solar

Article

Policies for Promising Prospects of Photovoltaics

Lucie McGovern [1,2,*] and Bob van der Zwaan [1,3,4]

[1] Faculty of Science (HIMS and IAS), University of Amsterdam, 1098 Amsterdam, The Netherlands
[2] Center for Nanophotonics, Amsterdam Institute for Molecular and Life Sciences, 1098 Amsterdam, The Netherlands
[3] Netherlands Organization for Applied Scientific Research, Energy Transition Studies (ETS), 1043 Amsterdam, The Netherlands
[4] School of Advanced International Studies (SAIS), Johns Hopkins University, 40126 Bologna, Italy
* Correspondence: lucie.mcgovern@free.fr

Abstract: As photovoltaics' (PVs) capacity will probably rapidly expand to tens of terawatts globally, the diversification of the PV technology portfolio becomes essential. Perovskite technology proffers promise for expanding solar energy market segments like building-integrated PVs and flexible PVs for the residential and industrial sectors. In this perspective, we calculate that under reasonably attainable values for the module cost, conversion efficiency, and degradation rate, a levelized cost of electricity (LCOE) of 10 EURct/kWh can be reached for perovskite PV in 2035. Furthermore, if, in 2035, the conversion efficiency can be increased to 25% and the degradation rate falls to below 1%, with a module cost of 50 EUR/m^2, the LCOE for perovskite PV could become around 8 EURct/kWh. For lower module costs, the LCOE would drop further, by which cost competitiveness with c-Si PV is in sight. We point out that even if the LCOE of perovskite solar modules may remain relatively high, they could still occupy an important role, particularly in the residential sector, thanks to their flexibility and lightweight properties, enabling a large suite of new applications. Overall, to push perovskite PVs towards successful commercialization, policy support will be indispensable.

Keywords: solar energy; perovskite modules; flexible PVs; technology push; market pull; LCOE

check for updates

Academic Editor: Jürgen Heinz Werner

Received: 28 February 2025
Revised: 13 May 2025
Accepted: 15 May 2025
Published: 19 May 2025

Citation: McGovern, L.; van der Zwaan, B. Policies for Promising Prospects of Photovoltaics. *Solar* **2025**, *5*, 22. https://doi.org/10.3390/solar5020022

1. Introduction

As the window to limit climate change to 1.5 °C is closing, calls to rapidly reduce greenhouse gas emissions are louder than ever, highlighting the urgency to phase out our global dependence on fossil fuels. While less stringent in its formulation, COP28's agreement took a step in this direction by mentioning for the first time a "transition away from fossil fuels". As of 2025, a total of 102 countries have pledged to reduce their CO_2 emissions to net zero by 2050, and 33 have already translated this target into law [1]. In the EU, these decarbonisation ambitions materialized with the European Green Deal (EGD), the EU's core action plan that aims to make Europe the first climate-neutral continent, which was later complemented by the Fit for 55 package, a set of policy proposals preparing the implementation of the EGD. Meanwhile, the energy crisis that followed the invasion of Ukraine by Russia in 2022 placed energy security at the forefront of the political agenda. In order to rapidly reduce its natural gas imports and to hasten the deployment of renewable energies, the EU proposed the REPower plan. With shifting international geopolitics and a growing influence of authoritarian regimes, the EU is face-to-face with the need to strengthen its energy systems' resilience and to guarantee Europe's long-term energy independence.

To address the two distinct but critical challenges of energy sustainability and energy security, a massive upscaling of renewable energy technologies is imperative, as outlined in COP28's agreement to triple the renewable energy capacity by 2030. In this regard, the recent success of photovoltaics (PVs) is particularly remarkable. The exponential growth of PV projects has been such that the milestone of 1 terawatt peak (TWp) of global installed capacity was reached in 2022, after 68 years of development in the field of PVs, while the next milestone of 2 TWp was reached only 2 years later, in 2024 [2,3]. This is largely due to PVs' incessantly decreasing levelized cost of electricity (LCOE). The unmatched increase in PV deployment is expected to continue during the coming decades [4]. For the future of PVs, this means that the road ahead of us will be written on the multi-terawatt scale [5].

As the global PV capacity continues to grow, a new question arises, related to the type of technologies that should underlie the PV sector, specifically in terms of their suitability to match a huge increase in demand. Currently, crystalline silicon (c-Si) PV technology dominates global sales, accounting for 95% of the total market share. This technology has enabled the record-breaking LCOE values achieved globally, with power purchase agreements attaining figures below 1.5 EURct/kWh [6,7]. Given its impressive LCOE benefits, c-Si technology is expected to continue to drive solar PVs forward, especially in the utility sector. However, this technology might not always be the most suitable option, for instance, when considering the heavy weight and the rigid architecture of the majority of c-Si modules to date. More broadly speaking, developing a rich portfolio of PV technologies can prove beneficial for strengthening the diversity and resilience of the PV sector, so as to answer the specific needs of a growing variety of market applications.

Current alternatives to c-Si (e.g., cadmium telluride, copper indium gallium selenide, and amorphous silicon) all show limited upscaling potential, either due to material scarcity, material toxicity, and/or low efficiencies in comparison to c-Si PV [8]. This presents an opportunity for new materials that may address these intertwined challenges. One promising candidate is perovskite PVs, which rely on abundant resources, offer larger theoretical efficiencies than c-Si PVs, and show potential for high-throughput manufacturing using roll-to-roll processes. Above all, perovskite material can be fabricated on top of plastic bottom layers, which means that perovskite-based solar PV modules can combine both flexible and lightweight properties. This combination of flexible and lightweight features renders perovskite technology a great candidate for certain expanding PV market segments, such as building-integrated PVs (BIPVs) and flexible PVs for the residential and industrial sectors [9], provided that c-Si modules do not also follow the same path.

A successful diversification of the PV technology portfolio relies on whether newcomers like perovskite solar modules manage to reach the commercialisation stage. With this perspective, we attempt to answer three questions. First, what LCOE could we expect from flexible perovskite solar modules until 2035? Second, how can the policymaking field contribute toward reaching these LCOE values? Third, how do these figures compare to those delivered by c-Si PV?

2. Methods

We calculated the LCOE of perovskite PVs using the discounting method [10], specifically mapping the LCOE values as a function of the efficiency and stability performances achievable for perovskite technology [11]. Efficiency is represented in terms of power conversion efficiency (CE), and stability is represented using the annual degradation rate (DR).

For our purposes, we focus on the residential sector, as this is the scale at which the low weight and flexible nature of perovskite modules are expected to have the most impact; however, we do not exclude that the industrial sector might also make use of these properties in larger PV systems. On the other hand, the utility sector will most probably not be the most fitting sector for flexible perovskite modules, even when explicitly including lower installation costs [11]. Our input values are taken from Fraunhofer ISE's report, which aggregates the costs found for residential sector PV installations in Germany for the year 2021 [12].

For the year 2025, we base the perovskite module cost at 75 EUR/m^2. The lowest estimates for perovskite production go as low as 18 EUR/m^2, but these are taken considering rigid modules, while manufacturing flexible modules is found to be more costly [11]. Additionally, some of these cost estimates already include economies of scale, which we expect will show their benefits in later years. Here, we consider the value of 75 EUR/m^2 to be more realistic, especially when considering the initial production phases of perovskite commercialisation. Applying a learning rate (LR) of 20% for modules [13,14], we achieved a projected module cost of 50 EUR/m^2 by 2035. (See Supporting Information for additional details on the learning rates used in this study).

The balance-of-system (BOS) costs for perovskite PVs are calculated based on those of silicon PVs, and these are expressed as a percentage of the total capital expenditures (CAPEX) of the c-Si PVs in the residential sector [15]. Specifically, we take 60% of the total 1300 EUR/kWp CAPEX as BOS costs [12,16], with 42% of that fraction dependent on module efficiency and the remaining 18% independent of module efficiency [17]. This results in BOS costs of 109.2 EUR/m^2 for the area-dependent BOS costs (to be divided by the perovskite CE of interest, to obtain a cost in EUR/kWp) and an additional 234 EUR/kWp representing the capacity-dependent BOS costs. For 2035, the BOS function remains the same, but the terms are recalculated to incorporate a 10% LR from BOS [18]. This is equivalent to 90.3 EUR/m^2 (again, divided by module CE to obtain the cost in EUR/kWp) and an additional fixed 193.4 EUR/kWp. (For additional considerations on factors impacting the LCOE, we refer to the Supporting Information.)

The speed at which perovskite production is expected to grow—also known as the compound annual growth rate (CAGR)—is set to 25% between 2025 and 2035, based on previous work for PV technologies [19]. This parameter is needed to calculate the values for module costs and BOS costs in 2035.

For the table presented at the end of this work, we followed the methodology described above, and selected the performance indicators as follows: 15% CE for perovskite modules in 2025, gradually increasing to 18% by 2035 (0.3% annual progress), and 2% DR in 2025, gradually decreasing to 1.5% by 2035 (0.1% annual progress). European irradiation conditions are set at 1200 kWh/m^2/yr, and high irradiation conditions are at 2400 kWh/m^2/yr.

3. Results and Discussion

3.1. Establishing a New Commercial Technology in 2025

Our goal in this work is to investigate the LCOE that perovskite solar modules may achieve by 2025, and further, by 2035. In Figure 1, we present the LCOE map of perovskite PVs for the residential sector in 2025, based on a module scenario of 75 EUR/m^2. This map demonstrates a range of LCOE values from 9.3 EURct/kWh to 36.3 EURct/kWh, indicating a substantial total variation of 27 EURct/kWh.

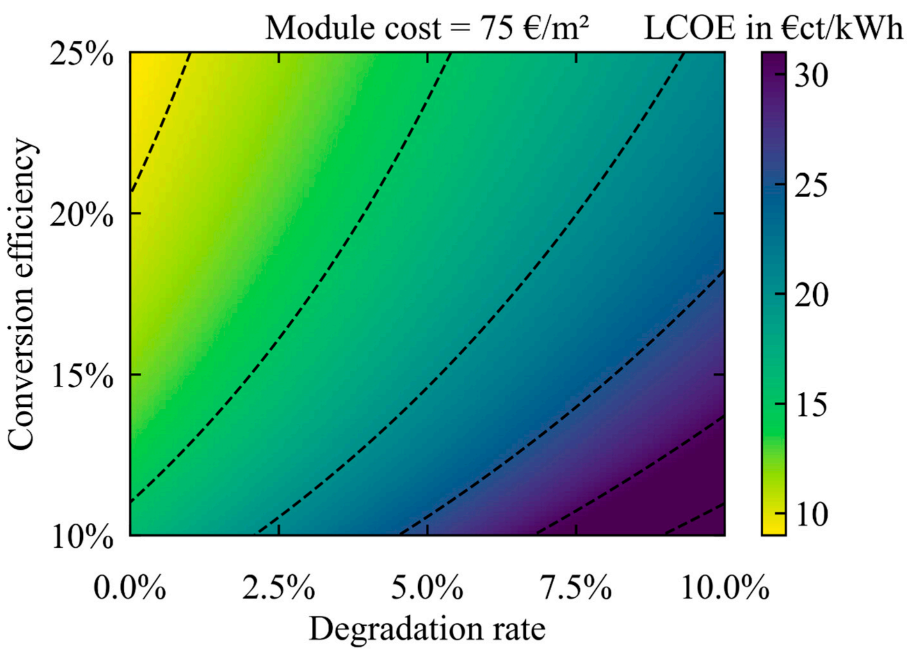

Figure 1. LCOE of flexible perovskite modules installed for the residential sector, as a function of their conversion efficiency and degradation rate, in 2025, for a manufacturing cost of 75 EUR/m^2.

The specific LCOE depends on both the efficiency and stability performances that the perovskite modules reach by that date. From the efficiency side, a theoretical module that would not experience any degradation (i.e., with DR fixed at 0%) would see its LCOE increase from 9 to 16 EURct/kWh when the module CE decreases from 25% to 10%. Even in the optimistic scenario of a 1% DR, the LCOE would still vary from 10 to 17 EURct/kWh under the same CE decrease. As expected, the module CE is thus found to be an essential aspect of the technology to reduce the overall LCOE. On the stability side, the impact is even more pronounced. Even with an optimistic CE of 25%, if the DR is set at the maximal limit in our map, 10%, the LCOE can reach as high as 22 EURct/kWh. This finding emphasizes that achieving low LCOEs for perovskite technology relies not only on efficiency, but also on stability performance. Within perovskite research, the shift in emphasis towards studying and improving the stability of perovskite modules [20,21] aligns with our findings.

Another notable finding from our perovskite LCOE map in 2025 is that, in general, the achieved LCOE of perovskite PVs remains higher compared to that of c-Si PVs taken under similar conditions. In our previous work, we determined the LCOE for c-Si PVs in the residential sector to be 11.7 EURct/kWh [15]. To achieve a comparable LCOE with perovskite PV modules in 2025, it would require a conversion efficiency (CE) exceeding 16% and an annual degradation rate (DR) below 2.5%. Overall, this represents only a small portion of the map from Figure 1. However, it is crucial to recognize the advantages offered by perovskite modules in terms of flexibility and lightweight properties. These characteristics enable their deployment in new and challenging scenarios. For example, they can be installed on rooftops with complex geometries and angles, or on buildings with lower structural integrity, where the load of c-Si modules was previously a limitation—even if we do acknowledge that the field of c-Si PVs could still also evolve towards lightweight and flexible modules. These novel settings align with the BIPV and flexible PV market segments, which currently both show largely untapped potential. Under present conditions, lightweight flexible perovskite modules thus offer an intrinsically interesting market proposition for the PV industry, even when their LCOE is higher than c-Si PVs.

On top of these considerations, we highlight that with significant R&D efforts, it is possible to reduce the cost gap between perovskite and c-Si PVs, and even to close it fully, in order to achieve the lowest LCOE possible for perovskite PVs in 2025. Indeed, considering a CE of 25% and a DR of 1%, perovskite modules could reach a LCOE of 10 EURct/kWh, making them cost-competitive with silicon PVs, and even surpassing this technology by a non-negligible margin of 1.7 EURct/kWh. This highlights the potential for perovskite PVs to become competitive with c-Si PVs, not only as a new market proposition, but also from an LCOE perspective, through appreciable advancements of the technology's performance indicators. Considering these promising possibilities, it is valuable to implement policies geared specifically towards technological innovations [22]. These policies, often referred to as technology push policies, would provide strategic support to foster the adoption of perovskite PVs, recognizing their potential to become a competitive alternative to c-Si PVs.

Specifically, technology push policies can support perovskite technology by developing research grants in three key directions. The first R&D direction aims at bridging the efficiency gap associated with scaling. There, we need to ensure that the high CEs observed in laboratory settings, when measuring perovskite solar cells under small aperture area conditions (of 1 cm^2 and smaller), can be maintained as we scale up the technology for larger devices, up to the few m^2 scale needed for complete devices (see Supporting Information for a further discussion on the technical challenges and strategies for scaling up perovskite solar cells). The second R&D direction aims at closing the efficiency gap linked to material processing. Here, it is important that the highest CEs obtained, which are those measured for rigid perovskite cells (i.e., when the perovskite layer is deposited onto rigid bottom layers), are also achieved when transitioning towards the plastic bottom layers, which form the flexible perovskite cells. Ultimately, this step is needed to deliver the lightweight and flexible properties desired. The third R&D direction is geared towards closing in on the stability gap. Here, it is crucial to extend our understanding of the failure mechanisms in perovskite materials and to design effective protection barriers against the main degradation pathways. This R&D direction also entails performing outdoor testing of perovskite solar modules (including for prolonged time durations, and for flexible modules used in various bending geometries), and increasing the reporting of accelerated aging tests [23,24]. If necessary, new aging tests specific to perovskite technology should also be developed [25]. With sufficient R&D funding, there is a higher likelihood for perovskite modules to meet all three objectives and excel in both CE and DR dimensions. Technology push policies, through the development of research grants and the allocation of necessary funding, can thus have a significant impact on driving perovskite PV technology forward.

3.2. Improving the Technology and Consolidating Its Market Share by 2035

We now move to the development of perovskite technology towards the year 2035, which we set as our second reference year after 2025, in order to explore the benefits that might be obtained within a ten-year span of technology development and policymaking. In 2035, we assume we have unlocked significant learning-by-doing, both in terms of module manufacturing and for the general installation of these modules. Specifically, we consider a 20% LR for modules and a 10% LR for BOS. In Figure 2, we show the resulting LCOE map for perovskite PVs in the residential sector in 2035, developed as a function of stability and efficiency of the perovskite solar modules.

This map shows a reduction in LCOE for the year 2035 compared to 2025. The range of achievable LCOE values has shifted, with the lowest now reaching 7.7 EURct/kWh and the highest, 29.5 EURct/kWh, thus reducing the total LCOE variation to 22 EURct/kWh (compared to 27 EURct/kWh in 2025). In detail, this represents a 1.6 EURct/kWh difference when comparing the best-case scenarios of 2025 and 2035, and a considerable 6.8 EURct/kWh difference when comparing the worst-case scenarios. For a time period of only 10 years, this represents a substantial decrease in the LCOE of perovskite PVs within the residential sector, and constitutes a significant justification for the development and successive upscaling of perovskite PVs between 2025 and 2035.

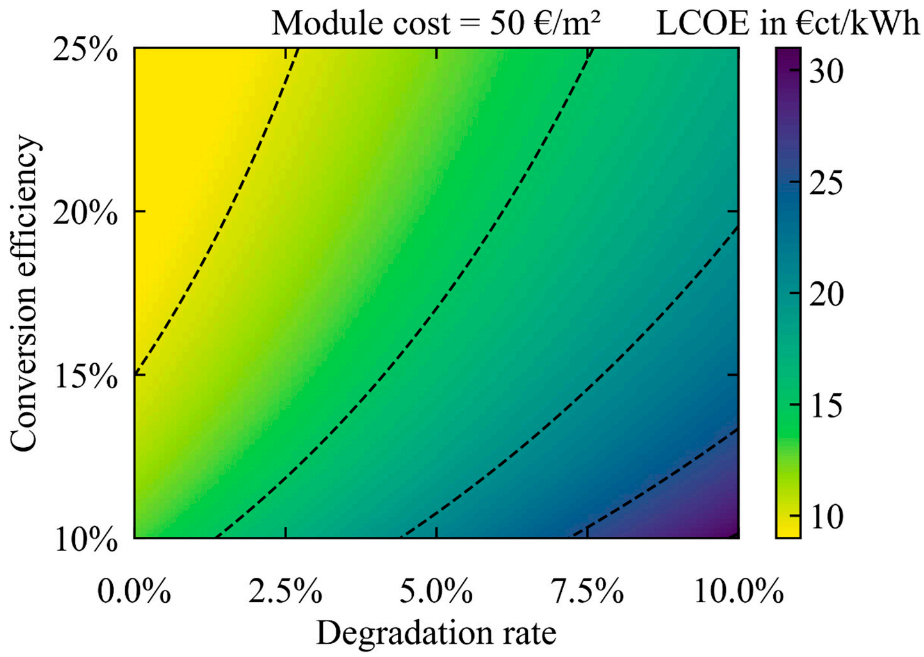

Figure 2. LCOE of flexible perovskite modules installed for the residential sector, as a function of their conversion efficiency and degradation rate, in 2035, for a manufacturing cost of 50 EUR/m^2.

The LCOE map presented in Figure 2 also highlights the potential benefits of implementing market pull policies. This type of policy focuses on creating market demand, encouraging the adoption of a technology, and creating favorable conditions for industry growth [22], in contrast to technology push policies, which aim at enhancing the value of a technology through technological innovations and enhanced performance. In the context of perovskite PVs, market pull policies can impact the timing at which the initial production of perovskite modules takes place, but also the speed at which the market for perovskite modules then further grows. Specifically, the significant reduction in LCOE, which we calculated for 2035, is the result of both the early onset of the production of the first perovskite modules in 2025 and the rapid extension of the market for these modules, with a 25% CAGR between 2025 and 2035. These two conditions both need to be met in order to benefit from the ambitious learning-by-doing proposed here, which, in turn, proves essential to achieve the notable LCOE reductions showcased in Figure 2.

Even with the general reduction in LCOE described above, it is important to note that achieving an overall low LCOE in 2035 still requires the combination of both high efficiency and high stability performances. We turn first to the impact of CE: considering a DR of 1%, increasing the CE from 10% to 25% leads to a decrease in LCOE from 14.3 to 8.5 EURct/kWh. Similarly, we look at the impact of DR. With an optimal CE of 25%, reducing the DR from 10% to a theoretical 0% leads to a decrease in LCOE from 17.6 to 7.7 EURct/kWh. Together with the early and rapid growth of the market for flexible perovskite modules, achieving a high CE and low DR thus remains a high priority. Continuing technology push policies, specifically aimed at unlocking the highest possible technology performances, will therefore continue to play a favorable role in reducing the LCOE of perovskite PVs. Lastly, if the cost competition with c-Si PVs is harder to project for 2035 than for 2025, the possibility of seeing a narrowing (and possibly overcoming) of the LCOE gap between c-Si PVs and perovskite PVs will clearly be positively affected by the pursuit and successful implementation of technology push and demand pull policies.

In Table 1, we summarize our findings and show the LCOE values that can be achieved by perovskite PVs within the residential sector, under a set of realistic conditions, both in 2025 and 2035. If the modeled LCOE of perovskite PVs is higher than that of c-Si PVs in 2025, perovskite PVs still show intrinsic value, thanks to the lightweight and flexible properties of the solar modules (provided these features are not unlocked by c-Si PVs, at a competitive cost, in the future). Additionally, the LCOE gap can be reduced and possibly overcome by 2035 through unlocking technological innovations (thereby increasing the efficiency and stability of the modules) and through creating a strong and rapidly expanding perovskite manufacturing industry that is capable of extending the BIPV and flexible PV market segments.

Table 1. LCOE of flexible perovskite modules installed in the residential sector, in 2025 and in 2035, under either European or high irradiation conditions, compared to the modeled LCOE of c-Si PVs for 2025.

LCOE (EURct/kWh)	In 2025	In 2035	c-Si PV (Model/2025)
Under European irradiation	15.0	10.5	11.7
Under high irradiation	7.5	5.3	5.9

4. Conclusions

In this perspective, we formulate scenarios for the cost development of perovskite PV technology by 2025 and until 2035. In 2025, assuming a 75 EUR/m^2 module cost, 15% CE, and 2% DR, we project a LCOE of 15 EURct/kWh for perovskite PVs in the residential sector. Looking ahead to 2035, with a 50 EUR/m^2 module cost, 18% CE, and 1.5% DR, the projected LCOE reduces to close to 10 EURct/kWh. These LCOE values may well be higher than those for c-Si PVs; for 2025, they most certainly are. Additionally, we recognize that the successful adoption of perovskite PVs also depends on establishing a reliable supply chain of perovskite modules (see the Supporting Information for additional details) and addressing the regulatory and safety challenges related to the stability and toxicity of lead, which have been discussed in the literature [26,27]. Yet, we argue that flexible perovskite solar modules are still able to serve new purposes, specifically in the residential sector, for which the PV market is expected to grow considerably over the coming years. Especially, flexible and lightweight PVs in the residential sector might prove particularly beneficial for rooftops with tilted angles, curved shapes, and/or low structural integrity, for which the use of c-Si PVs has only recently emerged, and for which perovskite PVs appear a strong candidate. We thus argue that the policy scene should not only prepare for, but also actively support, a successful diversification of the PV technology portfolio, as proposed in this perspective, since this will prove essential for the resilience of the PV sector when it moves towards multi-TWp capacities.

We propose two types of policies that could stimulate the deployment of perovskite PVs. First, technology push policies, for instance in the form of funding for R&D, can lead to the optimization of the performance of perovskite solar modules, not only in terms of efficiency, but also stability. A good example in case is the recently launched SolarNL program [28], in which enhanced fundamental research and market-oriented R&D are orchestrated in close collaboration with industry and the policy arenas in the Netherlands, and that could serve as a blueprint for other countries, notably in Europe. Second, market pull policies, such as tax breaks, subsidies, or other incentives for production facility construction (for instance, streamlined regulations or public procurement schemes) can play a crucial role, both by enabling early-stage manufacturing of perovskite solar modules and by providing a supportive ecosystem to rapidly expand the market segment.

Overall, adequate policy can contribute decisively towards the adoption of perovskite PVs, and allow this new technology to not only provide a viable alternative to c-Si PVs, but also, possibly, a cost-competitive one, especially in market segments in which c-Si PVs are hard to implement to date.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/solar5020022/s1.

Author Contributions: Conceptualization, B.v.d.Z.; methodology, investigation, and formal analysis, L.M.; writing—original draft, L.M.; writing—review and editing, L.M. and B.v.d.Z.; supervision, B.v.d.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the "Perovskite Foils by Roll-to-roll Manufacturing" (PerFoRM) consortium, where this paper was a recipient of a grant through NWO's KIC (Knowledge and Innovation Covenant) program, and was performed by L.M. at the University of Amsterdam under the supervision of B.v.d.Z. L.M. holds a guest position at the research institute AMOLF, where she benefited from direct interactions with members of the Light Management for PhotoVoltaics (LMPV) program. L.M. also benefited from the consortium members' expertise and knowledge, notably during site visits at TNO Eindhoven (partner in Solliance) and at HyET Solar, as well as through biannual progress meetings with all members of the consortium, namely VDL, SparkNano, Delmic, HyET Solar, TNO, Solliance, AMOLF, and UvA.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is contained within the article or Supplementary Materials.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Net Zero Tracker. Data Explorer. 2025. Available online: https://zerotracker.net/ (accessed on 28 February 2025).
2. IEA-PVPS. Snapshot 2023. Available online: https://iea-pvps.org/snapshot-reports/snapshot-2023/ (accessed on 1 September 2024).
3. pv Magazine International. *Global Installed PV Capacity Tops 2 TW*; pv Magazine International, 2024. Available online: https://www.pv-magazine.com/2024/11/13/global-installed-pv-capacity-tops-2-tw/ (accessed on 1 September 2024).
4. Victoria, M.; Haegel, N.; Peters, I.M.; Sinton, R.; Jäger-Waldau, A.; del Cañizo, C.; Breyer, C.; Stocks, M.; Blakers, A.; Kaizuka, I.; et al. Solar photovoltaics is ready to power a sustainable future. *Joule* **2021**, *5*, 1041–1056. [CrossRef]
5. Haegel, N.M.; Verlinden, P.; Victoria, M.; Altermatt, P.; Atwater, H.; Barnes, T.; Breyer, C.; Case, C.; De Wolf, S.; Deline, C.; et al. Photovoltaics at multi-terawatt scale: Waiting is not an option. *Science* **2023**, *380*, 39–42. [CrossRef] [PubMed]
6. pv Magazine International. *Strong Growth Predicted for Middle Eastern Solar PV*; 2021. Available online: https://www.pv-magazine.com/2021/06/25/strong-growth-predicted-for-middle-eastern-solar-pv/ (accessed on 1 September 2024).
7. SolarQuarter. *JinkoPower and EDF Renewables Consortium Sign the Power Purchase Agreement for the World's Single Largest Solar Project in Abu Dhabi*; SolarQuarter: Navi Mumbai, India, 2020.
8. Lee, T.D.; Ebong, A.U. A review of thin film solar cell technologies and challenges. *Renew. Sustain. Energy Rev.* **2017**, *70*, 1286–1297. [CrossRef]
9. Holzhey, P.; Prettl, M.; Collavini, S.; Chang, N.L.; Saliba, M. Toward commercialization with lightweight, flexible perovskite solar cells for residential photovoltaics. *Joule* **2023**, *7*, 257–271. [CrossRef]
10. Shen, W.; Chen, X.; Qiu, J.; Hayward, J.A.; Sayeef, S.; Osman, P.; Meng, K.; Dong, Z.Y. A comprehensive review of variable renewable energy levelized cost of electricity. *Renew. Sustain. Energy Rev.* **2020**, *133*, 110301. [CrossRef]
11. McGovern, L.; Garnett, E.C.; Veenstra, S.; van der Zwaan, B. A techno-economic perspective on rigid and flexible perovskite solar modules. *Sustain. Energy Fuels.* **2023**, *7*, 5259–5270. [CrossRef] [PubMed]
12. Fraunhofer ISE. *Levelized Cost of Electricity. Renewable Energy Technologies*; Fraunhofer ISE: Freiburg, Germany, 2021.
13. Haegel, N.M.; Atwater, H.; Barnes, T.; Breyer, C.; Burrell, A.; Chiang, Y.M.; De Wolf, S.; Dimmler, B.; Feldman, D.; Glunz, S.; et al. Terawatt-scale photovoltaics: Transform global energy Improving costs and scale reflect looming opportunities. *Science* **2019**, *364*, 836–838. [CrossRef] [PubMed]

14. Rubin, E.S.; Azevedo, I.M.L.; Jaramillo, P.; Yeh, S. A review of learning rates for electricity supply technologies. *Energy Policy* **2015**, *86*, 198–218. [CrossRef]
15. McGovern, L.; Alarcón-Lladó, E.; Garnett, E.C.; Ehrler, B.; van der Zwaan, B. Perovskite Solar Modules for the Residential Sector. *ACS Energy Lett.* **2023**, *8*, 4862–4866. [CrossRef] [PubMed]
16. Fraunhofer ISE. *Photovoltaics Report*; Fraunhofer ISE: Freiburg, Germany, 2023.
17. Zafoschnig, L.A.; Nold, S.; Goldschmidt, J.C. The Race for Lowest Costs of Electricity Production: Techno-Economic Analysis of Silicon, Perovskite and Tandem Solar Cells. *IEEE J. Photovolt.* **2020**, *10*, 1632–1641. [CrossRef]
18. Elshurafa, A.M.; Albardi, S.R.; Bigerna, S.; Bollino, C.A. Estimating the learning curve of solar PV balance–of–system for over 20 countries: Implications and policy recommendations. *J. Clean. Prod.* **2018**, *196*, 122–134. [CrossRef]
19. IEA. *Solar PV–Analysis*; IEA: Singapore, 2022. Available online: https://www.iea.org/energy-system/renewables/solar-pv (accessed on 1 December 2022).
20. Correa-Baena, J.P.; Saliba, M.; Buonassisi, T.; Grätzel, M.; Abate, A.; Tress, W.; Hagfeldt, A. Promises and challenges of perovskite solar cells. *Science* **2017**, *358*, 739–744. [CrossRef] [PubMed]
21. Rong, Y.; Hu, Y.; Mei, A.; Tan, H.; Saidaminov, M.I.; Seok SIl McGehee, M.D.; Sargent, E.H.; Han, H. Challenges for commercializing perovskite solar cells. *Science* **2018**, *361*, eaat8235. [CrossRef] [PubMed]
22. Kavlak, G.; McNerney, J.; Trancik, J.E. Evaluating the causes of cost reduction in photovoltaic modules. *Energy Policy* **2018**, *123*, 700–710. [CrossRef]
23. Mavlonov, A.; Hishikawa, Y.; Kawano, Y.; Negami, T.; Hayakawa, A.; Tsujimura, S.; Okumura, T.; Minemoto, T. Thermal stability test on flexible perovskite solar cell modules to estimate activation energy of degradation on temperature. *Sol. Energy Mater. Sol. Cells* **2024**, *277*, 113148. [CrossRef]
24. Suo, J.; Yang, B.; Mosconi, E. Multifunctional sulfonium-based treatment for perovskite solar cells with less than 1% efficiency loss over 4,500-h operational stability tests. *Nat. Energy* **2024**, *9*, 172–183. [CrossRef] [PubMed]
25. Khenkin, M.V.; Katz, E.A.; Abate, A.; Bardizza, G.; Berry, J.J.; Brabec, C.; Brunetti, F.; Bulović, V.; Burlingame, Q.; Di Carlo, A.; et al. Consensus statement for stability assessment and reporting for perovskite photovoltaics based on ISOS procedures. *Nat. Energy* **2020**, *5*, 35–49. [CrossRef]
26. Moody, N.; Sesena, S.; deQuilettes, D.W.; Dou, B.D.; Swartwout, R.; Buchman, J.T.; Johnson, A.; Eze, U.; Brenes, R.; Johnston, M.; et al. Assessing the Regulatory Requirements of Lead-Based Perovskite Photovoltaics. *Joule* **2020**, *4*, 970–974. [CrossRef]
27. Chen, C.-H.; Cheng, S.-N.; Cheng, L.; Wang, Z.-K.; Liao, L.-S. Toxicity, Leakage, and Recycling of Lead in Perovskite Photovoltaics. *Adv. Energy Mater.* **2023**, *13*, 2204144. [CrossRef]
28. SolarNL. National Dutch PV Research, Innovation and Industry Program [WWW Document]. 2023. Available online: https://www.solarnl.eu/ (accessed on 19 November 2023).