN and counted monthly. Months with insufficient valid data were excluded; otherwise, monthly values were normalized using the average of valid daily data multiplied by the total number of days in the month, as defined in Eq. (5). After filtering, horizontal irradiance was converted to plane-of-array irradiance using the HDKR anisotropic model in Eq. (1). Monthly PV efficiency was calculated using Eq. (2). Long-term degradation was then evaluated by applying linear regression to the monthly efficiency series using Eq. (3), and the annual degradation rate was obtained from Eq. (4).

Eq. (1)
$$I_t = (I_b + I_d A_i) R_b + I_d (1 - A_i) \left(\frac{1+\cos\beta}{2}\right) \left[1 + f \sin^3\left(\frac{\beta}{2}\right)\right] + I_{pg} \left(\frac{1-\cos\beta}{2}\right)$$

Eq. (2)
$$\eta_{month} = \frac{\sum_{j=1}^{N} \left(\sum_i E_{out,i}\right)_j}{\sum_{j=1}^{N} \left(\sum_i I_{t,i}\right)_j}$$

Eq. (3)
$$y = mt + n$$

Eq. (4)
$$R_d = \left[\left(\frac{n - y_N}{n}\right) \times \frac{12}{N}\right] \times 100$$

Data filtering and monthly normalization, Eq. (5)

Eq. (5)
$$X_m = \begin{cases} \text{NaN}, & \text{if } N_{\text{NaN},m} > N_{thr} \\ \left(\frac{\sum X_d}{D_m - N_{\text{NaN},m}}\right) \times D_m, & \text{if } N_{\text{NaN},m} \le N_{thr} \end{cases}$$

X_m	monthly input or output value
X_d	daily input or output value
N_{thr}	missing-data threshold
D_m	total number of days in month m
$N_{\text{NaN},m}$	number of missing (NaN) daily values in month m

■ DISCUSSION

The trendline slopes confirm that PV degradation is technology-dependent. Long-term field data show distinct performance losses for mono-Si, µc-Si/a-Si, and CdTe systems, highlighting the need for real outdoor measurements and regression-based analysis in PV performance evaluation.

■ RESULTS

- All PV technologies showed gradual performance loss over the 14-year monitoring period.
- Regression trend lines revealed technology-dependent degradation behavior.
- Mono-Si exhibited the most stable long-term performance trend.
- µc-Si/a-Si showed higher temporal fluctuations.
- CdTe thin-film followed a distinct degradation pattern compared with silicon-based modules.
- Long-term field data are essential for reliable PV degradation assessment.

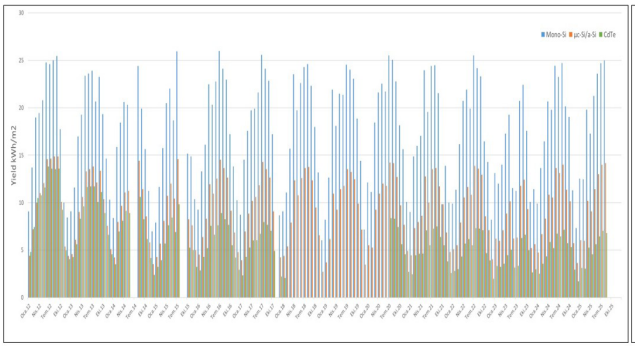


Fig. 2. The output data for fourteen years of the three systems

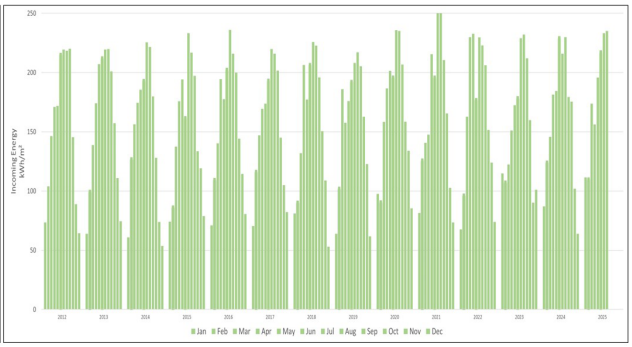


Fig. 3. The input data for fourteen years.

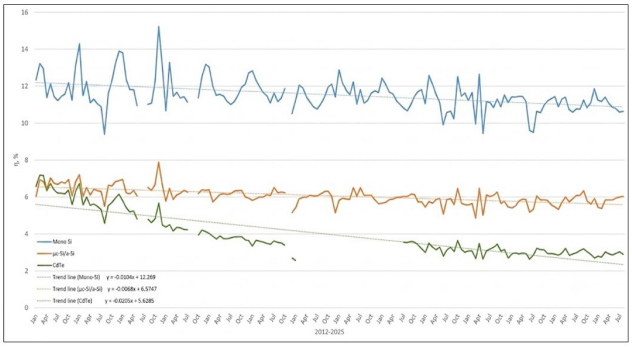


Fig. 4. Outdoor efficiency time series and trend lines for three systems.

Rd, (%/Year)	Previous Work (2017)	Previous Work (2020)	This Work
Mono-Si	0,4	0,69	**1,02**
µc-Si/a-Si	1,88	1,46	**1,24**
CdTe	10,60	-	**4,37**

Tab. 1. Degradation rates for three systems.

■ CONCLUSIONS

This study highlights the importance of long-term outdoor monitoring for reliable PV degradation assessment. Based on nearly 14 years of field data, mono-crystalline silicon, microcrystalline/amorphous silicon, and CdTe thin-film systems showed different energy production, efficiency, and performance ratio trends. The regression-based results confirm that degradation behavior is strongly technology-dependent. Therefore, PV technology selection should consider not only initial efficiency but also long-term stability and real-field energy yield.

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5th International Conference on Photovoltaic Science and Technologies
Middle East Technical University | Center for Solar Energy Research and Applications ODTÜ-GÜNAM | Ankara, Türkiye | 29 June - 1 July 2026

A MULTI-DIMENSIONAL ARCHITECTURAL ASSESSMENT OF COLORED BIPV: AESTHETIC, TECHNICAL, AND CONTEXTUAL DRIVERS OF ADOPTION

Tuğçe Aladı[1], Bilge Şentürk[1], Güneş Kurtuluş Şimşek[2], Pınar Derin Güre[1,3]

[1] Middle East Technical University, Center for Solar Energy Research and Applications (ODTÜ-GÜNAM), Ankara, Türkiye
[2] Artvin Çoruh University, Economics, Artvin, Türkiye
[3] Middle East Technical University, Economics, Ankara, Türkiye

Contact: tugce.aladi@metu.edu.tr

01 Introduction

From Add-on to Architectural Material

Building-Integrated Photovoltaics (BIPV) is now treated as an architectural material, yet conventional dark-blue modules limit visual acceptance, making aesthetics a primary barrier to uptake (Mao & Xiang, 2025; Sigounis & Athienitis, 2025). Colored BIPV via interference coatings, ceramic digital printing, and structural-color technologies is positioned as the bridge between energy generation and architectural expression, increasing acceptance (Zhou et al., 2024) but at a measurable efficiency cost (Li et al., 2025). The literature remains dominated by manufacturers and engineers, rarely isolating the decision logic of colored BIPV and the perspectives of architects who specify it. This gap is sharpened in Türkiye, where an immature market, high costs, and an evolving regulatory environment that collectively impact its integration. This study addresses that gap by investigating how architects assess colored BIPV across multiple decision scales.

02 Research Aim

The Architects' Assessment

The research aim is to investigate how architects across different subsectors evaluate and make decisions about colored Building-Integrated Photovoltaics (BIPV), thereby foregrounding the architectural profession's perspective, currently underrepresented in the literature, dominated by manufacturers and energy engineers on the adoption of these systems within the building envelope.

03 Research Question & Objective

Q: How do architects positioned across different subsectors in Turkish building sector assess and make decisions about colored BIPV across multiple decision scales, and what factors shape their willingness to adopt these systems within the building envelope?
O: The main objective is to foreground the architectural perspective on colored BIPV adoption by identifying the decision drivers that shape architects' evaluations across different subsectors of the Turkish building sector, examined through three thematic clusters: product attributes, systemic constraints, and contextual determinants.

03 Methodology

A Qualitative Study

03.1 Data

This research is based on 22 semi-structured interviews with architects operating across different subsectors. Participants were drawn from six segments: architecture offices (11 interviews), academia (4 interviews), facade manufacturers and suppliers (3 interviews), NGOs (2 interviews), facade consultancy (1 interview), and the public sector (1 interview).

Architecture Office	Academia	Manufacturer/-Supplier	NGOs	Façade Const.	Public Sector
11 interviews 357 units	4 interviews 118 units	3 interviews 95 units	2 interviews 49 units	1 interview 26 units	1 interview 22 units

03.2 Coding Scheme

The analysis followed a two-cycle coding procedure (Saldaña, 2021). In the first cycle, respondent meaning units were assigned by meaning to one of six categories (M1–M6) and thirty-five sub-categories. In the second, more analytical cycle, these sub-categories were consolidated via a fixed crosswalk into 13 sub-themes and 3 main themes, consistent with Saldaña's codes-to-theory progression. Coding was governed by a fixed codebook (v1.0) developed in line with MacQueen et al. (1998), in which each code carried an explicit definition and inclusion/exclusion criteria to ensure consistent application.

First Cycle / Descriptive — Second Cycle / Analytical

22 Interviews → **677** Coded Units → **6** Categories (M1-M6) → **35** Sub-Categories → **13** Sub-Themes → **3** Themes

Categories		Sub-Categories
M1	Technical Performance	1.1. Orientation, shading solar access / 1.2. Energy yield modeling & literacy / 1.3 Electrical integration / 1.4. Fire, heat & ventilation, safety / 1.5. Durability, degradation, maintenance
M2	Building System & Tectonic	2.1. Early design integration vs add-on / 2.2. Module dimensioning & sizing / 2.3. Compatibility with adjacent materials / 2.4. Façade, glass, structural detailing
M3	Chromatic & Aesthetic	3.1. Color palette preferences / 3.2. Chromatic performance / 3.3. Efficiency trade-off awareness / 3.4. Design flexibility (pattern,form) / 3.5. Visual comfort, glare and daylight
M4	Applications, Typology & Urban	4.1. Façade, spandrel, opaque envelope / 4.2. Roof, skylight, canopy, sunshade / 4.3. Commercial, public typologies / 4.4. Housing, residential constraints / 4.5. Heritage, religious & traditional / 4.6. Retrofit & renovation / 4.7. Urban scale & heat-island / 4.8. Public, landmark catalysts
M5	Regulation, Certification & Ecosystem	5.1. Building & energy regulations, codes / 5.2. Regulatory ambiguity & uncertainty / 5.3. Green certifications & declarations / 5.4. Public policy, incentives & financing / 5.5. Testing, warranty & service network / 5.6. Cross-disciplinary value chain
M6	Economics, Market & Acceptance	6.1. Initial investment, upfront cost / 6.2. Payback & feasibility / 6.3. Market availability & maturity / 6.4. Scale & project type economics / 6.5. Sustainability as design responsibility / 6.6. Education, awareness & demonstration / 6.7. Collective, sectoral awareness

03.3 Procedure

Each meaning unit received a single primary code, preserving one-to-one traceability between quote and code. Double-coding occurred in 0% of cases, well within the protocol limit of ≤10%. The complete corpus comprised 667 coded units. The full sub-category-to-theme crosswalk is presented.- Fig. 5.

04 Results

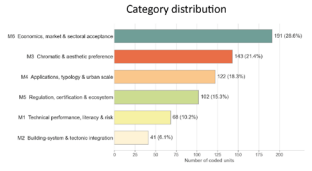


Fig.01 - Category distribution (initial phase), 667 units. M6 Economics 191 (28.6%), M3 Chromatic/aesthetic 143 (21.4%), M4 Applications/typology 122 (18.3%), M5 Regulation/ecosystem 102 (15.3%), M1 Technical 68 (10.2%), M2 Tectonic 41 (6.1%).

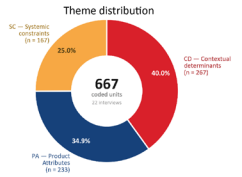


Fig.02 - Three main themes. Contextual determinants 40.0% (n=267). Product attributes 34.9 % (n=233). Systematic constraints 25.0 % (n=167).

Main Theme Emphasis Differs by Participant Segment

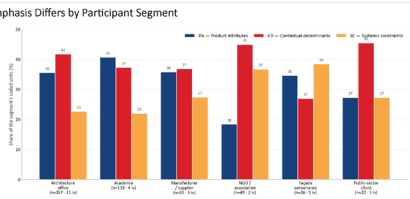


Fig.03 - Main theme emphasis by participant segment. Academia foregrounds product attributes (PA 41%, CD 37%, SC 22%); NGO the least on product attributes (PA 18%, CD 45%, SC 37%); Façade consultancy weights systemic constraints most (PA 35%, CD 27%, SC 38%); Architecture office shows CD leaning (PA 36%, CD 42%, SC 23%).

Findings

Color & Application Preferences

Grey and mineral/earth/terracotta tones represent the primary preferences, framed as a timeless, low-risk, and architect-approved palette. Among chromatic options, blue emerged as the leading preference, followed by yellow, green, orange, and pink. A distinct minority favored vivid colors predominantly by manufacturers, alongside a widespread demand for a broader, curated color palette.
Coloured PV was overwhelmingly placed on the façade: opaque, spandrel, and blind-wall surfaces, framed as a direct replacement for cladding materials. The roof was seen as most practical for yield, but its colour is wasted where it can't be seen reinforcing that a coloured product's value lands on the visible façade. A smaller shading potential also appeared: coloured PV as sun-shades, brise-soleil, and canopies that generate power while controlling solar gain.

04 Results

Analysis of Architects' Preferences

Sub-Category Groundedness: Prevalence x Frequency

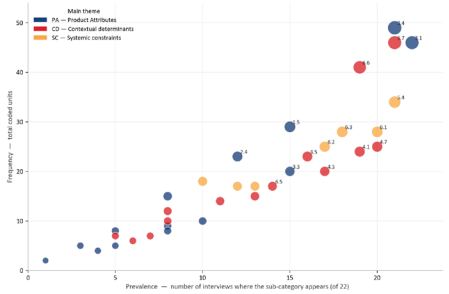


Fig.04 - Sub-category groundedness: prevalence x frequency. Each bubble is one of the 35 sub-categories, plotted by how widely it appears (x = interviews, of 22) against how often it was coded (y = units; bubble size also = frequency); colour = main theme. Frequency tracks prevalence (tight diagonal, empty top-left), so the heavy codes: 3.4 design flexibility, 3.1 colour palette, 6.7 collective awareness, 6.6 demonstration, 5.4 incentives are genuinely

Illustrative Quotes

What Architects Say

Product-related

> *"Colors, I think, will be something that expands the architect's playground there too. Whereas before we were confined to a few colors, we'll become able to create somewhat more varied compositions."*

> *"BIPV... it's also a system that needs servicing on the maintenance and repair side... there needs to be a service network that operates throughout the building's lifespan... Your product, the parts you use, the system must pass certain certifications, have certain tests done... installation, mounting, anchoring...all of these also need to be fully worked out, certified, and tested."*

System-related

> *"In the long run, something whose extra cost really isn't that high... that's exactly what sustainability means anyway. I mean, the fact that its continuity can be ensured... I would expect it to be something that works without a drop in efficiency, and that yields returns for many years."*

> *"They need to come before the public with some statistics and say... we're making this mandatory... A certain amount being made law... Even law alone doesn't work, in fact. This needs to be incentivized... tax exemption or a floor-area-ratio increase. A reward mechanism... like, 'I'm giving you credit.'"*

Context-related

> *"When a new material comes out... if one architect were using it and other architects saw it from that architect, and it aligned with their aesthetic sensibilities... I think it would spread... once it enters that trend, I think it will happen."*

> *"Schools especially are very important. I mean, if they applied these to schools, and explained it to students too, raised their awareness... schools are buildings used during the day, active during the hours when the sun is shining... structures that can directly use the electricity they generate at that very moment."*

Factors, Shaping Colored-BIPV Adoption: Category - Sub-Category - Main Theme

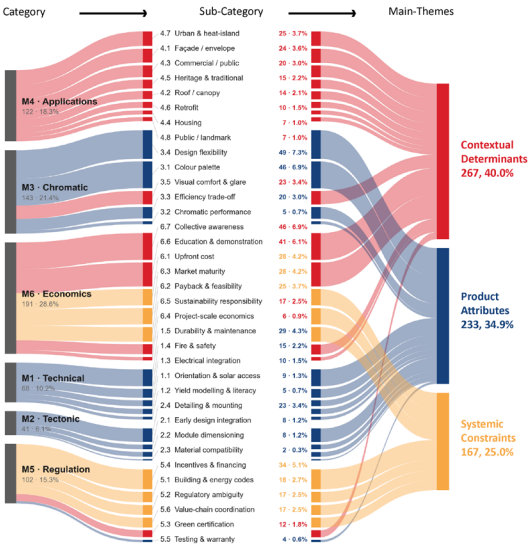


Fig.05 - Factors shaping coloured-BIPV adoption. Three-stage flow of 667 coded units (22 interviews) from six categories. (M1–M6) through 35 sub-categories to three themes. Contextual determinants (40%), Product attributes (35%), Systemic constraints (25%).

05 Discussions

Architects as Gatekeepers of Colored BIPV Adoption

The findings suggest that acceptance of colored BIPV is shaped less by overt resistance and more by a structured set of conditions. These are analyzed through a three-level lens (PA, SC, CD), offered as an interpretive overlay rather than a tested causal model, given the parallel and overlapping boundaries of the themes.

Product Attributes (PA)
Whether the R&D product itself is acceptable to architects? Color fidelity, design flexibility, yield, tectonic fit, durability and lifecycle.

Systematic Constraints (SC)
Whether the enabling conditions permit adoption? Regulation, incentives cost, payback, and market maturity.

Contextual Determinants (CD)
Where, for whom, and with what awareness does it actually get specified? Building type, urban fit, collective/sectoral disposition.

06 Conclusion

A Three-Level Action Framework

To unlock the potential of colored BIPV, the industry must shift its focus away from public pushback and tackle the true bottleneck: professional acceptance and market readiness. Scaling this technology requires a synchronized push across three fronts, zeroing in on the exact practical concerns architects and builders care about most:

- Product & Palette: Expanding color palettes and maximizing design flexibility to meet strict aesthetic standards without sacrificing efficiency.
- Enabling Conditions: Driving down upfront cost and securing clear financial incentives to make projects financially viable.
- Contextual Fit: Building industry awareness, education and trust through high-visibility demonstration projects that prove the technology works in the real world.

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Keywords: architectural decision-making, building envelope, colored BIPV, social acceptance criteria

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Developing Sub-micron Pyramidal Texturing Approach on Large Area for Next-Generation Perovskite/Silicon Tandem Cells

İrem Nur Manaz[1*], Bülent Arıkan[1], Furkan Çiçek[1], İlkcan Erdem[1] and Raşit Turan[1,2]

[1] ODTU-GUNAM, Middle East Technical University Ankara, Turkiye
[2]Middle East Technical University, Ankara, Turkiye
irem.manaz@odtugunam.org

Motivation

The transition to next-generation Perovskite/Silicon tandem and HJT cells requires advanced surface engineering to surpass the limits of conventional solar technology. Conventional texturing methods can lead to coating issues in sensitive thin-film layers and cause electrical shunting due to micron-sized pyramid structures. The sub-micron morphology proposed in this study is specifically designed for advanced architectures such as perovskite/silicon tandem cells, aiming to minimize shunt formation by enabling improved conformal coverage of thin-film layers.
This study is motivated by the need for:

•**Enhanced Compatibility:** Developing sub-micron morphology to ensure superior layer deposition and reduced surface recombination.

•**Process Optimization:** Creating a stable, controlled texturing window and post-treatment to refine pyramid tips.

•**Industrial Scalability:** Utilizing cost-effective, industry-proven chemicals for high-efficiency production on large-area wafers.

•**Sustainability:** Optimizing chemical utilization to provide a more eco friendly route for high-efficiency silicon solar cell manufacturing.

Experimental Methodology

1. Substrate and Pre-SDE Stage

•**Pre-treatment:** All processes were initiated with a standardized Pre-SDE (Saw Damage Etching) stage.

•**Conditions:** Wafers were immersed in a KOH solution at 80°C for 1 minute.

•**Cleaning:** This initial step was followed by a dedicated acidic cleaning and drying sequence.



•For the main texturing step, three different KOH-based recipes (with additives) were evaluated:

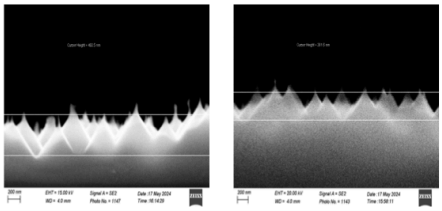
Recipe	KOH Concentration	Temperature	Time	Additive
R1	0.40%	80°C	7 minutes	x
R2	0.50%	75°C	5 minutes	x
R3	1%	70°C	5 minutes	2x

To reduce the sharp tips of the pyramidal structures, two different post-treatment methods were tested on the optimized surface. This post-treatment step was applied to the third recipe, which showed the best performance.

•KOH-based Etching: Exposure to a KOH-containing solution at 28°C for varying durations (15, 25, 50, 75, and 100 seconds).

•O_3- oxidation-HF Method: A cyclic process involving an ozone O_3 oxidation step followed by an HF bath to strip the oxide layer.

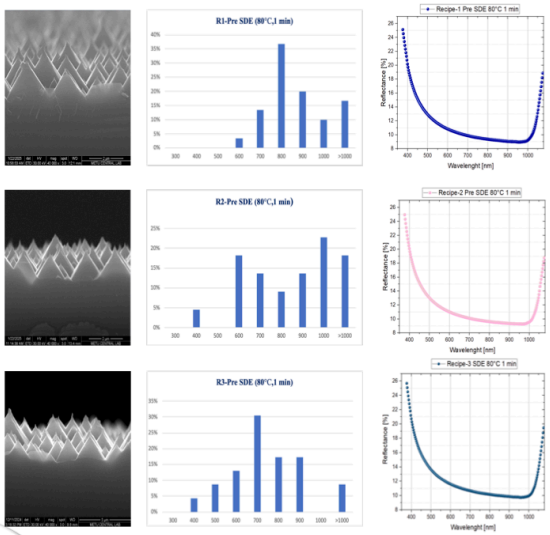
•Number of cycling: This sequence was repeated for 1, 2, 3, and 5 cycles to achieve progressive tip reduction.



Results

1. Morphology & Size Distribution

- All experiments were performed on an industrial-scale wet bench. Among the three texturing recipes, **Recipe 3** produced the most uniform pyramidal morphology with a narrow, unimodal size distribution (700–800 nm) and low reflectance. SEM images, pyramid size distribution, and reflection analysis graphs are shown below ((a),(b),(c)), respectively.

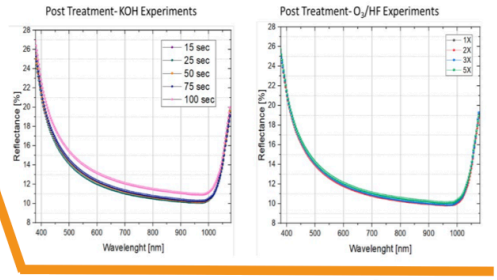


(a) (b) (c)

2. Post-Treatment & Tip Rounding

- A **post-treatment step** was applied to reduce sharp pyramid tips. **O_3/HF cycling** outperformed KOH etching, effectively rounding tips without deforming the pyramids. The most significant tip reduction was observed at **5 cycles**, while maintaining stable reflectance.

- Overall, the combination of **Recipe 3 texturing** and **5× O_3/HF post-treatment** provided the best morphology and optical performance.



Conclusion

•Successful Demonstration: A reliable, industrial-scale sub-micron texturing method was successfully developed.

•Process Synergy: The combination of Recipe 3 and 5x O_3-HF cycling yielded the most homogeneous morphology and effective tip rounding.

•Performance: O_3-HF post-treatment outperformed KOH etching by removing sharp tops without compromising optical reflectance.

•Future Work: Ongoing studies focus on measuring the electronic impact, passivation quality (iVoc, lifetime), and thin-film coating compatibility.

Contact Information:
İrem Nur Manaz
Center for Solar Energy Research and Application (ODTU-GUNAM)
irem.manaz@odtugunam.org

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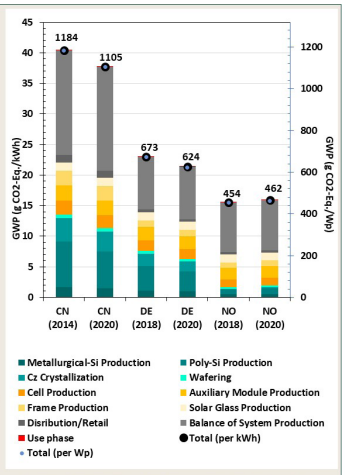
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Optimising Solar PV Resource Efficiency and Sustainability

Karl-Anders Weiß, Estelle Gervais, Sina Herceg, Yijiang Xu, Elsen Aydin, Alexis Barrou,
Claire Agraffeil, José María Medianero Martín, Tayfun Hiz, Alessandro Virtuani

Motivation

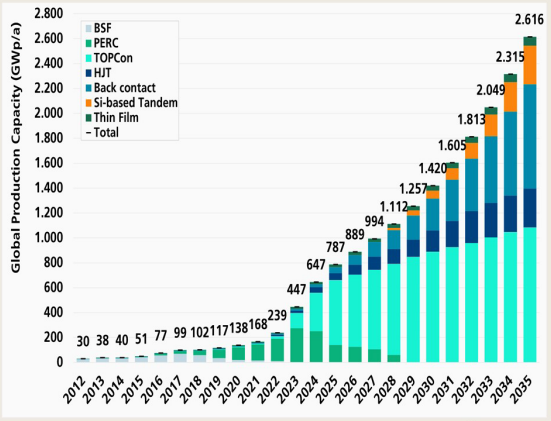
- Photovoltaics expected to be the main pillar of the future global energy system by 2050.
- Strengthening circularity in PV is key to reducing the EU's energy dependency and enhancing supply resilience.
- Growing PV deployment increases the responsibility for resource efficiency over future decades.



Global Warming Potential (GWP) of PERC PV system by location and year of net electricity mix [1]

Objectives

- Provide an **open-access PV data repository** for sustainability assessments.
- Create a **web-based PV scenario analysis tool** for environmental impacts, material use, supply risks and circularity potential.
- Develop lifecycle-based **guidelines and EU circularity roadmap**.
- Deliver **policy recommendations** to support decision-making.
- Support **PV stakeholder networking** and data/knowledge exchange.



Global PV Production Capacity per Cell Technology [2]

Methodology

- Collect PV **LCI data for all relevant PV technologies, value stages and market scenarios.**
- Create a **web-based tool** to investigate PV LCA, circularity and supply risks.
- Build **market development scenarios**.
- Engage PV stakeholders via **Expert Groups** and **Industrial Advisory Board**.

Stakeholder Involvement

- **Expert Group**
  - Provides technical and methodological input
  - Supports validation of results
- **Industrial Advisory Board**
  - Ensures market relevance and policy alignment
- **Stakeholder Group**
  - Receives newsletters on SOLARIS progress and events.

Scan the QR Code to register and participate in different groups!

Scenario Analysis Tool

- Interactive web tool **comparing PV technologies** across environmental, supply risk, cost and circularity aspects.
- **Parametric "what-if" analysis** beyond static LCA databases.
- Exportable **PV LCI data** and analysis results.
- Fully **open stack** enabling transparent, open-access results.

Conclusion

SOLARIS will support the PV sector by:

- **Collecting** and distributing relevant **data** for LCA
- **Connecting people** and stakeholders
- Providing **recommendations** and **open-access tools** for a sustainable European and Global PV industry

SOLARIS Sustainability Workshops

Join our network on PV sustainability and contribute to the exchange of research, industry, and policy insights.
Share your perspectives in interactive workshops and training sessions.

Next Workshop:
28 April 2027
In Türkiye

Contact

Dr. Karl-Anders Weiß
Dr. Estelle Gervais
Fraunhofer Institute for Solar Energy Systems ISE
info@solaris-project.eu
https://www.solaris-project.eu/

Link to Project Website

1 Khan et al. (2023). Sensitivity of Global Warming Potential of PERC Solar System to Production Electricity Mix, Installation Location and System Lifetime (EUPVSEC).

2 Based on ITRPV (2025): 2024 Results, 16. Edition, and SolarPower Europe (2024): Global Market Outlook for Solar Power 2024 – 2028 (High Scenario).

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Novel Dye-Sensitized Solar Cell Architecture Based on Er-Doped TiO_2 Nanorods and Pt/Pd Catalytic Counter Electrodes

S. Kaya[1*], T. Çetinkaya[2,3,4,5]

[1]Central Research Laboratory, Kastamonu University, 37100, Kastamonu, Turkiye

ORCID: https://orcid.org/0000-0002-6894-9082

[2]Department of Metallurgical and Materials Engineering, Engineering Faculty, Sakarya University, Esentepe, Sakarya, 54050, Turkiye

[3]Research, Development and Application Center (SARGEM), Sakarya University, Esentepe, Sakarya, 54050, Turkiye

[4]NESSTEC Energy & Surface Technology Inc., Technology Development Zones, Sakarya University, Esentepe, Sakarya, 54050, Turkiye

[5]Nanotechnology Centre, CEET, VŠB -Technical University of Ostrava, Ostrava, Poruba, Czech Republic

ORCID: https://orcid.org/0000-0001-7509-8856

*Corresponding Author's E-mail: seydanurkaya@kastamonu.edu.tr

Abstract

This study presents a novel DSSC architecture employing vertically aligned Er-doped TiO_2 nanorods grown directly on FTO substrates and Pt/Pd catalytic counter electrodes prepared by sputtering. Er incorporation improved the nanorod morphology, reducing the average diameter from 73 to 38 nm and the surface roughness from 36.6 to 28 nm, while producing a more homogeneous film structure. Optical measurements showed enhanced visible-light transmittance and a reduced band gap from 3.21 to 3.09 eV. Pt/Pd counter electrodes with different deposition times were investigated, and thicker coatings (120–150 s) exhibited superior photovoltaic performance, resulting in higher fill factor and open-circuit voltage values.

Photoanode preparation

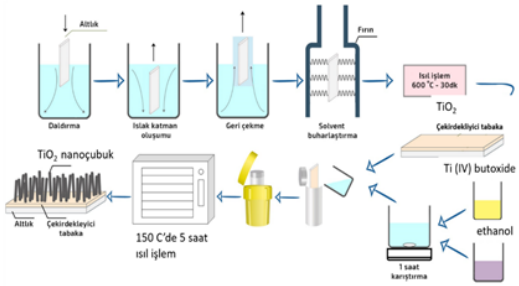


Figure 1. Fabrication process of Er-doped TiO_2 nanorod photoanodes.

Structural and Morphological Analysis

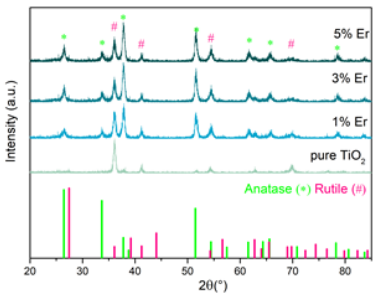


Figure 2. XRD patterns of pure and Er-doped TiO_2 nanorods showing anatase (*) and rutile (#) phases..

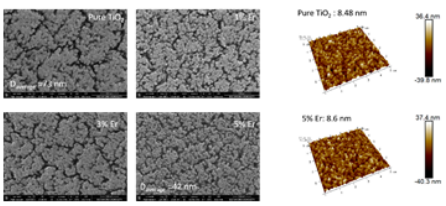


Figure 3. SEM micrographs of pure and Er-doped TiO_2 samples.

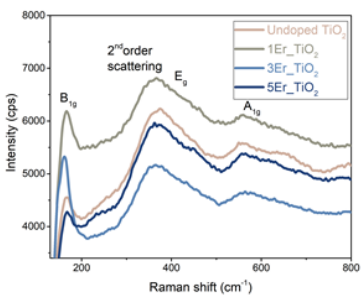


Figure 4. Raman spectra of undoped and Er-doped TiO_2 samples showing the characteristic B_1g, Eg, and A_1g vibrational modes of TiO_2

Photocathode preparation

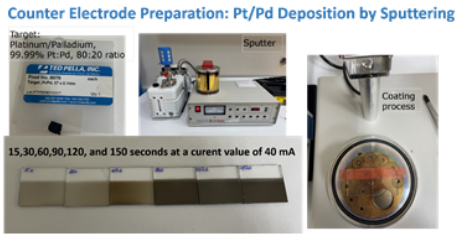


Figure 5. Fabrication of Pt/Pd counter electrodes by sputter deposition. Pt/Pd coatings were deposited on FTO substrates for 15–150 s at a sputtering current of 40 mA.

N719 Dye loading

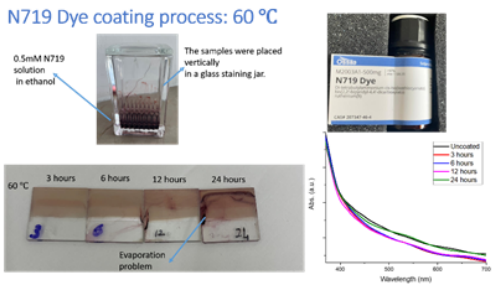


Figure 6. Photographs of TiO_2 electrodes sensitized with N719 dye at 60 °C for different immersion times and their corresponding UV–Vis absorption spectra.

DSSC device application

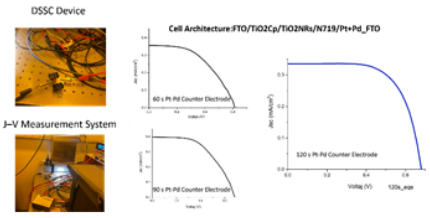


Figure 7. Fabricated DSSC device, J–V measurement setup, and photovoltaic performance of DSSCs employing Pt-Pd counter electrodes deposited for different sputtering times.

Conclusion

- Er doping improved TiO_2 nanorod morphology.
- Surface roughness decreased significantly.
- Enhanced visible light absorption was observed.
- Pt/Pd counter electrodes deposited for 120–150 s showed the best performance.
- Further efficiency improvement requires increased dye loading.

Acknowledgements

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PVCON 2026 5th International Conference on Photovoltaic Science and Technologies

An Innovative Business Model Approach: Cooperatives and Private Investors in Agrivoltaics

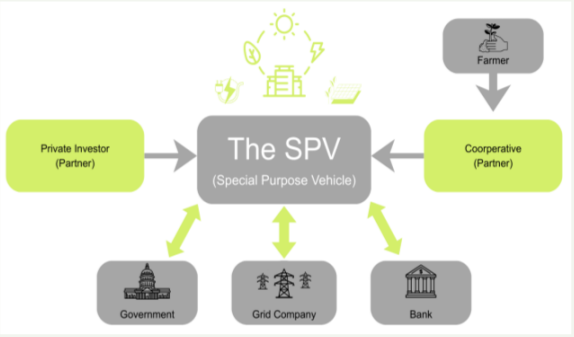
Dila AYERDEM [1,2], Azra Verda KOÇAK [1], Nazenin Miray ÇAKMAK [1]
[1] Middle East Technical University/ Economics, Ankara, Türkiye
[2] ODTÜ-GÜNAM, Ankara, Türkiye

Introduction

Globally, the intersection of sustainable energy and agriculture has emerged as a critical topic, leading to increased interest in and spread of agrivoltaic systems. This study aims to reduce the barriers to market entry for agrivoltaics by proposing a Special Purpose Vehicle (SPV) business model, which operates as an independent, newly established legal entity. The proposed SPV model is built on the traditional farming practices, while considering the dynamics of the current solar energy market. Taking the identified barriers to agrivoltaic investments into account, we argue that an SPV-based business model offers significant advantages.

The suggested SPV model is a viable pathway to reduce operational costs and facilitate compliance with the energy and agricultural regulations. To minimize financial risks in investments and establish a secure institutional framework, the model suggests a strategic partnership in which agricultural cooperatives and energy corporations serve as the core executing parties.

The SPV business model for agrivoltaic practices



Methodology

Literature Review	Case Study
SPVs usage and investment capacity for agrivoltaics	Scenario-based integration in a Turkish vineyard

Research Design: The analysis adopts a multi-dimensional framework: financial dimension, technical dimension, and legal dimension.

Case Study: In addition to the SPV business model, a simulation study was conducted to further evaluate the profitability of agrivoltaic systems for both farmers and investors.

As the reference crop, grapes were selected due to its compatible integration with agrivoltaic systems. Expense and income analysis of the agricultural production outputs were derived from a grape production analysis in Denizli, Türkiye (Kadakoğlu et al, 2025). Agrivoltaic performance estimates in this study were generated using the KU Leuven Agrivoltaics Web Tool. The tool simulates crop yield, light availability, and photovoltaic electricity production under different agrivoltaic configurations. Inputs related to the PV module (width, length, angle, power etc.) are referenced from a successfully implemented agrivoltaic vineyard study conducted in the Puglia region of Southern Italy (Magarelli et al, 2025). This methodology was followed in order to provide a comprehensive and realistic approach to the simulation.

The reduction in costs of agricultural production was argued under two headings. Firstly, the savings achieved from electricity use in irrigation as a result of the energy produced. Secondly, the saving in irrigation volume due to the shading effect. And together with the extra income from the sale of the excess electricity to the grid, the results of the simulation show that agrivoltaic systems promise significant increase in profits of the SPV company.

Analysis

The analysis focuses on the risk-mitigating and cost-reducing capacity of Special Purpose Vehicles (SPVs) within agrivoltaic systems.

Opportunities of SPV in Agrivoltaics

Risk Isolation and Diversification
The SPV ensures that any technical or financial failure in the solar infrastructure remains contained.

Eligible for Government Incentives
The SPV provides clear legal structure making it easier to access subsidies, grants, and tax benefits.

Lowering Financial Barriers
The collective pooling of assets, transforms a high-risk operation into a bankable project.

Boosting Local Solar Business
It creates a centralized counterparty that can sign long-term supply contracts with local solar businesses.

Promoting Social Equality
It enables traditionally marginalized groups to actively participate in and profit from the green energy transition.

Institutional Shield For Security
The SPV provides an institutional shield that protects individual investor and farmers.

Another point to be considered is that this study is subject to certain limitations at this stage. The limitations can be mainly stated as the analysis conducted by secondary data and findings may vary depending on country-specific regulatory frameworks and market conditions.

Challenges of SPV in Agrivoltaics

The Requirement for Expertise
It requires advanced operational experience and expertise.

Legal/Regulatory Challenges
Most countries do not have any framework for agrivoltaics and complex SPV structure yet.

Conclusion

Creating a sustainable market for **agrivoltaics (AgriPV)** requires lowering the barriers to entry faced by vulnerable agricultural segments. This study demonstrates that establishing a collaborative framework with cooperatives and private investors through a **Special Purpose Vehicle (SPV)**, promises long-term productivity. Through utilizing an SPV, farmers and investors can pool resources, reduce capital costs, and benefit from the risk isolation. The main focus of this study is maximizing investment capacity while creating opportunities for disadvantaged groups, specifically for women and young farmers. Ultimately, integrating social policy with financial models not only reduces the greenhouse gas (GHG) emissions but also secures rural development and food-energy security.

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Contact Us
verda.kocak@metu.edu.tr
dila.ayerdem@metu.edu.tr

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