VIPERLAB

FULLY CONNECTED VIRTUAL AND PHYSICAL PEROVSKITE PHOTOVOLTAICS LAB

DELIVERABLE REPORT

# D6.11 Final version of the Strategic Research and Innovation Agenda (SRIA) for European perovskite PV technology available

Version: 1.0
Date: 29.11.2024


# FULLY CONNECTED VIRTUAL AND PHYSICAL PEROVSKITE PHOTOVOLTAICS LAB VIPERLAB

## DELIVERABLE

# D6.11 FINAL VERSION OF THE STRATEGIC RESEARCH AND INNOVATION AGENDA (SRIA) FOR EUROPEAN PEROVSKITE PV TECHNOLOGY AVAILABLE

**Project References**

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|---|---|
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**DISCLAIMER**

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## EXECUTIVE SUMMARY

The VIPERLAB project has committed itself to establishing a Strategic Research and Innovation Agenda (SRIA) for single-junction perovskite PV via the organization of several strategic workshops and other types of interaction with all stakeholders. As starting point for the VIPERLAB SRIA, we took the chapter on single-junction perovskite PV from the recently published European Strategic Research and Innovation Agenda for Photovoltaics (EU SRIA-PV)[1], drafted in 2022 by ETIP-PV and EERA-PV. In this report, we describe the process how we drafted the VIPERLAB SRIA for perovskite single-junction PV technology, its content and its impact.

Central to the drafting of the VIPERLAB SRIA was the organisation of two workshops. The first strategic VIPERLAB workshop (D6.2) was organized in September 2022 as a parallel event to the WCPEC-8 conference in Milano, Italy. The approximate fifty attendees were mainly people belonging to the VIPERLAB stakeholder list, the VIPERLAB advisory board, the EERA-PV community, and the ETIP-PV community. This first workshop resulted in some clear recommendations to improve the content of the chapter on single-junction perovskite PV modules of the EU SRIA-PV document. Moreover, it resulted also in the redefinition of three Key Performance Indicators listed for 2030.

The second strategic VIPERLAB workshop was organized on the 22nd of March 2023 during the "Energy Conversion and Storage Days" event organized by the Karlsruhe Institute of Technology (KIT) in Karlsruhe, Germany. The attendees were mainly people belonging to the VIPERLAB stakeholder list, the VIPERLAB advisory board, the (Perovskite) PV and the storage technologies research communities. This second strategic workshop (D6.5) succeeded in the identification of clear steps towards the definition of a unified roadmap and the definition of specific timelines for the three KPIs of the SRIA on single-junction perovskite PV modules, identified in the first strategic workshop.

The results of these two workshops together with the perovskite-PV chapter of the EU SRIA-PV drafted by ETIP-PV and EERA-PV formed the basis of the VIPERLAB SRIA on single-junction perovskite PV. This VIPERLAB SRIA was further fine-tuned during the final year of the project via public consultations with stakeholders at various events. The finalized VIPERLAB SRIA was disseminated at the second public VIPERLAB event with industry and policy makers, which took place in Vienna in September 2024 at the EU-PVSEC, and at the third strategic VIPERLAB workshop, which took place in November 2024 as part of the BecomePV workshop in Brussels.

Finally, the VIPERLAB SRIA was fed back into the updated EU SRIA-PV in September 2024, a document that will be used as the basis for the co-programmed partnership on

[1] EU SRIA-PV: The full document can be downloaded here: https://media.etip-pv.eu/filer_public/85/68/8568e2ee-ad42-4198-8211-27b703e15e1a/sriapv-fullreport_web.pdf

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photovoltaics[2] that is being set up in Horizon Europe. This ensures the impact of our VIPERLAB SRIA on the definition of future funded PV project calls within Horizon Europe in the field of perovskite PV.

# 1. INTRODUCTION

As part of the perovskite community building work, the VIPERLAB project had set itself the goal of developing and streamlining a European Research Area in the field of perovskite PV technology. One of the tools for achieving this was the creation of a joint European Strategic Research and Innovation Agenda (SRIA) for perovskite PV technology that will be widely accepted and supported by the European PV industry and research community. The VIPERLAB project committed itself to establishing such a SRIA for perovskite PV by organizing several strategic workshops where various stakeholders came together with members of the VIPERLAB Consortium to work on such a SRIA.


Figure 1. Cover of the EU SRIA-PV document published by ETIP-PV and EERA-PV in May 2022.

At the start of the VIPERLAB project (June 2021), many of the consortium partners were involved in the drafting of the European Strategic Research and Innovation Agenda for Photovoltaics (EU SRIA-PV) by ETIP-PV and EERA-PV. This EU SRIA-PV document[3] was finalized after a public consultation and published in May 2022 (see Figure 1). It covers the whole range of photovoltaic science, technology, and applications in Europe, including but not limited to perovskite PV. The VIPERLAB consortium therefore decided to take the

[2] https://etip-pv.eu/events/other-events/the-new-european-ri-framework-for-pv-the-co-programmed-partnership-and-its-impact-on-the-strategic-ri-agenda-eupvsec24/#:~:text=The%20European%20Commission%20announced%20a,the%20European%20PV%20value%20chain.

[3] EU SRIA-PV: The full document (2022 version) can be downloaded here: https://media.etip-pv.eu/filer_public/85/68/8568e2ee-ad42-4198-8211-27b703e15e1a/sriapv-fullreport_web.pdf

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perovskite PV chapter of this EU SRIA-PV as the starting point for its own VIPERLAB SRIA for European perovskite PV technology. Moreover, the VIPERLAB consortium decided to focus its SRIA on single-junction perovskite PV technology.

Two workshops were organized in which the backbone of the VIPERLAB SRIA was defined.

## 2. OUTCOME OF WORKSHOP 1

The first strategic VIPERLAB workshop was organized in September 2022 as a parallel event to the WCPEC-8 conference in Milano, Italy[4]. The approximate fifty attendees were mainly people belonging to the VIPERLAB stakeholder list, the VIPERLAB advisory board, the EERA-PV community, and the ETIP-PV community. The program consisted of several introductory talks on the VIPERLAB project, the EU SRIA-PV document, and the outcome of a prior VIPERLAB workshop on harmonization/standardization challenges for perovskites. These talks were then followed with some discussions in parallel groups on the content of the perovskite single junction module chapter of the EU SRIA-PV.

| KPI | Target Value 2030 |
|---|---|
| LCOE (original) | LCOE of Pk-PV technology should be equal to or lower than that for c-Si |
| Efficiency (new) | Large-scale (> 1 m2) single-junction Pk-PV module demonstrators should be available with energy conversion efficiency above 23% |
| CO2 footprint (original) | The yield specific CO2 footprint of Pk-PV should be <80% of c-Si production and Pk-PV modules should be fully recyclable |
| CO2 footprint (remained) | The yield specific CO2 footprint of Pk-PV should be <80% of c-Si production and Pk-PV modules should be fully recyclable |
| Manufacturing (original) | Commercially available, Pk-based modules with an efficiency of > 23% |
| Manufacturing (modified) | Pk-based modules fully processed in Europe are commercially available and should comply with all European safety and toxicity rules across their whole life cycle |

Figure 2. The original KPI's for perovskite PV by 2030 in red (as taken from the EU SRIA-PV starting document) and the modified VIPERLAB KPI's in black.

The workshop resulted in some clear recommendations to improve the content of the chapter on single-junction perovskite PV modules of the EU SRIA-PV document. In

[4] First VIPERLAB strategic workshop: https://www.viperlab-kep.eu/workshop.asp?i=9&t=1st_Viperlab__SRIA_Strategic_Workshop

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particular, we redefined the Key Performance Indicators listed for 2030 (see Figure 2). It also became clear from this workshop that further work is needed to add a clear timeline and clear priorities to this EU-SRIA-PV document for single-junction perovskite module R&D and this became the focus of the second strategic workshop.

## 3. OUTCOME OF WORKSHOP 2

The second strategic VIPERLAB workshop was organized on the 22nd of March 2023 during the "Energy Conversion and Storage Days" event organized by the Karlsruhe Institute of Technology (KIT) in Karlsruhe, Germany[5]. Similarly, as the first workshop, this second workshop encouraged in-person attendance to perform round table discussions in small groups. In addition, a few participants attended the workshop virtually. In total around thirty-five people attended “in-person” and “online”. The audience consisted of people belonging to the VIPERLAB stakeholder list, the VIPERLAB advisory board, the (Perovskite) PV and the storage technologies research communities.

This second strategic workshop was a follow-up of the first strategic workshop (summarized above) and focused on the drafting of a roadmap and timeline to achieve the three identified KPIs for single-junction Pk-PV by 2030 as defined in the first strategic workshop.

The workshop succeeded in enabling the identification of clear steps towards the definition of a unified roadmap and specific timelines for the three identified KPIs of the SRIA on single-junction perovskite PV modules.

The outcome of the discussions in the break-out groups is summarized in this part. We divided the audience into three groups, each group focusing on defining a clear roadmap and timeline starting their discussion with one of the three identified KPIs of the SRIA (see Figure 2).

### 3.1 Large-scale demonstrators with efficiency > 23%

In this KPI, modules with stable efficiency above 23% on at least 1 $m^2$ area need to be established by 2030. Currently, large-area modules with 17-18% and small modules with 23% have been demonstrated, so this KPI seems feasible by 2030. However, one potential bottleneck might be that most perovskite-oriented companies in Europe are currently focused on tandem devices (e.g. Oxford PV).

The main challenge was defined as finding the right technology to perform a homogeneous large-area deposition which will be needed to achieve high efficiencies on large area. There are potentially several industrially viable technologies for this such as inkjet printing, slot-die

[5] Second VIPERLAB strategic workshop: https://www.viperlab-kep.eu/workshop.asp?i=24&t=VIPERLAB_roadmapping_workshop_for_perovskite_PV_technology_development_and_harmonization_in_Europe

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coating, evaporation with linear sources, pulsed laser deposition for inorganic compounds, etc.

Therefore, a major intermediate goal that needs to be achieved before 2027 is to identify which of these large area deposition techniques can provide the required homogeneous growth of the perovskite PV layers on large areas. If no technique can be found for this, the back-up option will be to switch to cell-to-module fabrication for single-junction perovskite PV by growing the perovskite cell structures on smaller areas instead of directly at the module level size. This “plan B” would likely benefit from advancements in perovskite-on-silicon tandem technology.

Another point that should be carefully investigated is the stability of single-junction perovskite devices compared to tandem devices. Especially the reverse bias problems for single-junction perovskite might be more difficult to control.

Tool manufacturers in Europe will need to be involved from an early stage to ensure that we have suitable manufacturing tools for the emerging European PV perovskite industry that can enable manufacturing perovskite modules with efficiencies >23% reproducibly. The efficiency and size-related milestones were defined to enable reaching this KPI by 2030 (see Figure 3).

<table>
<tr><th>Year</th><th>Dimensions</th><th>Performance</th><th>Stability</th><th>Manufacturing</th></tr>
<tr><td>2023</td><td>2025 cm$^2$</td><td rowspan="3">18 % (mpp)</td><td></td><td rowspan="2">Focus on intrinsically scalable fabrication methods</td></tr>
<tr><td>2024</td><td rowspan="3">20 cm$^2$ x 20 cm$^2$ mini module</td><td>> 1000 hrs stability (based on $T_{80}$) demonstrated at:<ul><li>85%rh/85°C</li><li>1sun/65°C</li></ul></td></tr>
<tr><td>2025</td><td>20 % (mpp)</td><td rowspan="2">Demonstration of 1-year outdoor performance</td><td rowspan="2">Manufactured with scalable processes using green solvents</td></tr>
<tr><td>2026</td><td rowspan="2">22 % (mpp</td></tr>
<tr><td>2027</td><td rowspan="4">> 1 m$^2$ Module</td><td rowspan="3">23 % (mpp)</td><td rowspan="2">Ready for demonstration of 3-year lifetime</td></tr>
<tr><td>2028</td><td rowspan="2">Green manufacturing strategy for 1 m$^2$ module mass-production identified</td></tr>
<tr><td>2029</td><td rowspan="2">Demonstrated 3 yrs outdoor lifetime</td></tr>
<tr><td>2030</td><td></td></tr>
</table>

Figure 3. Efficiency and size-related milestones to enable reaching large-scale demonstrators with efficiency > 23% by 2030.

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### 3.2 $CO_2$ footprint smaller <80% of Si and fully recyclable

The following questions were identified that need to be answered in the SRIA for this KPI:
- Production: Should the $CO_2$ footprint be compared to c-Si fabricated in Europe or anywhere in the world?
- Production: What do current calculations/estimations take into account? Energy mix/source of the place of fabrication?
- Operation: How to factor in and reliably estimate the operational lifetime of perovskite PV?
- Recycling: Are there established recycling strategies? Who would be the recyclers, manufacturing industry or third parties? What are the incitements for recycling (toxicity but no significant monetary gain)? Will the industry have to come up with a "closed cycle" like the case of CdTe (FirstSolar)?

The following steps were identified that we can do within VIPERLAB to increase the success of reaching this KPI by 2030:

- **Step 1: Establish "state of knowledge"**
  Together with LCA experts (WP10) establish the current "state" of $CO_2$ footprint (and LCA) analysis and define the potential "lack of information" and needs for better estimation of CO2 footprint. What is the current state of knowledge?
  Recycling: here we might need to do an independent literature search and probably also reach out to Perovskite PV manufacturers to ask whether they consider this.

*Question: How can LCA become a more integral part of the research process?*
  - Initiate/prepare educational resources from WP10 as a starting point for more widespread education of PV scientists in LCA methodology.

- **Step 2: Define a "question catalogue"** regarding KPIs for Pk-PV defined in the SRIA to reach out to different stake-holders - especially industry - to gather more information.

- **Step 3: Define activities and resources that can be pushed/developed through VIPERLAB** that can contribute to enabling reaching and assessing the feasibilities of the KPIs.
  - Educational resources on KEP on LCA
  - JRAs of VIPERLAB generating output that can be collected/disseminated
  - Data infrastructure capturing full manufacturing, operation, and recycling potential of Pk-PV for better LCA

- **Step 4: Updated SRIA is ready by end of the VIPERLAB project** & identify strategy & stakeholders that can promote and continue to support the roadmap to ensure the Pk-PV KPIs get reached by 2030.

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| Year | $CO_2$ footprint | Recyclability |
|---|---|---|
| 2023 | In collaboration with WP 10 of VIPERLAB: Compare LCA methods and difference in input parameters on predicted $CO_2$ footprint of Pk-PV compared to Si; define strategy to do reliable $CO_2$ footprint analysis including different global and regional scenarios. | Identify state-of-the art of recycling approached for Pk-PV and need for critical recycling steps |
| 2024 | By end of VIPERLAB: $CO_2$ footprint of Perovskite PV compared to competing technologies identified | By end of VIPERLAB: Needs, requirements and opportunities for module recycling identified |
| 2025<br>2026<br>2027<br>2028<br>2029<br>2030 | *Set target for $CO_2$ footprint of Pk-PV to be < 80% of Si will influence manufacturing approaches as well as required operational performance and lifetime of Pk-PV including end-of-life recycling.* | *Recycling concepts will be likely developed further by industry; yet unclear, which industry will be taking care of this; options are:*<br>*- Module manufacturers*<br>*- Recycling companies for other electronic devices*<br>*- New specialized companies* |

Figure 4. Yearly steps suggested to reach the milestone "$CO_2$ footprint smaller <80% of Si and fully recyclable".

### 3.3 Commercially available modules fully processed in Europe

By 2023/2024 a report on toxicity requirements and rules for perovskite PV should be published by the EC and this report should clearly state whether Pb is or will be allowed in PV Modules in Europe in the future. This will be crucial to determine the technology route of the perovskite-based PV technologies. More research is needed on toxicity issues and here VIPERLAB can help by updating the White paper on Pk-PV that was published in 2019 by EPKI[6]. Lead-free Pk modules are unlikely to be able to fulfil the "Commercially available modules fully processed in Europe" KPI by 2030. Therefore, public opinion is very important,

[6] https://epki.eu/

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and the PV community needs to make sure that there is sufficient acceptance for a Pb-based product. We need a clear communication strategy for the advantages of the technology.
In-line Quality Control tools are required to achieve this KPI. An important question that needs to be addressed is how to better exploit synergies with tandem Si/PSK cells and modules.

| Year | Toxicity | Deployment strategy |
|---|---|---|
| 2023 | Collect information on toxicity concerns and potential mitigation strategies | Develop unified communication strategies and initiatives to assess societal acceptance of Pb-based PV product development |
| 2024 | By end of VIPERLAB: Updating the White paper on Pk-PV that was published in 2019 by EPKI[7] including definition of measures to mitigate risks of Pb-based PV technology and development of societal acceptable perovskite PV products differentiating use cases. | |
| 2025 | *In case no alternative "Pb-free" materials identified, industrial deployment and large-scale utilization will depend on:*<br>*- Product safety (Pb-leakage mitigation strategies)*<br>*- use case (large-scale PV installations vs consumer products, space PV etc. …)*<br>*- end of life recycling strategies* | |
| 2026 | | |
| 2027 | | |
| 2028 | | |
| 2029 | | |
| 2030 | | |

Figure 5. Yearly steps suggested to reach the milestone the "Commercially available modules fully processed in Europe".

## 4. HARMONIZATION / STANDARDIZATION RECOMMENDATIONS

In WP4 of the VIPERLAB project, a set of recommendations for harmonization and standardization of perovskite PV technology was developed. These recommendations were also incorporated into the VIPERLAB SRIA and are listed in this section. Besides recommendations for single-junction perovskite PV, there are also recommendations for perovskite-based tandem PVs.

### 1. Development of Tailored Testing Standards

Perovskite PVs exhibit distinct properties such as ionic conductivity and environmental sensitivity, which existing silicon-based standards, like IEC 61215, fail to adequately address. To ensure reliable evaluation, testing protocols should account for:

[7] https://epki.eu/

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- Material-specific degradation: Mechanisms such as ion migration, delamination, and photochemical instability require unique stress tests under controlled humidity, temperature, and UV light exposure.
- New device architectures: Tandem perovskite-silicon PVs and other emerging designs necessitate revised testing frameworks to accurately measure performance and stability.
- Specialized or new applications: Perovskite-based PV technologies exhibit high potential for specific applications like vehicle-integrated photovoltaics (VIPV), consumer applications or product-integrated PV (PIPV) or building-integrated PV (BIPV) that may need adapted or even specific validation requirements.

### 2. Harmonization of Measurement Protocols

A critical bottleneck in perovskite PV research and commercialization is the lack of consistent measurement and reporting protocols. Divergent practices lead to variability in reported data, hampering comparability across studies and creating market uncertainty. VIPERLAB therefore recommends to:

- Establish uniform efficiency measurement methods tailored to tandem cells, such as spectral matching and multi-lamp sun simulation for accurate current-voltage (I-V) assessments.
- Use streamlined formats for reporting key metrics like open-circuit voltage (Voc), short-circuit current (Isc), and power conversion efficiency (PCE), beyond the raw I-V curves traditionally used.

### 3. Stability and Durability Testing

Perovskite PV cells and modules face unique stability challenges, including degradation from environmental exposure to moisture, oxygen, and temperature cycling. To enhance product durability and market confidence, VIPERLAB recommends:

- Developing aging protocols that simulate long-term operational conditions in diverse climates.
- Investigating novel encapsulation materials and techniques to protect perovskites without compromising performance.

### 4. Scaling Manufacturing Processes

The scalability of perovskite PVs remains a major challenge as current laboratory processes must transition to industrial-scale manufacturing. Issues include:

- Reproducibility: Ensuring uniform material quality and consistent device performance across large device geometries (modules) and/ or production batches.
- Manufacturing methods: Adapting scalable techniques like roll-to-roll coating and inkjet printing to perovskite fabrication while maintaining high efficiency.
- Environmental sustainability: Mitigating concerns about lead usage through recycling frameworks and exploring non-toxic alternatives.
- Collaboration: between research, industry stakeholders and standardization bodies to integrate scalable solutions into the standardization landscape.

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**5. Toxicity and Environmental Impact**

The presence of lead in many perovskite formulations raises environmental and health concerns, which may need to be addressed to align with global sustainability goals. Depending on possible lead leaking concerns or (adapted) regulations, VIPERLAB advocates for:

- Development of recycling and waste management protocols for perovskite modules.
- Research into lead-free perovskite materials and their performance optimization.

**6. Engagement with International Standards Bodies**

VIPERLAB has established a strong collaboration with key standards organizations, including IEC and ISOS, to integrate its findings into global frameworks. Specific actions include:

- Contributions to IEC Technical Committees 82 (and possibly 113) to develop guidelines for metastable PV devices.
- Enhancing ISOS protocols to address unique testing requirements for perovskite modules, such as advanced maximum power point tracking (MPP) and spectral response analysis for tandem devices.

**7. Community Building and Knowledge Dissemination**

VIPERLAB has organized strategic workshops and webinars to foster collaboration among stakeholders from academia, industry, and policy. These events have identified actionable recommendations for harmonization and showcased advancements in protocols and testing methodologies, and should therefore be continued, i.e. in a follow-up project, the upcoming partnership or the EERA environment.

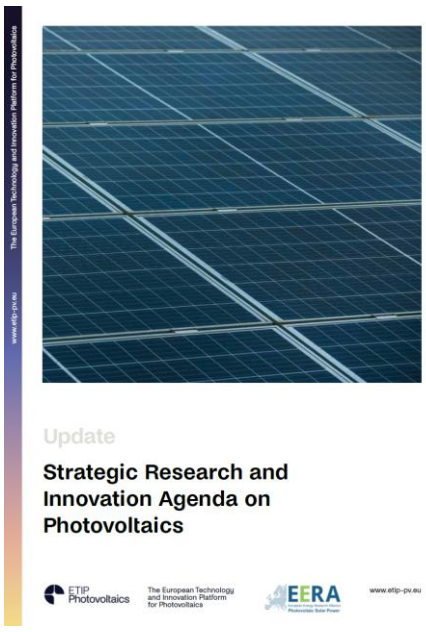


Figure 6. Cover of the updated EU-SRIA-PV document published by ETIP-PV and EERA-PV in September 2024.

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## 5. INCORPORATION INTO THE UPDATED EU SRIA-PV

The EU SRIA-PV of EERA-PV and ETIP-PV, originally published in 2022, was updated in the course of 2024[8]. Various partners of the VIPERLAB project were actively involved in drafting this updated document and as a result, many parts of our VIPERLAB SRIA are incorporated into the single junction perovskite PV part of the updated EU SRIA-PV.

Since this updated EU SRIA-PV will be used as the basis for the co-programmed partnership on photovoltaics[9] that is being set up in Horizon Europe, our VIPERLAB SRIA will have impact on the definition of future funded PV project calls within Horizon Europe in the field of perovskite PV.

## 6. OUTCOME OF WORKSHOP 3

The finalized VIPERLAB SRIA was disseminated at the second public VIPERLAB event with industry and policy makers, which took place in Vienna in September 2024 at the EU-PVSEC, and at the third strategic VIPERLAB workshop, which took place in November 2024 as a session with three talks and a panel discussion of the BecomePV workshop in Brussels.

The goal of our third strategic workshop was to disseminate the content and the importance of the VIPERLAB SRIA to a wider audience, whereas the goal of the BecomePV workshop was to focus on how to bridge the gap between current research and the commercialisation of cutting-edge PV technologies such as perovskite PV. We therefore carefully selected the topics of the three presentations and the panel discussion to be in line with both goals.
In the first presentation, Ivan Gordon (IMEC) presented the VIPERLAB SRIA and the process that led to its creation. Moreover, in this presentation, it was shown how the VIPERLAB SRIA was fed back into the updated EU-SRIA-PV, published in September 2024 by EERA-PV and ETIP-PV. In the second presentation, Damien Gautier of Becquerel Institute presented his in-depth study of the potential of perovskite PV, based on work that was done in the frame of the VIPERLAB project (D6.4). Finally, Thomas Garabetian (SolarPower Europe) presented more information about the updated EU-SRIA PV in which the VIPERLAB SRIA on perovskite PV was partially incorporated and highlighted how this document will be used as the basis of the new co-programmed partnership on PV that is being set up within Horizon Europe.

[8] The updated EU SRIA-PV can be downloaded from https://etip-pv.eu/publications/
[9] https://etip-pv.eu/events/other-events/the-new-european-ri-framework-for-pv-the-co-programmed-partnership-and-its-impact-on-the-strategic-ri-agenda-eupvsec24/#:~:text=The%20European%20Commission%20announced%20a,the%20European%20PV%20value%20chain.

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The ensuing panel discussion then gave the audience the chance to ask more in-depth questions to the speakers on the topics described above.

## 7. CONCLUSION

The VIPERLAB project has been crucial in advancing perovskite PV technology in Europe by creating a clear Strategic Research and Innovation Agenda (SRIA). Through workshops and collaboration with key stakeholders, the project has ensured its work aligns with European goals and has been incorporated into the updated EU SRIA-PV. This integration will guide future funding and research efforts under Horizon Europe.
The SRIA outlines practical steps to overcome challenges like improving efficiency, recyclability, and setting consistent standards, while also focusing on scaling up production. By bringing together researchers, industry leaders, and policymakers, VIPERLAB has laid the groundwork for a strong and sustainable European perovskite PV industry.
This work positions Europe as a leader in renewable energy innovation, helping to turn cutting-edge research into real-world solutions and contributing to a cleaner energy future.

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