VIPERLAB

D 10.6

BEST PRACTICES FOR ENERGY YIELD MODELLING

DELIVERABLE
REPORT

Version: 1.3

Date: 28.11.2024

FULLY CONNECTED VIRTUAL AND PHYSICAL PEROVSKITE PHOTOVOLTAICS LAB
VIPERLAB

DELIVERABLE

D 10.6 BEST PRACTICES FOR ENERGY YIELD MODELLING

Project References

Project Acronym	VIPERLAB
Project Title	Fully connected **vi**rtual and physical **per**ovskite photovoltaics **lab**
Project Coordinator	Helmholtz-Zentrum Berlin
Project Start and Duration	1st June 2021, 42 months

Deliverable References

Deliverable No	D 10.6
Type	Report
Dissemination level	Public
Work Package	WP10
Lead beneficiary	Fraunhofer Gesellschaft zur Förderung der angewandten Forschung e.v
Due date of deliverable	30 Nov 2024
Actual submission date	30 Nov 2024

Document history

Version	Status	Date	Beneficiary	Author
1.0	First Draft	10.11.2024	Fraunhofer, CENER	B. Blaesi, E. Zugasti
1.1	Consolidated Draft	22.11.2024	Fraunhofer	B. Goraya
1.2	Reviewed Draft	28.11.2024	Fraunhofer	M. Schubert
1.3	Final Draft	28.11.2024	Fraunhofer, HZB	B. Goraya, N. Maticiuc

DISCLAIMER

‘Fully connected virtual and physical perovskite photovoltaics lab' VIPERLAB is a Collaborative Project funded by the European Commission under Horizon 2020. Contract: 101006715, Start date of Contract: 01/06/2021; Duration: 42 months.

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1. Executive Summary

VIPERLAB is an infrastructure project that aims to create a European environment, where various physical and virtual infrastructures from 13 VIPERLAB partners can be accessed by different users from Europe and abroad. VIPERLAB identifies perovskite PV as the key emerging technology that will be the lever for a future market penetration of EU-based PV production with lowest costs and lowest carbon footprint.

The overall goal of the work package 10 is to provide guidance for the infrastructure and technology development within VIPERLAB by evaluating and optimizing the environmental, social and economic impact of new perovskite-based technologies. To this end, this work package will:

- Provide the data (material, process flows etc.) necessary for such an evaluation

- Evaluate the environmental (Life Cycle Assessment, LCA), social and economic (Levelized Cost of Electricity, LCOE) impact of new perovskite-based technologies and how this impact is affected by the application, device design, choice of equipment and process.

This report presents the insights and methodology in energy yield modelling from three members of the project consortium – Fraunhofer, CENER and HZB for both single and multi-junction photovoltaic technologies. The aim is to provide a consolidated view of their available energy yield models to obtain better and more accurate energy yield estimates, specifically in the case of new technologies like perovskite and perovskite-silicon tandem solar cells and modules. The report details the current status and challenges related to tandem energy yield modelling including luminescence coupling between top and bottom cells, temperature dependence, stability and degradation amongst others as critical topics in need of further investigation. At one of the partner institutes, HZB working together with the University of Ljubljana, the energy yield modelling approach has also been validated with outdoor data on tandems and single junctions exposed in Berlin and Ljubljana to account for light soaking effects and, subsequently, implement these effects back into the available energy yield model for better simulations and energy yield estimates.

2. Introduction

As the global demand for renewable energy continues to grow, solar photovoltaic (PV) technology has emerged as a key solution in the transition to sustainable energy systems. Conventional single-junction silicon cells, while widely used and technologically mature, face inherent limitations in energy conversion efficiency due to their inability to fully utilize the solar spectrum. In recent years, the development of tandem solar cells, particularly those based on perovskite and silicon, has demonstrated a promising path to overcoming these efficiency constraints. Perovskite-silicon tandem cells achieve this by leveraging the unique optical and electrical properties of perovskite materials, which can absorb light efficiently in the visible range, combined with silicon’s strong absorption capabilities in the near-infrared range. This dual-junction approach enables a broader absorption of the solar spectrum, thus increasing the theoretical efficiency limit from around 29% for silicon-only cells to approximately 45% for perovskite-silicon tandems.

To realize the potential of perovskite-silicon tandem technology in practical applications, accurate energy yield assessment models are essential. These models must capture not only the inherent material properties of the tandem cells but also account for environmental variability, which can significantly impact energy production in real-world conditions. Unlike laboratory conditions, outdoor settings introduce factors such as fluctuations in irradiance, temperature, and shading. Addressing these factors through robust energy yield models will allow researchers and developers to optimize tandem cell performance, guide system design, and provide reliable forecasts for energy production in diverse environments. Moreover, enhanced energy yield predictions support the economic viability of tandem cell technology by providing reliable data on expected returns and informing investors and policymakers about the potential advantages of tandem cell installations. Furthermore, the model’s ability to accommodate real-time data and adapt to environmental changes strengthens its applicability for large-scale installations and distributed generation systems, which require precision in energy output forecasting to balance grid demand and supply effectively.

3. Energy Yield Modelling for Perovskite-Si Tandem Solar Cells and Modules

This section contains the procedure for energy yield modelling at Fraunhofer ISE and CENER as well as points out work done by HZB which has already been published in the field of outdoor testing and numerical modelling for tandems and considerations to be made for better energy yield estimations.

3.1. Fraunhofer ISE

Fraunhofer ISE has extensive experience in yield modelling for single and multi-junction solar cells and modules ([1], [2], [3], [4], [5], [6], [7], [8]). Aspects that have been investigated are irradiance data, the effects of module encapsulation, anti-reflection coatings or textures on cover glass, angular dependent radiation in-coupling concentrator PV and the special challenges in multi-junction devices (e.g. current matching or limitation and its effects on the overall cell current as well as fill factor, performance dependence on the irradiance spectrum, luminescence coupling).

Based on the model “YieldOpt”, which was developed for concentrating III-V semiconductor based multi-junction solar cells [3], it was subsequently adapted to Si based tandem solar cells, implementing perovskite [6] as well as III-V top cells [7]. The main difference between the III-V based solar cells which basically consist of planar wafers or layers and Si bottom cells is that the latter also involve textured interfaces, leading to complex optical interactions and multi-pass light paths within the tandem cell. To address this challenge, the efficient optical formalism OPTOS (Optical Properties of Textured Optical Sheets) [9] was combined with YieldOpt. With this model, it is possible to investigate fundamental properties of tandem cells dependent on textures, average photon energy of the irradiance spectrum [6], the impact of irradiance data such as spectral bands (“Kato Bands” [10]), [8] and the dependence of the performance on top cell bandgap and locations in different climate zones [7].

While the model described above can be used to investigate fundamental effects and trends dependent on cell or location properties, several challenges remain, which have partly already been investigated at Fraunhofer ISE, but have also been addressed by other researchers:

Textures: With the OPTOS tool described above, combinations of textures, also involving photonic or wave optical interactions, can be simulated efficiently, but every change in a texture (including adding a layer) causes an additional initial effort making it unflexible for texture or layer variations. A very flexible and efficient simulation tool is Sunsolve/PV-Lighthouse [11]. However, the available texture geometries and sub-cell models are very limited at the present stage. There are several other models in use, e.g. EYCalc by KIT [12], but a very flexible and efficient investigation of textures and texture combinations is still a challenge. This is very relevant since Si front texture modifications are driven by the perovskite top cell processes (e.g. pyramid size or rounding of pyramids), and the effect of these modifications needs to be better understood.

Irradiance data: The availability of high-quality irradiance data is still very limited. Due to the high quality, many models are applied and validated using NREL data which are limited to US locations [13]. Another data set which is very often used is Standard reference climatic profiles [14]. Furthermore, satellite data [15] are widely used for single junction PV, but also applied to tandems. Even if some important studies have been performed, e.g. [8], the applicability of satellite data for tandem yield modelling needs to be further investigated in future studies.

Temperature dependence: The temperature dependence of the cell and module performance is very complex. In single junction Si solar cells, the dependence is rather simple, well understood and can be considered via a temperature coefficient. Also for III-V or III-V//Si multi-junction solar cells, the basic effects have been well understood and integrated into yield models [7]. For perovskites and perovskite based tandem cells, the interplay between temperature, bandgap and EQEs is more complex [16]. This is a very important topic of ongoing research, in the context of outdoor measurements [17] as well as model implementation [18]. At Fraunhofer ISE, the implementation of temperature dependent indoor characterization and the integration of advanced temperature models in the yield modelling are planned within the next 2 years.

Luminescence coupling: With increasing solar cell performance, radiative recombination is getting more and more important, especially for direct semiconductors with high radiative efficiency such as III-V semiconductors or perovskites. While these effects have been well understood and described for single junction solar cells, e.g. in the context of the radiative limit [19], for multi-junction devices emission in one sub-cell can partly lead to re-absorption in another sub-cell. This process is called luminescent coupling [5]. While first models for describing luminescence coupling in perovskite based tandem solar cells have been published [20], the integration into yield simulation is the topic for future work.

Mono-/bifacial: A very interesting and relevant question is the location/climate optimized top cell bandgap/thickness. Since most locations have a larger average photon energy (APE) than the AM1.5g spectrum, the ideal top cell bandgap for mono-facial tandem systems is higher than for STC ([7], [21]). However, if bifacial illumination is considered, a too high bandgap of a top cell can lead to top cell current limitation. Consequently, a top cell bandgap lower than for STC can be favourable, with the optimization result strongly depending on the albedo ([22], [23]). A very important, and so far, not yet fully considered aspect in this context is the temperature dependent behaviour, see above. This is the object of ongoing research. Very important data in this context will be acquired in indoor and outdoor measurements of tandem modules ([24], [17]).

Degradation: Stability/degradation is a hot topic in perovskite/Si tandem PV research. While in cell development efforts are made to identify and eliminate degradation mechanisms and increase the cell/module stability, the integration of degradation effects in yield modelling is at a very early stage [25]. This will increasingly be the object of future research.

3.2. CENER

The evaluation of the energy yield of tandem devices is carried out with the simulation software developed by CENER called SIMPV, see Figure 1.

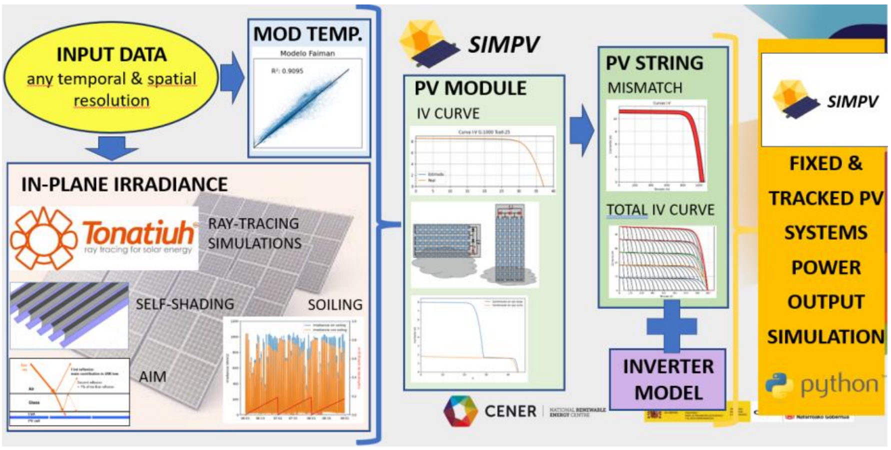
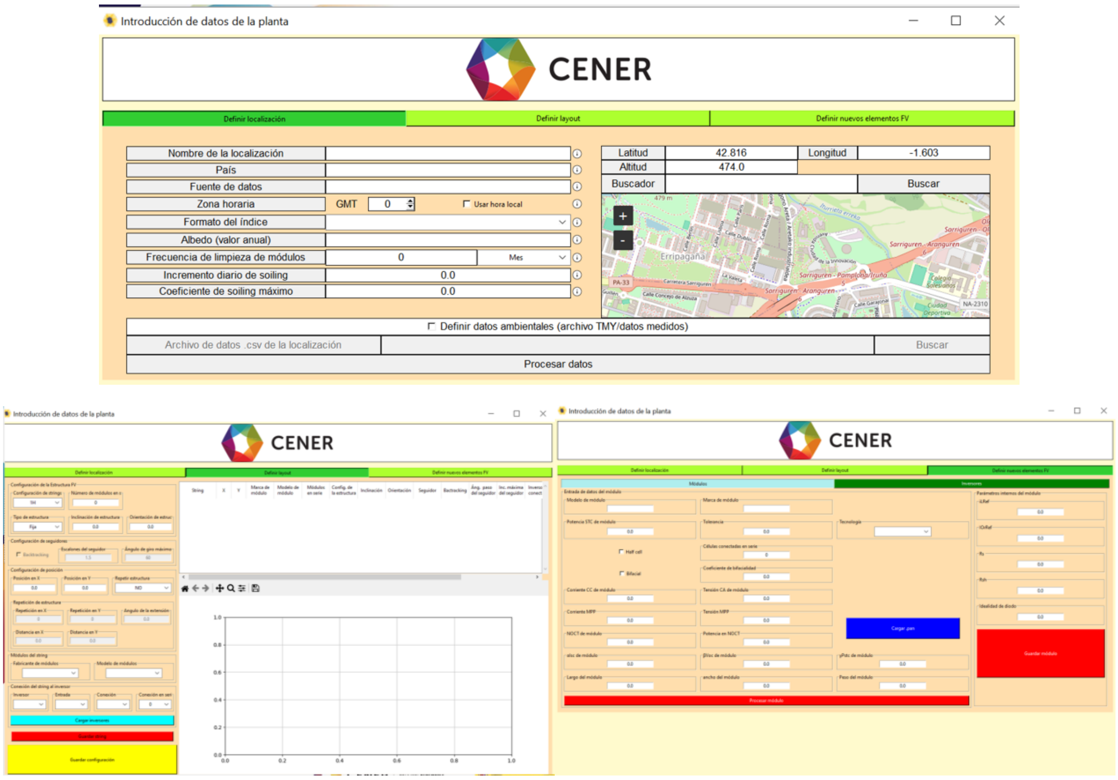


Figure 1: Data Flow and Simulation Principles of CENER's SIMPV Software for Photovoltaic Systems

This software, based on the Python PVLIB library [26] estimates the energy produced by a PV system using meteorological data as input and taking into account different effects which affect the performance and the power generation of PV installations, see Figure 2.


Introducción de datos de la planta

Zona horaria: GMT 0 ☐ Usar hora local
Frecuencia de limpieza de módulos: 0 Mes
Incremento diario de soiling: 0.0
Coeficiente de soiling máximo: 0.0
Latitud: 42.816
Longitud: -1.603
Altitud: 474.0
☐ Definir datos ambientales (archivo TMY/datos medidos)

Figure 2: Input parameters for SIMPV software defining the localization, layout and the PV components of the PV system under evaluation

The methodology applied for the estimation of the energy produced by any PV system implemented in SIMPV can be divided in two steps: (i) the estimation of the effective irradiance impinging the system and (ii) the estimation of the electrical output based on the specific model of the solar modules' behaviour under such irradiation. In both steps, various effects described in the following subsections are taken into account.

The main advantage of the in-house simulation software, SIMPV, is that there is no limitation in the layout of the PV installation, the definition of the characteristics of the module or in the temporal resolution of the meteorological data to be used as input data and the subsequent power output estimation. These capabilities make SIMPV suitable for the detailed evaluation and comparison of the performance of the different PV technologies, including tandem approaches.

The current energy yield model for perovskite-silicon tandem systems incorporates a range of parameters critical to estimating accurate energy output. These parameters include solar irradiance absorption of the layers and spectral response for each of the tandem cells, and the effects of cell temperature, angle of incidence, and optical interactions between the layers. Together, these parameters establish a framework for calculating the real-world energy generation potential of tandem cells.

Irradiance and Spectral Sensitivity: The effective irradiance captured by the PV modules enables to transform the energy of the received photons to electric energy due to the photoelectric effect. Perovskite and silicon materials exhibit distinct responses to different segments of the solar spectrum. The top perovskite solar cell, optimized for visible light absorption, operates synergistically with the silicon solar cell beneath, which primarily absorbs near-infrared light. Accurately capturing the interaction between these solar cells is essential, as each solar cell's energy conversion efficiency depends on the distribution of photons across the spectrum and the tandem structure's ability to direct light optimally. The energy yield model therefore will incorporate spectrally resolved irradiance and spectral response data to reflect the cell’s spectral sensitivity across various environmental conditions.

Temperature Effects: There are various effects that limit the efficiency of the transformation of the received photons to electric energy modifying the ability of the module to produce electricity, like the temperature of the solar cells. Temperature is a well-known factor affecting PV efficiency. The efficiency of most PV technologies decreases as the cell temperature increases, with an average loss of 0.33%/°C, although this value depends on the module technology. The solar cell temperature has been calculated by a model developed by SANDIA [27], considering the improvement in sub-hourly simulations developed by Prilliman [28] with the objective of achieving a better temperature estimation. In perovskite-silicon tandem cells, temperature sensitivity varies between the two materials, with perovskite materials generally exhibiting a more favourable temperature coefficient than silicon. This differentiation will allow the model to predict how tandem cells will perform in regions with extreme temperature variations, enhancing its applicability across diverse climatic zones.

Incidence Angle and Optical Modelling: The angle of solar incidence on the cell's surface also impacts on the energy conversion efficiency. As the angle of incidence between the solar direction and the normal to the module's surface increases, the reflected irradiance increases, reducing the irradiance that can be absorbed. By simulating the angle-dependent optical properties of the tandem device, the model accounts for variations in light absorption as a function of the angle of incidence, which changes throughout the day and year. The model implemented in the simulation tool is the ASHRAE model [29], which by means of the incidence angle modifier factor, commonly known as IAM factor, accounts for these losses derived from the optical effect of the reflections on the module. An IAM factor of 0.05 is considered by default, although it could be adjusted to the tandem technology. Furthermore, based on the module's orientation and inclination angles and the irradiance data (either long-term timeseries of any temporal resolution or the typical meteorological year (TMY) datasets), SIMPV estimates the global, diffuse, direct, and reflected incident irradiance on the module's surface for each simulation step, using the three-component anisotropic model defined by [30].

Current–Voltage Curves: The conversion of solar radiation to electrical energy depends on the working point of the cell, defining a current–voltage curve (or I–V curve) that includes all the working points of the module. This curve depends on the irradiance level and cell temperature, modifying the working points and the performance of the module. For tandem devices, based on the effective irradiance absorbed by each layer (after considering absorption, spectral response and angle of incidence), the current generated should be estimated. Identify the limiting layer, the one with the lowest current, and that would be the current of the module or cell. The estimation method implemented in SIMPV for the definition of the working points of the curve was developed by [31], applying the Lambert W-function for the resolution of the I–V curve expression.

Electrical Connection: The electrical connection of the modules can also modify the I–V curve, so much so that the working point that would allow the maximum power generation by the modules connected in series could be different from the optimum working point of the modules if they were not connected in series. This effect has been modelled adding all the individual modules' I–V curves of the string, calculating the maximum power point on the final curve.

Electrical Effect of Shadings: The differences between the incident irradiance on the cells connected in series modify the I–V curve of the module, reducing the module's power output. These shading losses depend on the position of the shading on the module and on the electrical layout of the module, and it may be one of the main energy losses in a PV plant. The shaded cells receive only the diffuse component of the irradiance, which means that, considering the effect of the bypass diodes, the I–V curve will be different depending of the position of the shading.

Material Degradation and Stability Considerations: An important challenge for perovskite-based cells is material stability, as perovskites are more sensitive to environmental degradation than silicon. The model can incorporate degradation rates based on laboratory-tested endurance metrics, allowing it to predict the gradual decline in yield over the cell's lifespan. This functionality is vital for accurately assessing the long-term economic and energy return on investment for tandem installations.

By integrating these parameters, the model implemented in SIMPV provides a comprehensive basis for assessing the energy yield of perovskite-silicon tandem cells under real-world conditions.

To enhance the model's accuracy and adaptability, several improvements are underway, aimed at refining the predictive accuracy of the energy yield assessment for tandem cells.

Real-Time Environmental Data Integration: SIMPV has already incorporated real-time environmental data to the model to adapt it to changing conditions, such as fluctuations in irradiance levels, ambient temperature, and cloud cover. By integrating meteorological data, the model can provide dynamically adjusted predictions for energy yield, making it possible to provide highly accurate, site-specific performance forecasts. However, efforts must be made to be able to include and consider spectral irradiance data on the model.

Algorithmic Optimization for Orientation and Tracking: Advanced algorithms are being developed to optimize the orientation and alignment of tracking systems throughout the day. Traditional PV systems often employ single-axis or dual-axis tracking to maximize irradiance capture [32], however, tandem cells will require more nuanced control due to their multi-layer structure and specific spectral sensitivities.

Simulation-Based Validation and Scenario Testing: Improvements should include extensive simulation-based testing across diverse environmental scenarios to validate the model predictions and refine the algorithmic controls. By applying data from regions with different climatic profiles, such as high diffuse-to-direct light ratios, the model of tandem devices will be calibrated for accurate yield predictions in specific locations. This testing process is integral to improving the model’s robustness and adaptability, providing insights into potential deployment strategies for tandem cells in both high and low irradiance level regions.

Enhanced Material Degradation Modelling: Recognizing the unique degradation patterns of perovskite materials, enhancements are also being made to improve the model's capability to forecast degradation-related efficiency losses. This involves including degradation coefficients specific to perovskite materials and adjusting them based on empirical data from accelerated aging tests. This feature allows for predictive maintenance scheduling and supports long-term planning by offering an accurate estimate of energy yield decline over the lifetime of a perovskite-silicon installation.

3.3. Helmholtz Zentrum Berlin (HZB) & University of Ljubljana

HZB, working together with the faculty of Electrical Engineering at the University of Ljubljana, recently published their work on using energy yield modelling to extract information about the behaviour of 2T PK-Si tandem devices in realistic operation [21]. Their main goal was to qualitatively and quantitatively evaluate the long-term electrical energy production of PK-Si PV devices operating under realistic conditions and to optimize their structures with respect to the bandgap of the top perovskite sub-cell. The above paper contains details of the developed energy yield model in which each aspect of device operation is handled in a comprehensive way, including all relevant temperature-induced variations. In their subsequent work, detailed in [33], the modelling approach was validated with outdoor data on tandems and single junctions exposed in two different locations - Berlin and Ljubljana. During the validation, it was observed that it is essential to account for the daily reversible light-soaking effect (LSE) to reproduce the outdoor data with the simulation results and upgrade the model to account for this effect. Their work also investigated the energy losses associated with the light soaking effect at different locations using the upgraded energy yield model over the course of one typical meteorological year, for different types of devices operating in different geographical locations and in different orientation/installation cases. Their results showed that, depending on the location/climate, yearly LSE losses can amount to up to 3% in an optimally oriented PK-Si tandem solar cell, and monthly even up to 8%. This not only highlights the notable impact of LSE and the necessity for its accurate evaluation, but also reveals that in geographic regions with pronounced seasonal variations, wintertime performance of perovskite-based solar cells can be significantly lower than summertime performance – contrary to conventional PV technologies. With the presented methodology of combined outdoor measurement and EY modelling, both can be easily evaluated, leading to faster development of perovskite solar cells on their road towards commercialization.

4. Summary

Fraunhofer ISE, CENER and HZB all have available energy yield models, as described in the sections above, with significant expertise in yield modelling for solar cells, particularly single and multi-junction types, addressing various factors like irradiance data and encapsulation effects as well as the impact of light soaking effects on the final energy yield for tandems. Challenges, especially for perovskite tandem cells, remain in modelling textures efficiently, acquiring high-quality irradiance data, and understanding the temperature dependence of performance. Additionally, luminescence coupling and the optimization of top cell bandgap for different locations and illumination types are areas requiring further exploration. Finally, stability and degradation in perovskite-Si tandem cells are critical topics that are still in the early stages of yield modelling integration. For addressing these challenges, the extensive characterization possibilities at the partner institutes of the project consortium will make an invaluable contribution.

5. Publication bibliography

[1] Ballif, C.; Dicker, J.; Borchert, D.; Hofmann, Thomas (2004): Solar glass with industrial porous SiO2 antireflection coating: measurements of photovoltaic module properties improvement and modelling of yearly energy yield gain. In *Solar Energy Materials & Solar Cells* 82 (3), pp. 331–344. DOI: 10.1016/j.solmat.2003.12.004.

[2] Ebert, M.; Stascheit, H.; Haedrich, I.; Eitner, U. (2014): The Impact of Angular Dependent Loss Measurement on PV Module Energy Yield Prediction. 4 pages / 29th European Photovoltaic Solar Energy Conference and Exhibition; 3244-3247. In: 29th European PV Solar Energy Conference and Exhibition. 29th European PV Solar Energy Conference and Exhibition. Amsterdam, 22.-26.09.2014.

[3] Steiner, Marc; Siefer, Gerald; Hornung, Thorsten; Peharz, Gerhard; Bett, Andreas W. (2015): YieldOpt, a model to predict the power output and energy yield for concentrating photovoltaic modules. In *Prog. Photovolt: Res. Appl.* 23 (3), pp. 385–397. DOI: 10.1002/pip.2458.

[4] Dirnberger, Daniela; Blackburn, Gina; Müller, Björn; Reise, Christian (2015): On the impact of solar spectral irradiance on the yield of different PV technologies. In *Solar Energy Materials and Solar Cells* 132, pp. 431–442. DOI: 10.1016/j.solmat.2014.09.034.

[5] Walker, A. W.; Höhn, Oliver; Micha, D. N.; Wagner, L.; Helmers, H.; Bett, A. W.; Dimroth, F. (2015): Impact of photon recycling and luminescence coupling on III–V single and dual junction photovoltaic devices. In *J. Photon. Energy* 5 (1), p. 53087. DOI: 10.1117/1.JPE.5.053087.

[6] Tucher, Nico; Höhn, Oliver; Murthy, J. N.; Martinez, J. C. Steiner, M.; Armbruster, A.; Lorenz, E. et al. (2019): Energy yield analysis of textured perovskite silicon tandem solar cells and modules. In *Optics Express* 27 (20), A1419. DOI: 10.1364/OE.27.0A1419.

[7] Höhn, O.; Hanser, M.; Steiner, M.; Lorenz, E.; Bläsi, Benedikt; Glunz, S. W.; Dimroth, F. (2021a): Energy Yield and Performance Ratio of III-V on Silicon Dual Junction Solar Cells in Different Climate Zones. 6 pages / 38th European Photovoltaic Solar Energy Conference and Exhibition; 515-520. DOI: 10.4229/EUPVSEC20212021-3BV.2.66.

[8] Höhn, Oliver; Murthy, Jayanth N.; Steiner, Marc; Tucher, Nico; Lorenz, Elke; Goldschmidt, Jan Christoph et al. (2021b): Impact of Irradiance Data on the Energy Yield Modeling of Dual-Junction Solar Module Stacks for One-Sun Applications. In *IEEE J. Photovoltaics* 11 (3), pp. 692–698. DOI: 10.1109/JPHOTOV.2021.3064562.

[9] Tucher, Nico; Eisenlohr, Johannes; Gebrewold, Habtamu; Kiefel, Peter; Höhn, Oliver; Hauser, Hubert et al. (2016): Optical simulation of photovoltaic modules with multiple textured interfaces using the matrix-based formalism OPTOS. In *Optics Express* 24 (14), pp. A1083. DOI: 10.1364/oe.24.0a1083.

[10] Kato, Seiji; Ackerman, Thomas P.; Mather, James H.; Clothiaux, Eugene E. (1999): The k-

distribution method and correlated-k approximation for a shortwave radiative transfer model. In *Journal of Quantitative Spectroscopy and Radiative Transfer* 62 (1), pp. 109–121. DOI: 10.1016/S0022-4073(98)00075-2.

[11] Keith McIntosh, Malcolm Abbott, Ben Sudbury et al.: PV Lighthouse: SunSolve™. accessed 20 April 2020. Available online at https://www.pvlighthouse.com.au.

[12] Gota, Fabrizio; Schmager, Raphael; Farag, Ahmed; Paetzold, Ulrich W. (2022): Energy yield modelling of textured perovskite/silicon tandem photovoltaics with thick perovskite top cells. In *Opt. Express* 30 (9), pp. 14172–14188. DOI: 10.1364/OE.447069.

[13] Wilcox, S.; Marion, W. (2008): Users Manual for TMY3 Data Sets (Revised). NREL (TP-581-43156)

[14] International Standard 61853-4, 2018: Photovoltaic (PV) module performance testing and energy rating – Part 4: Standard reference climatic profiles.

[15] Amillo, Ana; Huld, Thomas; Vourlioti, Paraskevi; Müller, Richard; Norton, Matthew (2015): Application of Satellite-Based Spectrally-Resolved Solar Radiation Data to PV Performance Studies. In *Energies* 8 (5), pp. 3455–3488. DOI: 10.3390/en8053455.

[16] Aydin, Erkan; Allen, Thomas G.; Bastiani, Michele de; Xu, Lujia; Ávila, Jorge; Salvador, Michael et al. (2020): Interplay between temperature and bandgap energies on the outdoor performance of perovskite/silicon tandem solar cells. In *Nature Energy* 5, pp. 851–859. DOI: 10.1038/s41560-020-00687-4.

[17] Chojniak, David; Steiner, Marc; Reichmuth, Sebastian Kasimir; Rößler, Torsten; Schmid, Alexandra; Siefer, Gerald; Glunz, Stefan W. (2023): Outdoor measurements of a full-size bifacial Pero/Si tandem module under different spectral conditions. In *Prog Photovoltaics* to be published, Article pip.3753. DOI: 10.1002/pip.3753.

[18] Jošt, Marko; Lipovšek, Benjamin; Glažar, Boštjan; Al-Ashouri, Amran; Brecl, Kristijan; Matič, Gašper et al. (2020): Perovskite Solar Cells go Outdoors: Field Testing and Temperature Effects on Energy Yield. In *Adv. Energy Mater.* 10 (25), p. 2000454. DOI: 10.1002/aenm.202000454.

[19] Shockley, William; Queisser, Hans J. (1961): Detailed Balance Limit of Efficiency of p-n Junction Solar Cells. In J. Appl. Phys. 32 (3), p. 510. DOI: 10.1063/1.1736034.

[20] Aeberhard, Urs; Zeder, Simon J.; Ruhstaller, Beat (2024): Effects of Photon Recycling and Luminescent Coupling in All-Perovskite Tandem Solar Cells Assessed by Full Opto-electronic Simulation. In *Sol. RRL* 8 (14), Article 2400264. DOI: 10.1002/solr.202400264.

[21] Tomšič, Špela; Jošt, Marko; Brecl, Kristijan; Topič, Marko; Lipovšek, Benjamin (2023): Energy Yield Modeling for Optimization and Analysis of Perovskite-Silicon Tandem Solar Cells Under Realistic Outdoor Conditions. In *Advcd Theory and Sims*, p. 2200931. DOI: 10.1002/adts.202200931

[22] Lehr, Jonathan; Langenhorst, Malte; Schmager, Raphael; Gota, Fabrizio; Kirner, Simon; Lemmer, Uli et al. (2020): Energy yield of bifacial textured perovskite/silicon tandem photovoltaic modules. In *Solar Energy Materials and Solar Cells* 208, p. 110367. DOI: 10.1016/j.solmat.2019.110367.

[23] Dupre, Olivier; Tuomiranta, Arttu; Jeangros, Quentin; Boccard, Mathieu; Alet, Pierre-Jean; Ballif, Christophe (2020): Design Rules to Fully Benefit From Bifaciality in Two-Terminal Perovskite/Silicon Tandem Solar Cells. In *IEEE Journal of Photovoltaics* 10 (3), pp. 714–721. DOI: 10.1109/JPHOTOV.2020.2973453.

[24] Chojniak, David; Schachtner, Michael; Reichmuth, S. Kasimir; Bett, Alexander J.; Rauer, Michael; Hohl-Ebinger, Jochen et al. (2024): A precise method for the spectral adjustment of LED and multi-light source solar simulators. In *Prog Photovoltaics* 32 (6), Article pip.3776, pp. 372–389. DOI: 10.1002/pip.3776.

[25] Orooji, Seyedamir; Paetzold, Ulrich W. (2024): Energy Yield Modeling of Perovskite–Silicon Tandem Photovoltaics: Degradation and Total Lifetime Energy Yield. In *Energy Technol.* to be published, Article 2400998. DOI: 10.1002/ente.202400998.

[26] W. F. Holmgren, C. W. Hansen, M. A. Mikofski, J. Open Source Software 2018, 3, 884

[27] D. L. King, W. E. Boyson, J. A. Kratochvil, Sandia Report SAND2004-3535, Sandia National Laboratories, Albuquerque, USA 2004.

[28] M. Prilliman, J. S. Stein, D. Riley, G. Tamizhmani, IEEE J. Photovoltaics 2020, 10, 1053.

[29] A. F. Souka, H. H. Safwat, Sol. Energy 1966, 10, 170.

[30] R. Perez, P. Ineichen, R. Seals, J. Michalsky, R. Stewart, Sol. Energy 1990, 44, 271

[31] A. Jain, A. Kapoor, Sol. Energy Mater. Sol. Cells 2004, 81, 269.

[32] I. Muñoz, A. Guinda, G. Olivares, S. Díaz, A.M. Gracia-Amillo and L. Casajús. Sol. RRL 2023, 2300507

[33] Remec et. al (2024): From Sunrise to Sunset: Unraveling Metastability in Perovskite Solar Cells by Coupled Outdoor Testing and Energy Yield Modelling. Advanced Energy Materials. DOI: 10.1002/aenm.202304452