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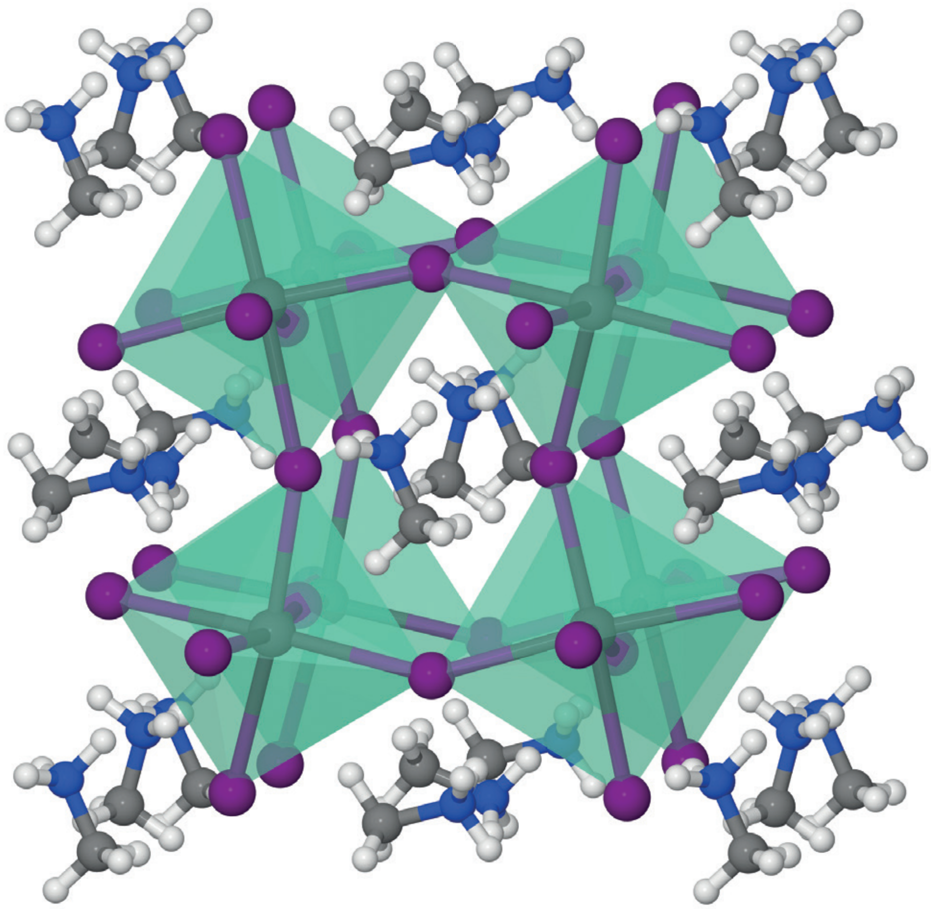
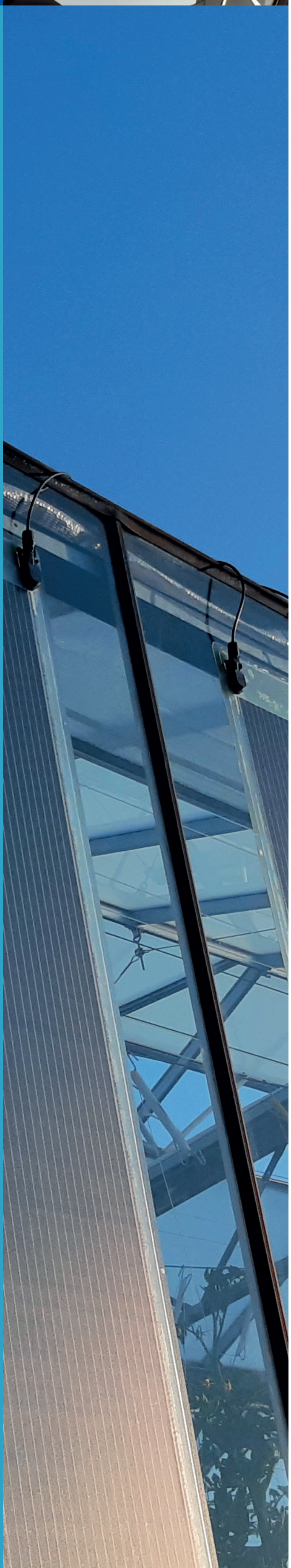
Perovskite-based photovoltaics: A unique chance for European PV-industry

A White Paper from the European Perovskite Initiative

September 2019





"Front page illustration from CNR-IMM Institute for Microelectronics and Microsystems Catania, Italy."

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EPKI – Perovskite-PV European White Paper

Foreword: EPKI stands for European Perovskite Initiative. We are assembling most of the players working on Perovskite photovoltaics in a Pan-European approach across the continent: Research Institutes, Universities and Companies. Today EPKI represents 73 entities from 18 countries and so gathers more than 800 researchers and engineers working on this subject *(cf. EPKI member's page 16)*. This whitepaper reflects on the current status of this very promising technology.

EXECUTIVE SUMMARY

- While Photovoltaic is among the most promising renewable energy sources for the coming decades,
- Perovskite-based PV has become top-priority among the PV research community worldwide. It is now considered as a key material for the next generation PV modules. This abundant class of materials, combines high versatility, low processing costs and very high performance.
- Enormous technology progress has been realized last decade, and of course, still a lot of work needs to be done prior to its commercialization. Hence, this new paradigm represents an extraordinary opportunity for Europe's PV Industry, whose market share dramatically fell below 3%. It is time to seriously consider how to wisely re-invest into this booming and strategic sector, especially in this new perovskite based PV technology.
- Europe hosts many research centers working in this field and it should be noted that several of the records mentioned in this paper were achieved by European research institutes and industries, highlighting the excellent position of Europe in the field of perovskite PV. In order to leverage on this, immediate and strong support by national and European institutions as well as an increased involvement from European industry players are essential.
- At EPKI, we strongly believe that perovskite PV represents a great opportunity which has just begun to unravel itself. Through the edition of this whitepaper the European Perovskite PV community is acting as a voice for all its partners asking for further support and plans to raise awareness among investors and industrial community.

Introduction

The global solar photovoltaics (PV) industry has entered a new era, as since 2018 the electricity generation from PV has become one of the cheapest, or in some cases, the cheapest, energy harvesting technology available to date[1]. Due to the global challenge to address climate change, any new source of electricity should be generated by sustainable energy harvesters like PV.

Many electricity generation scenarios are pointing towards a massive PV implementation in the coming decades, projecting PV to be the most important electricity generation technology in 2050. A comprehensive overview composed by Fraunhofer ISE is shown in Figure 1.

[1] *https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/EN2018_Fraunhofer-ISE_LCOE_Renewable_Energy_Technologies.pdf – page 2*

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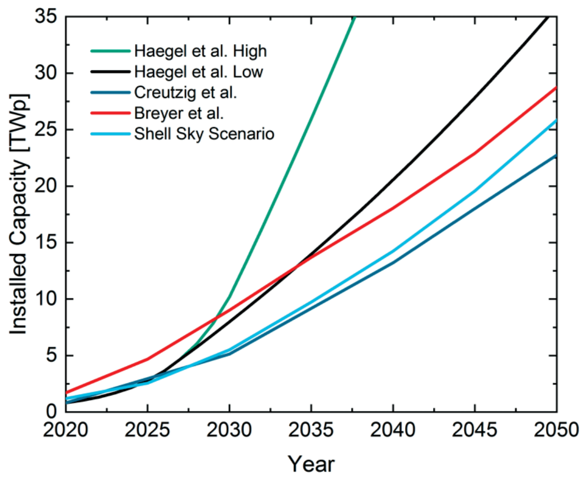
PV Development Scenarios

Photovoltaics is the most important technology for cost-optimized climate change mitigation



Ca. 2021/2 already 1 TW
2030 ca. 5 TW
2030 yearly addition > 1 TW/a

[1] N. Haegel et al. Science 2019
[2] F. Creutzig et al. Nature Energy 2017
[3] C. Breyer et al. Progress in Photovoltaics 2018

Fraunhofer

Figure 1: *Overview of several recent global PV deployment scenario's (Fraunhofer ISE)*

On November 28th 2018, the European Commission presented its strategic long term vision for a prosperous, modern and climate-neutral economy by 2050. This includes the complete decarbonization of Europe's energy supply through a large-scale electrification of our energy system coupled with the deployment of renewables[2] . PV is envisioned to play a major contribution towards this strategic goal.

The global PV Market has witnessed an annual growth rate of 24% between 2010 and 2017[3]. To fulfill the strategic climate goals the PV-markets both in Europe and the rest of the world will continue to grow between 10% and 30% up to 2030[4]. In order to enable the realization of this enormous PV deployment, improved, new and widely accepted PV technologies will be required besides the current existing PV technologies.

As safe and uninterrupted electricity supply will be an important strategic asset for a healthy and prosperous society, Europe should strive towards a firm guardianship and maybe even a high level of self-control on PV technology. This means that Europe should seriously re-consider to re-master again large part of the value chain of PV technology. This asks for a triple helix approach, where government, industry and science bundle forces. Investing today is required to meet the clean energy needs of tomorrow.

The Levelized Costs of Electricity (LCoE) of PV is already competitive or even the lowest as compared to other energy harvesting sources, and there is plenty of space for further improvements, wherein new PV technologies are required to continue cost reduction as well as to overcome the current theoretical efficiency limits.

[2] European Commission. European Commission Available at: https://ec.europa.eu/clima/policies/strategies/2050_en (Accessed: 5th March 2019) https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018DC0773&from=EN and European Commission. European Commssion Available at: https://ec.europa.eu/clima/policies/strategies/2050_en. (Accessed: 5th March 2019)
[3] https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf
[4] http://itrpv.vdma.org/documents/27094228/29066965/ITRPV02019.pdf/78cb7c8c-e91d-6f41-f228-635c3a8abf71

Global LCOE of utility-scale renewable power generation technologies, 2010-2018

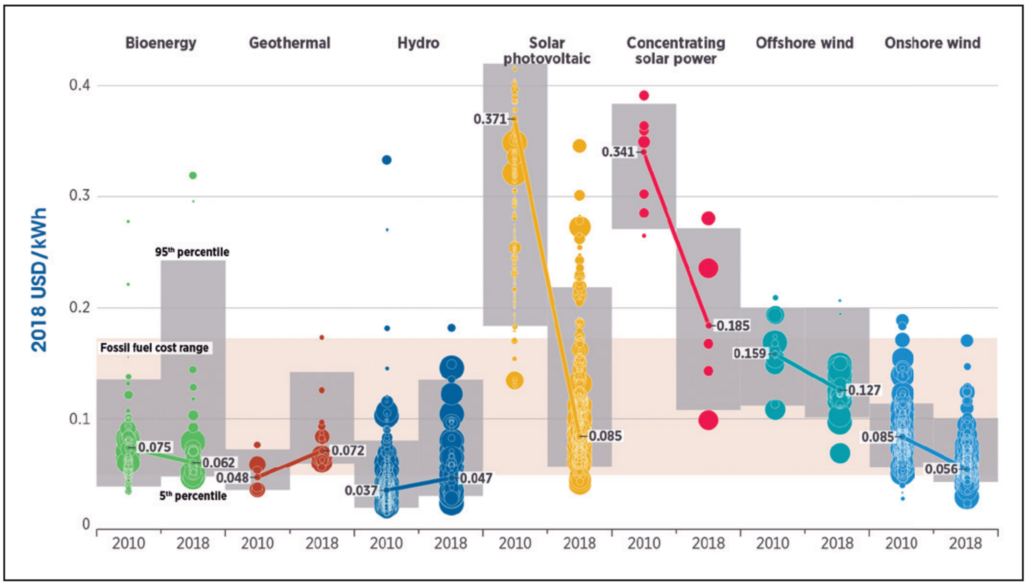


Figure 2: *Evolution of the LCoE, Levelised Cost of Electricity, from 2010 to 2018: The LCoE for utility-scale PV dropped 77%, the largest cost reduction among all renewables*[5]

Hybrid perovskites are a class of low cost semiconducting materials, which has been the subject of very active scientific investigations in the last decade. In case of perovskite-based PV, materials usage, energy usage, low cost and high-speed production methods will significantly contribute to further reduce module costs. In case of single junction perovskite PV, it is expected that module efficiencies will be comparable to the current existing PV technologies within a timeframe of 5 years.

Perovskite based PV, Pk-PV, can also be used as an additional PV element on top of existing technologies like e.g. c-Si and CIGS (i.e. hetero-junction PV), but also on another perovskite layer to create homo-multi-junction devices. This approach will yield module efficiencies above 30%, which in turn will further lower the LCoE and decrease the area usage. Meanwhile, the large number of potential embodiments of this new perovskite PV technology will allow to intimately and seamlessly integrate PV in our society. Ultimately, PV will be an inseparable part of our infrastructure, environment, mobility solutions and appliances. By improving the integration of PV within the man made interface, the non-module costs are also being lowered, again contributing to a further drop in LCoE.

The potentials of lower cost, high conversion efficiency, easy integration, low carbon emissions during lifetime as well as higher recyclability are the merits that perovskite-based PV has to offer. Therefore, it is ideally positioned to deliver and constitute the best candidate to become the next generation PV technology. Moreover, this could be achieved within Europe, if we combine strong efforts in R&D as well as appropriate scaling-up and industrialization.

[5]RENA (2019), Renewable Power Generation Costs in 2018, International Renewable Energy Agency. ISBN 978-92-9260-126-3

Unique features of Perovskite

Perovskite-PV (Pk-PV) technology combines numerous advantages:

1. the possibility to be deposited by simple solution-based methods or by sublimation on multiple types of substrates, flexible or rigid;
2. the bandgap tunability by chemical modification for high efficient homo- or hetero- multi-junctions;
3. the possibility to create opaque or semi-transparent devices, the latter to be used as bifacial PV modules, as top cell(s) for multi-junction devices and/or as BIPV elements;
4. the potential for very low-cost fabrication due to the low-cost and abundant materials, very thin electro-active layers, low-temperature processing and high throughput compatibility.

Due to the variety of substrates and device lay-outs that can be used, this new Pk-PV technology can be implemented into almost all PV applications one can imagine such as: utility-scale PV farms, building added and integrated PV, infrastructure integrated PV, vehicle integrated PV, consumer electronics integrated PV and for powering IoT devices.

Efficiency

The worldwide experiences gathered in thin film PV technologies during the last decades as well as the unique chemical properties of Pk-PV allowed its efficiencies to increase from 3.8% at its discovery in 2009 to an astonishing 25.2%[6] mid 2019 in a single-junction architecture turning it into the fastest-advancing solar technology to date (Figure 3).

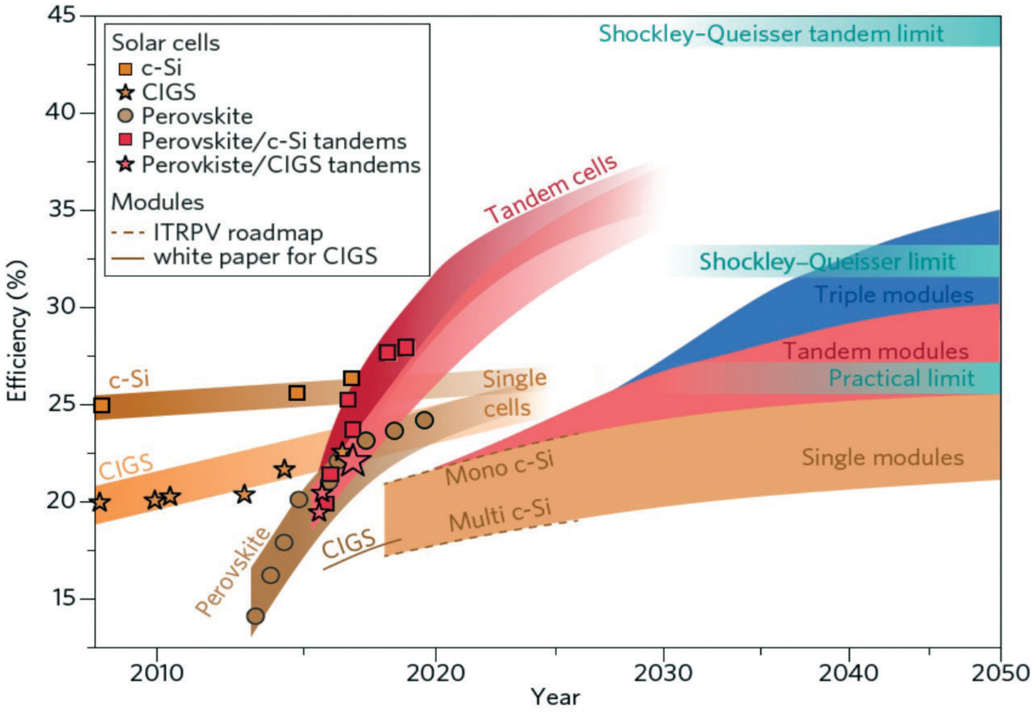


Figure 3: *Comparative chart of the various photovoltaic technologies showing the sharp growth of Pk-based PV cells*[7]

[6]New world record for #perovskite solar cells at 25.2% by KRICT/MIT. https://www.nrel.gov/pv/assets/pdfs/best-research-cell-efficiencies.20190802.pdf
[7]Adapted from Albrecht, S., & Rech, B. (2017). Perovskite solar cells: On top of commercial photovoltaics. Nature Energy, 2(1), 16196. doi:10.1038/nenergy.2016.196 (https://doi.org/10.1038/nenergy.2016.196)

Rigid | opaque | Pk-PV module

In addition, the combination of semi-transparent Pk devices on top of other PV devices, already resulted in a 28% Si/Pk tandem efficiency, a 25.6% CIGS/Pk tandem efficiency, both above record cell efficiencies of the bottom PV cells and a 25% Pk/Pk tandem efficiency[8]. These multi-junction devices have the potential to reach cell efficiencies well above 30%. Demonstration of cells efficiencies as high as 35% and possibly higher might be expected in the coming years. As Pk has a very low-cost potential, this stacking will enable a substantial efficiency increase at comparable costs.

Stability

Considering that perovskite PV is an organic-inorganic hybrid semiconductor, concerns about the stability of the material, observed for the very first perovskite based solar cell in 2009, have been addressed in recent years to close the gap for market exploitation. Pk-PV is still perceived to be unstable, but this is not the case anymore: improvements in selection and mastering of materials (i.e. electro-active materials), device stack designs and processes have already solved many of the early-days concerns on thermal-, humidity- and light stability as well as the observed hysteresis behavior. Examples of improved stability, fulfilling the international requirements, can be found in [Nat. Mater Reviews 4, pages 4–22 (2019)]. This article indicates that in the early days of Pk-PV research the performance was depending on the measurement bias direction during I-V tests, thus adding a potential source of instability. Meanwhile, many groups found several ways to overcome this undesired behavior, by changing materials, material compositions, stack designs and processing conditions[9]. Today several groups have already showed very promising stability results after applying parts of the IEC stress test protocols on stable scaled (mini-) modules[10]. Oxford PV has already passed and in many cases exceeded the key standard IEC accelerated stress tests for their Pk/Si 2 terminal tandem devices: damp heat at 85°C/85% RH (> 1.000 hours), light soak @ 60°C (> 1.000 hrs) and thermal cycling (-40°C to +85°C, 200 cycles).

In spite of such developments, further progress is still required to be made, as high efficiency, low-cost, scalability and stability should all come together into affordable and bankable Pk modules. Outdoor measurement tests of scaled and packaged Pk modules are nowadays being performed at several groups and locations[11], and many more are planned in coming years to better frame the degradation trajectories and enable fast mitigation of potential instabilities issues (also far beyond today's IEC standard tests protocols and requirements).

To further accelerate the progress on stability of Pk-PV, the annual International Summit on Organic and Hybrid Photovoltaics Stability (ISOS) is focusing specifically on that point since a couple of years. Sharing information, deeper understanding of occurring and potential degradation mechanisms, remedying degradation pathways as well as potentially developing additional stress tests to be embedded in future IEC protocols are the main targets of ISOS. A consensus paper on the stability topic for Pk-PV is currently under preparation.

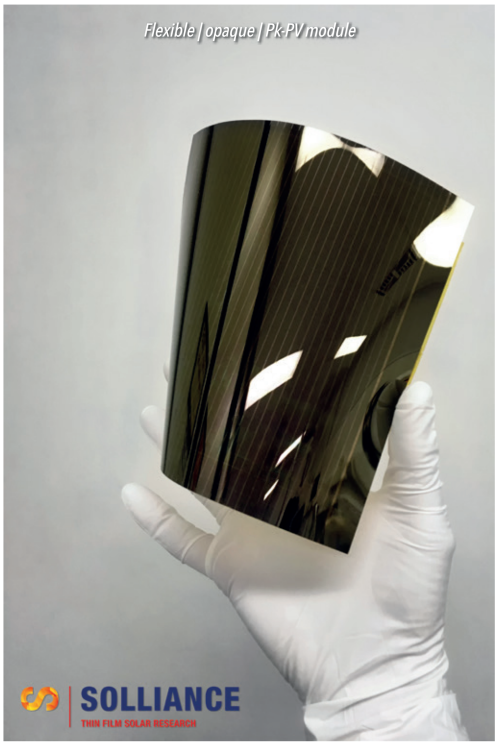
[8] *Green, M. A. et al. Solar cell efficiency tables (Version 53). Prog. Photovoltaics Res. Appl. 27, 3-12 (2019)*
[9] *From ACS Energy Lett. 2018, 3, 2136−2143*
[10] *S.-H. Turren-Cruz et al., Science 10.1126/science.aat3583 (2018); R. Cheacharoen et al., Sustainable Energy & Fuels, Issue 11, 2018*
[11] *Z. Fu et al., Adv. Funct. Mater. 2019, 29, 1809129*

Answers and solutions for these questions will determine the final LCoE of this technology, which is the crucial element to evaluate the relevance of large scale deployment of a new PV technology. But today, there is a strong and unanimous consensus among the community that these challenges will be overcome.

Manufacturing

The photo-active layer of Pk-PV devices can be processed by applying inks (coating, printing) or via gas phase deposition (evaporation/ sublimation) or a combination of both. The charge selective contact layers, potential additional interlayers and electrodes can be applied by existing and proven scaled deposition technologies such as coating, printing, sputtering, e-beam assisted deposition, evaporation, spatial atomic layer deposition and many more. The resulting film uniformity, crystallinity and reproducibility suggests these methods being viable choices for cost-efficient manufacturing. Production of Pk-PV on rigid substrates such as glass or c-Si wafers for 2T tandem configurations demands sheet-to-sheet or batch processes, whereas production of Pk-PV on flexible substrates, like plastic, metal or even flexible glass, is preferably done by applying Roll-to-Roll deposition processes in order to allow proper web handling. With the latter, if wet-chemical coating processes are applied, very high (10 – 100's of m/min) throughput processes should be feasible on web widths from one to several meters. This would allow to install in the future a single production facility of several tens of GWp annual production capacity.

Most of the processing techniques that have been explored and applied for Pk-PV stack deposition are already available for mass production processes, meaning access to production equipment will not be a hurdle. With the proper process choices and the high throughput and low energy usage potential, the manufacturing costs can be further decreased substantially. With all this, in combination with the use of low-cost and abundant materials as well as the very low material usages per m^2, it is expected that future large-scale production costs for highly efficient Pk-PV modules will further decrease. According to various



calculations and cost assumptions by different institutes, production costs of Pk-PV modules in the range of 4 - 8 Eurocent/Wp should be feasible in the coming decades (20-30 years), depending on the final module efficiency, the materials price erosion and the execution of the learning curve due to the scaling-up.

Similar to other thin film PV technologies, water ingress into the module stack should be avoided. For glass based Pk-PV modules, existing or slightly adapted packaging approaches are applicable.

For packaging of flexible Pk-PV modules barrier foils used for existing flexible PV technologies like CIGS and OPV can be applied, and alternatively direct encapsulation technologies such as currently used in curved OLED displays could also be further developed and adapted. Even flexible glass could become an important alternative for substrate and/or packaging applications. Anyway, if this market will grow, prices of current encapsulation and barrier foils will go down further.

As mentioned earlier, it is also expected that the intrinsic water sensitivity of the Pk and other electro-active layers could and will be substantially improved by the fine tuning of material and processing choices. Once Pk-PV production starts it is expected that - as in c-Si PV - standardization of materials, stacks, and processes will gradually take place as the community will continuously gather together at exhibitions, conferences and events in order to further improve their production approaches.

Although Pk-PV can still be considered to be in a very early phase when it comes to industrialization, worldwide more than 20 companies from start-ups to large sized enterprises are currently developing manufacturing processes for Pk-PV modules, targeting different applications (IoT, BIPV, energy harvesting, power production, …). Depending on the information sources (public announcements at exhibitions and conferences and personal communications), about 0.4 to 1.3 GWp of Pk-PV production capacity will be built in the coming 2-3 years.

Levelized Costs of Electricity (LCoE)

Although the LCoE of PV in general is already very competitive and even sometimes the lowest as compared with other existing energy harvesting sources, in the case of Pk-PV, material usage, energy usage and production speed can all contribute significantly to further lower the module costs. With single junction perovskite PV, it can be expected that PV module efficiencies comparable to currently existing ones will be achievable within five years. Even more, Pk-PV can be used to be stacked with existing technologies like e.g. c-Si and CIGS, but also with perovskite as such. This approach will likely yield module efficiencies of 30% and even higher within the coming decade, which will further lower the LCoE. Also, by integrating Pk-PV close to the human interface, like in buildings, infrastructure, vehicles, etc. …, the non-module costs can also be lowered, again contributing to further lowering the LCoE.

As mentioned and explained above, manufacturing costs of Pk-PV modules have the potential to be very low. Final costs will depend on materials, stack design and process-selection as well as on the aimed application and its subsequent market size. Taking all this into account, it is believed that Pk-PV modules can be produced within a cost range of 20 Euro-cent/Wp in the coming 5 to 10 years and could go down further towards 10 and maybe even to 4 Euro-cent/Wp, depending on the learning curve and actual efficiency values of the scaled Pk-PV modules. Numerous discussions and studies on the LCoE potential describe scenarios with underestimated lifetimes, mostly based on single laboratory data. In view of current massive progress on stability, it would be better to consider LCoE estimations with lifetime expectations required for the final targeted applications. With these scenarios in mind, the LCoE of Pk-PV systems has the potential to become much lower compared to other PV technologies, even taking into account that the non-module or Balance of System (BoS) costs will be the same[12].

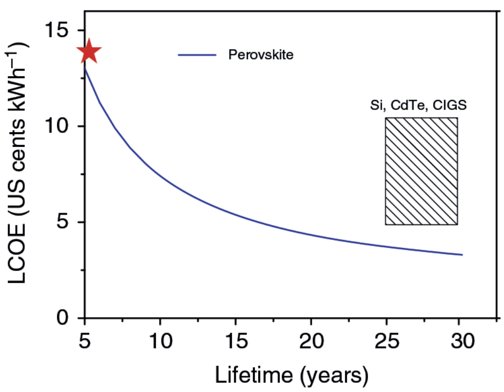


Figure 4: *Relation between LCoE and the expected life time of a PSC (from Yang et al., Nat. Comm. 2018, 9, 5265)*

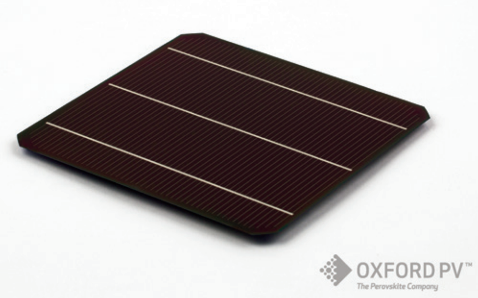
[12] *https://pubs.rsc.org/en/content/articlelanding/2017/EE/C7EE00757D#!divAbstract*

Environmental aspects of Perovskite Photovoltaics

As other renewable sources of energy, photovoltaic system components are under strong scrutiny with regard to their environmental impact, sometimes even more than fossil-based one. To address such issues, a number of studies have performed life cycle assessments (LCA) on perovskite solar cells to quantify the potential environmental impacts of these materials, both as a single junction and as a top layer in tandem configurations[13 14 15 16]. These studies were performed at laboratory or pre-industrial processes, which have not been optimized for industrial applications. In addition, since the expected lifetime is a critical but still unknown parameter in LCA, we are therefore still not having clear conclusions. However, thanks to the usage of abundant synthetic components (avoiding mining or heavy purification processes), combined with very low material usage and a low processing temperature, Perovskite PVs have very strong arguments to become one of the most environmental friendly technologies holding very high performances in terms of CO2/kWh g compared with other technologies as well as a very good Energy Payback Time (EPBT) or Energy Return on Investment (ERoI). For example, the EPBT of lab scale processed Pk-PV has been estimated to be able to be around 0,2 year with respect to e.g. the 2 to 2,5 years of Si technology[17] . With the introduction of scalable processes, this will only improve.

In spite of the above argument, current Pk-PV devices are not completely free of a potential environmental impact as most commonly used perovskite materials contain alkali metal lead and tin halides, employing the ions of heavy metals Pb^{2+} and/or Sn^{2+}, respectively.

Rigid | semi-transparent | Pk-PV cell | on top of a cSi cell



Typical thicknesses of the absorber layer are about 0.3 µm, resulting in around 1g of lead iodide per m^2 [18]. The health and environmental risks associated with the use of lead are well known[19]. The RoHS directive restricts the use of hazardous substances in electrical and electronic equipment and requires the substitution of heavy metals such as lead through safer alternatives. While the substitution or reduction of lead in perovskite is an active area of research, as of today no fully suitable alternatives have been found yet. As the lead content in consumer products is limited to 0.1% in any homogeneous layer, this applies to the 0.3 µm Pk-layer and Pk modules are in conformity with the RoHS directive[20 21].

Saying so, the risk of a Pb-washout from a damaged Pk-modules is not null. However, in the worst case scenario that all the lead of the Pk layer would leach to the environment, the total release of lead would still be less than 1% of the emissions of a coal power plant for the same amount of generated energy[11]. Meanwhile, properly encapsulated modules introduce very low risk of Pb leakage and the usage of self-healing encapsulants and/or other containment concepts will further mitigate potential leakage rate levels (0.08 $mgh^{-1}m^{-2}$)[22].

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[13] Serrano-Lujan, L. et al. Tin- and Lead-Based Perovskite Solar Cells under Scrutiny: An Environmental Perspective. Advanced Energy Materials 5, 1501119 (2015)
[14] Lunardi, M. M., Ho-Baillie, A. W. Y., Alvarez-Gaitan, J. P., Moore, S. & Corkish, R. A life cycle assessment of perovskite/silicon tandem solar cells. Progress in Photovoltaics: Research and Applications 25, 679–695 (2017)
[15] Celik, I. et al. Environmental analysis of perovskites and other relevant solar cell technologies in a tandem configuration. Energy & Environmental Science 10, 1874–1884 (2017)
[16] Alberola-Borràs, J.-A. et al. Perovskite Photovoltaic Modules: Life Cycle Assessment of Pre-industrial Production Process. iScience 9, 542–551 (2018)
[17] Energy Environ Sci 5 (2012) 9163; RSC Adv 3 (2013) 17633; Energy Environ Sci 8 (2015) 1953; T.Ibn-Mohammed et al., Renewable and Sustainable Energy Reviews, Volume 80, December 2017, Pages 1321-1344; T. Camp, Undergraduate Honors Theses, University of Colorado, Boulder, 2019
[18] Hauck, M., Ligthart, T., Schaap, M., Boukris, E. & Brouwer, D. Environmental benefits of reduced electricity use exceed impacts from lead use for perovskite based tandem solar cell. Renewable Energy 111, 906–913 (2017)
[19] https://onlinelibrary.wiley.com/doi/abs/10.1002/cssc.201901296
[20] Babayigit, A., Boyen, H.-G. & Conings, B. Environment versus sustainable energy: The case of lead halide perovskite-based solar cells. MRS Energy & Sustainability 5, (2018)
[21] Kadro, J. M. & Hagfeldt, A. The End-of-Life of Perovskite PV. Joule 1, 634 (2017)
[22] Ref: 10.1038/s41560-019-0406-2. Nature Energy, volume 4, pages585–593 (2019)

Flexible semi-transparent Pk-PV module

With regard to the end of life, the recyclability of Pb is a crucial issue. Taking into account that the lead recycling industry is very well established since Pb is present in many products (e.g., car batteries), this is considered as an advantage for lead-containing PVs compared to other toxic materials, which would need to develop specific recycling industry from scratch.

The entire Perovskite community is dedicated to work on the reduction of the environmental impacts this new class of material would carry, however today already a detailed study has shown that the avoided impacts on eco-toxicity through the use of Pk-PV were significantly outweighing the additional impacts[23 24].

Further examples of LCA studies supporting the case of perovskite PV:

- Pk-PV offers more environmentally friendly and sustainable option, with the least energy payback period, as compared to other PV technologies, Renewable and Sustainable Energy Reviews 80 (2017) 1321–1344.
- The results demonstrate that perovskite solar modules possess the shortest EPBT, and future research should be directed to improving the system performance ratio and the device lifetime and reducing precious metal consumption and energy-intensive operations to lower the CO_2 emission factor, Energy Environ. Sci. 8 (2015) 1953.
- The environmental impact of Pk-PV in the operational phase and the decommissioning phase representing a cradle-to-grave analysis is currently not possible and will have to await large scale outdoor demonstration but there are no compelling reasons to dismiss lead-containing perovskites as a solar cell technology, Solar Energy Materials & Solar Cells 137 (2015) 303– 310.
- The effect of substituting lead with tin in perovskite-based solar cells (PSCs) has shown that lead is preferred over tin by a lower cumulative energy demand. The results that also include end-of-life management show that a recycling scenario that carefully handles emission of lead enables use of lead in Pk-PV with little environmental impact (e.g. incineration). All other scenarios (e.g. landfill) result in catastrophic emission of lead to the environment that would spell an end to widespread use of lead in Pk-PV, Adv. Energy Mater. 5, 20 (2015) 1501119.
- To mitigate the risks of lead, the CHEOPS project assessed the environmental impact of the material and concluded that it is not a considerable threat if applied in the small doses used in perovskite solar cells. Mixed Pb/Sn halide perovskites offer specific advantages, for instance they have the lowest bandgap achievable for this family of materials (down to 1.25 eV) and have both excellent absorption and charge transport properties, http://www.cheops-project.eu/.

[23] *Hauck, M., Ligthart, T., Schaap, M., Boukris, E. & Brouwer, D. Environmental benefits of reduced electricity use exceed impacts from lead use for perovskite based tandem solar cell. Renewable Energy 111, 906–913 (2017)*
[24] *Hailegnaw, B., Kirmayer, S., Edri, E., Hodes, G. & Cahen, D. Rain on Methylammonium Lead Iodide Based Perovskites: Possible Environmental Effects of Perovskite Solar Cells. The Journal of Physical Chemistry Letters 6, 1543–1547 (2015)*

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Efficiency and stability roadmap

Within the EPKI-alliance, there is a general agreement on the following potential performance developments for Pk-based PV modules within certain, but not exhaustive, configurations.

Single Junction opaque on glass (rigid)		2020	2022	2024	2026	2028	2030
PCE (%)	Lab cell	25%	26,5%	28%	29%	30%	30,5%
PCE (%)	Scaled packaged module (≥ 100 cm²)	17%	19%	21%	23%	25%	26%
85°C/85% RH & light soak	Scaled packaged module (≥ 100 cm²)	IEC	IECx2	IECx3			

Multiple Junctions opaque on glass (rigid)		2020	2022	2024	2026	2028	2030
PCE (%)	Lab cell	25%	27%	30%	32%	33%	34%
PCE (%)	Scaled packaged module (≥ 100 cm²)	15%	18%	21%	24%	27%	29%
85°C/85% RH & light soak	Scaled packaged module (≥ 100 cm²)		IEC	IECx2	IECx3		

c-Si/Pk Tandem packaged in glass (rigid)		2020	2022	2024	2026	2028	2030
PCE (%)	Scaled packaged module (≥ 100 cm²)	28%	30%	31%	33%	35%	36%
PCE (%)	Scaled module (≥ 1.000 cm²)	25% 4-6 cells	26-27% Full scale				
85°C/85% RH & light soak	Scaled packaged module (≥ 100 cm²)		IEC	IECx2	IECx3		

Single Junction opaque on foil (flexible)		2020	2022	2024	2026	2028	2030
PCE (%)	Lab cell	19%	21%	23%	24.5%	26%	27%
PCE (%)	Scaled packaged module (≥ 1000 cm²)	10%	15%	20%	21.5%	23%	24%
85°C/85% RH & light soak	Scaled packaged module (≥ 1000 cm²)	IEC	IECx2	IECx3			

** PCE : Power Conversion Efficiency*

Applications

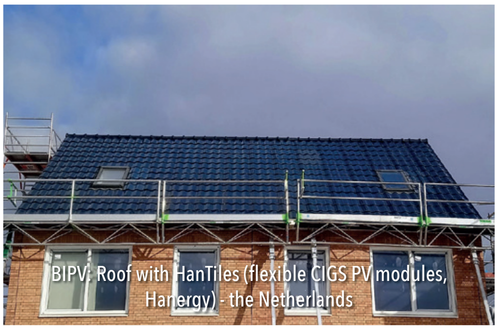
Perovskite photovoltaic modules can be elaborated in many ways, leading to different products that have specific properties, such as:

- High power density
- Semi-transparency
- Flexibility and conformability
- Lightweight
- Specific electrical output

These features can be combined to serve different applications, which can be listed in the following main categories:

Specialty PV modules applications:

Building, Infrastructure, Vehicle & Consumer Electronics Integrated PV: Customized modules: glass or flexible substrates, opaque or semi-transparent, variety in dimensions, shape and IV output.



BIPV: Roof with HanTiles (flexible CIGS PV modules, Hanergy) - the Netherlands

BIPV: Rise Institute with SolarLab PV façade system and Kromatix coloured solar glass by SwissINSO

BIPV: Photovoltaic Glass for Buildings based on translucent thin film Si – Onyx Solar - Spain

BAPV: Greenhouse with added flexible ASCA OPV elements of Armor - Nantes in France

VIPV: Vehicle integrated PV: 3D formed cSi on an electric car – LightYear – The Netherlands

IIPV: Flexible CIGS (MiaSolé – Hanergy) integrated in a bicycle road – the Netherlands

Future LCoE improvements by:

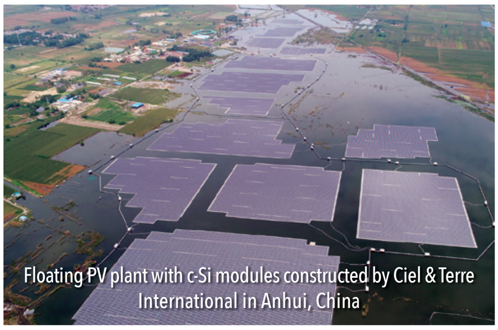
- Pk Single Junction PV
- Pk Multi Junction PV
- Si/Pk Tandem PV
- CIGS/Pk Tandem PV

Future aesthetic and mass customization improvements by:

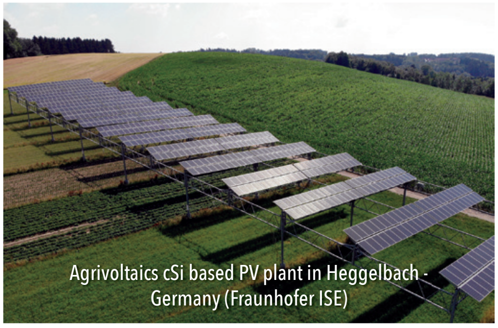
- Adapted and novel high volume/high mix manufacturing processes, compatible with Industry 4.0
- Freedom of substrate choice, module size, shape and IV-output, semi-transparency and customized packaging. Manufacturing processes for BIPV, IIPV, VIPV, CEIPV components

Standard PV modules applications:

Ground-mounted utility-scale PV modules with First Solar CdTe



Floating PV plant with c-Si modules constructed by Ciel & Terre International in Anhui, China



Agrivoltaics cSi based PV plant in Heggelbach - Germany (Fraunhofer ISE)

BAPV with glass-based CIGS PV panels (Solar1)

Ground mounted c-Si PV plant in Lelystad (NL) by IZEN

Future LCoE improvements by:

- Pk Single Junction PV
- Pk Multi Junction PV
- Si/Pk Tandem PV
- CIGS/Pk Tandem PV

Other applications:

Concentrated PV: using optical elements to amplify the irradiance and focus on small solar cells for a higher efficiency. The use of high irradiance on a PSC was found to increase its efficiency, opening an exciting new line of research.

PV for spacecrafts, satellites, drones, etc. ...: due to its high efficiency potential in combination with light-weight[25] when using flexible substrates, Pk-PV could also become an important PV technology for space related applications[26].

Other, non-PV applications: hybrid organic-inorganic metal halide-based perovskite materials and crystals can also be applied for applications like lasers, LEDs, photodetectors, ionizing radiation detectors…

[25] *Saewon Kang et al. J. Mater. Chem. A. 2019, 7, 1107*

[26] *I. Cardinaletti et al., Solar Energy Materials and Solar Cells 182 (2018) 121-127; R. Brown et al., ACS Appl. Energy Mater., 2019, 2, 1, 814*

Conclusions

Perovskite PV has an extraordinary high potential to make significant contributions towards the ambitious strategic goal of a carbon-free energy supply and deserves to be investigated further. Next to the increase of the overall efficiency and stability, the further understanding of the eco-sustainability and environmental impacts in industrial scenarios will be part of these investigations. Besides that, further unity in the characterization process and further standardization in up-scaling are to be encouraged for successful commercialization.

Hence, this new paradigm represent an extraordinary opportunity for Europe's PV industry, which market share dramatically fell below 3%. It is the time to seriously consider how to wisely re-invest into this booming and strategic sector. Europe hosts many research centers working in this field and it should be noted that many of the efficiency records mentioned in this paper were achieved by European research institutes and industries, highlighting the excellent position of Europe in the field of Pk-PV. In order to leverage on this, immediate and strong support by national and European institutions as well as an increased involvement from European industry players are essential.

Within EPKI, gathering the voices of 73 entities, we have the ambition to organize the perovskite community in the best possible way to tackle these challenges, in connection with centralized institutions such as: European Commission, DGRTD and IWG, EERA-PV, ETIP-PV, EUREC, SPE, PV-THIN, EIT InnoEnergy etc. This will involve circular models-like collaborative frameworks with integration, interface and integrity of the various stakeholders being the way to success.

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EPKI

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as of 4th September 2019

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