Energy & Environmental Science

ROYAL SOCIETY OF CHEMISTRY

MINIREVIEW

View Article Online
View Journal | View Issue

Cite this: *Energy Environ. Sci.*, 2023, **16**, 421

The levelized cost of electricity from perovskite photovoltaics†

Michele De Bastiani, * Valentina Larini, Riccardo Montecucco and Giulia Grancini *

The levelized cost of electricity (LCOE) is a techno-economic analysis that evaluates the cost potential of any electricity-producing technology. LCOE represents a powerful metric to compare the most efficient renewable resources in the framework of the energy transition. Perovskite solar cells (PSCs) are an emerging technology with great potential to establish a leading position in the photovoltaic (PV) market, particularly in those regions that cannot rely on crystalline silicon manufacturing. However, like many emerging technologies, their positioning in the PV market is still quite speculative. Here, we revise the different models to evaluate the LCOE of PSCs, paying attention to the impact of performance, stability, and manufacturing costs. We consider the difference in performances from lab-record devices to modules fabricated in industrial production lines. We identify the key role of the degradation that is hindering the commercialization of PSCs and we analyze the manufacturing cost and the supply chain availability. From our analysis, we restricted the LCOE to 3–6 cents (USD) per kWh, which is competitive with the best of the mainstream silicon technologies (passivated emitter and rear contact, PERC). In conclusion, we highlight the future challenges to refine the LCOE calculations, including temperature effects.

Received 27th September 2022,
Accepted 16th December 2022

DOI: 10.1039/d2ee03136a

rsc.li/ees

Broader context

Renewable energies have an enormous potential to stand out against the climate crisis, replacing fossil fuels as the main source of energy. The choice between one or another source is often dictated by geographical location and socio-economic factors. Nevertheless, it is important to have a universal parameter that defines the overall competitiveness of each technology. Since renewable energies are mostly dedicated to the production of electricity, the levelized cost of electricity (LCOE) is a valuable parameter that sets common ground among all renewable sources. In its simplest expression, the LCOE defines the ratio between the costs required to produce electricity and the total electricity generated by a system. The LCOE is usually expressed in currency per kilowatt hour. Furthermore, LCOE allows for competitive analysis within the same branch of a specific renewable source. For example, the LCOE can be used to evaluate emerging photovoltaic (PV) technologies that are, otherwise, judged only on their performances. This is the case of halide perovskites, a recent class of semiconducting materials with an outstanding performance of light-to-electricity conversion. Despite this enormous potential, many uncertainties related to the stability of the perovskite, the efficiency of industrial modules, and the costs of the manufacturing process, hinder a precise evaluation of the LCOE. Thus, here we address in this minireview all the critical factors, pointing out the main challenges and open issues that need to be solved in order to attain a reliable LCOE value.

Introduction

The levelized cost of electricity (LCOE) is a common analysis that defines the market competitiveness of different energy sources for the production of electricity. In its simplest expression, the LCOE defines the ratio between the costs required to produce electricity and the total electricity generated by a system.[1] The LCOE is usually expressed in currency per kilowatt hour (often USD cent or EUR cent, c$ per kW h; c€ per kW h). A common use of the LCOE is a comparative analysis of similar technologies, for example, the competitivity of different types of photovoltaic (PV) systems. In solar panels, the power conversion efficiency (PCE) depends mostly on the type of technology used, varying from 10% to more than 20% for commercial products.[2] However, an evaluation of the competitivity only based on the PCE is a limitation. Indeed, we need to consider also the costs related to the manufacturing, installation, maintenance, and stability of the performance. On the contrary, the LCOE gives an absolute metric of evaluation which enables

[1]*Department of Chemistry & INSTM Università di Pavia, Via T. Taramelli 14, Pavia 27100, Italy. E-mail: michele.debastiani@unipv.it, giulia.grancini@unipv.it*

† Electronic supplementary information (ESI) available. See DOI: https://doi.org/10.1039/d2ee03136a

comparative analysis. Moreover, the LCOE becomes progressively important for the evaluation of emerging technologies that are, otherwise, judged only on their PCE. This is the case of halide perovskites, a recent class of emerging semiconducting materials with an outstanding performance of light-to-electricity conversion.[3] In a decade of research, perovskite solar cells (PSCs) have achieved in lab-scaled devices a conversion efficiency of 25.7%,[4] which is close to the record of the crystalline silicon technologies at the research level.[5] Moreover, the combination of perovskites with the best crystalline silicon technology enables multijunction solar cells with an astonishing PCE $>31\%$.[6] Despite this surge in device performance, there are still many uncertainties regarding the impact of PSCs in the near future PV market. This skepticism stems from the lack of a precise evaluation of the LCOE, which is due to multiple assumptions that span from the stability of the perovskite to the efficiency of industrial modules, and to the costs of the manufacturing process.[7]

Here, we discuss the challenges that affect the evaluation of the LCOE for PSCs providing critical insight into the assumptions and approximations that are commonly considered. Initially, we analyze the various definitions proposed for the LCOE and summarize the specific models adopted for PSCs. Then, we address the challenges for the performance evaluation of perovskite PVs, which are hindered by the uncertainties relating to large area modules' efficiency. Indeed, while most of the reported records are achieved on relatively small active areas (0.1 to 1 cm^2),[4,8] medium area modules (500–1000 cm^2) have only displayed modest performances, and large area modules ($>10\,000$ cm^2) have not been reported yet, showing that a lot of efforts are required to scale-up the fabrication process.[9] Subsequently, we address the predictions for the stability of the solar modules, information that is still widely extrapolated from preliminary laboratory experiments. Most PSCs stability experiments are limited to a hundred hours of operating conditions,[10–12] while silicon-based PVs are granted with warranties over 30 years.[2] In this direction, over the last year, we have witnessed significant progress with early reports of accelerated stability experiments in compliance with the international standards IEC 61215.[8] Next, we discuss the issue of the supply chain. Most of the materials suppliers are operating on a small-scale market, targeting research institutions. Also, a production line manufacturer with industrial-size capacity is still missing. Therefore, it is quite arbitrary to set a manufacturing price for the perovskite technology. Towards the conclusions, we shift our focus on the short-term challenges that are required to improve the precision of the LCOE predictions, based on new outdoor studies and refined energy yield prediction, to bring PSCs to the forefront of the energy transition.

Discussion

The LCOE of a system (eqn (1)) can be defined as the ratio of its total cost (C) over the total energy produced (E), discounted over its lifetime N (when n is considered for the single year), using the discount rate r.[13]

$$\mathrm{LCOE} = \frac{\sum_{n=1}^{N} \frac{C_n}{(1+r)^n}}{\sum_{n=1}^{N} \frac{E_n}{(1+r)^n}} \quad (1)$$

Starting from this general definition, several models have been created for attributing a concrete value to this metric. The National Renewable Energy Laboratory (NREL) is one of the many institutions that provide a model for the LCOE (see equn (2)). It defines the LCOE, which we named $\mathrm{LCOE_{NREL}}$, in terms of the annual cost of electricity, identifying the minimum price at which energy must be sold for an energy project to break even.[14] Eqn (2) accounts for both financial and technological expenses, as well as for the amount of energy produced, through the capacity factor (CF) parameter.

$$\mathrm{LCOE_{NREL}} = \frac{C_0 \times \mathrm{CRF} \times (1 - T \times D_{\mathrm{PV}})}{8760 \times \mathrm{CF} \times (1-T)} + \frac{\text{fixed O \& M}}{8760 \times \mathrm{CF}} + \text{variable O \& M} + f \times h \quad (2)$$

where C_0 is the capital cost, CRF is the capital recovery factor, T is the tax rate, D_{PV} is the present value of depreciation, O & M is the operation and maintenance costs, f is the fuel price, and h is the heat rate.[15]

The CRF is a parameter, expressed in eqn (3), which addresses the costs of financing the capital for the project, relating a constant annual payment amount to a single value.[14,16]

$$\mathrm{CRF} = \frac{r(1+r)^N}{(1+r)^N - 1} \quad (3)$$

where r is the discount rate and N is the number of years over which the LCOE is evaluated.

A different LCOE model was produced by the British Department for Business, Energy & Industrial Strategy (BEIS), which defines it as the discounted lifetime cost of ownership and use of a generation asset, converted into an equivalent unit of cost of generation in currency per MW h. The $\mathrm{LCOE_{BEIS}}$ divides the discounted sum of costs by the discounted sum of the energy production, as shown in eqn (4),

$$\mathrm{LCOE_{BEIS}} = \frac{\sum_{n=1}^{N} \frac{C_n + \text{fixed O \& M}_n + \text{variable O \& M}_n}{(1+r)^n}}{\sum_{n=1}^{N} \frac{E_n}{(1+r)^n}} \quad (4)$$

where C_n, O & M_n, and E_n are, respectively, the capital cost, the operation, the maintenance costs, and the energy generated in year n.[14]

Since the $\mathrm{LCOE_{BEIS}}$ accounts for the present value of costs and energy outputs, which are discounted through r to predict future values, it can also be defined as discounting LCOE. The discounting method is opposed to the annuitizing method, where costs are calculated over the system lifetime and then converted to an equivalent annual cost and divided by the

average annual electrical output. $\mathrm{LCOE}_{\mathrm{annuitizing}}$ is set out in eqn (5).

$$\mathrm{LCOE}_{\mathrm{annuitizing}} = \frac{\left(\sum_{n=0}^{N} \frac{C_n}{(1+r)^n}\right)\left(\frac{r}{1-(1+r)^{-n}}\right)}{\left(\sum_{n=1}^{N} E_n\right)/N} \quad (5)$$

Hence, the annuitizing method converts costs and energy output to a constant flow over the lifetime of the system.

Since PV technologies do not produce a constant electricity output over their entire lifetime, discounting methods are preferred to evaluate the LCOE in the solar sector.[1] Moreover, specific models have been proposed for the calculation of the LCOE for PV systems, which account for the energy production decrease with time, through the degradation factor (d). An example is provided by eqn (6), which displays the formula proposed by Lai *et al.* to evaluate the LCOE of a PV system.[1]

$$\mathrm{LCOE}_{\mathrm{PV}} = \frac{\sum_{n=0}^{N} \frac{(I_n + \mathrm{O\ \&\ M}_n + F_n)}{(1+r)^n}}{\sum_{n=0}^{N} \frac{E_n}{(1+r)^n}} = \frac{\sum_{n=0}^{N} \frac{(I_n + \mathrm{O\ \&\ M}_n + F_n)}{(1+r)^n}}{\sum_{n=0}^{N} \frac{S_n(1-d)^n}{(1+r)^n}} \quad (6)$$

where I_n is the initial investment, F_n is the interest expenditures, and S_n is the rated energy output per year.

Table 1 Comparison between variables and assumptions for each model considered

Model	Variables	Assumptions
NREL (eqn (2))	C_0 (capital cost)	The degradation of the system is considered through CF
	CRF (capital recovery factor) (eqn (2))	Fuel is needed for the system operation
	r (discount rate)	
	N (number of years)	
	T (tax rate)	
	D_{PV} (present value of depreciation)	
	CF (capacity factor)	
	O & M (operation and maintenance cost)	
	f (fuel price)	
	h (heat rate)	
BEIS (eqn (4))	N (number of years)	The system does not degrade over time
	n (year)	
	C_n (capital cost in year n)	
	O & M_n (operation and maintenance cost in year n)	
	r (discount rate)	
	E_n (energy generated in year n)	
Annuitizing (eqn (5))	N (number of years)	Costs are calculated over the system lifetime and then converted to an equivalent annual cost
	n (year)	The system does not degrade over time
	C_n (capital cost in year n)	
	r (discount rate)	
	E_n (energy generated in year n)	
PV (eqn (6))	N (number of years)	The PV system undergoes a time-dependent exponential degradation
	n (year)	
	I_n (initial investment in year n)	
	O & M_n (operation and maintenance cost in year n)	
	F_n (interest expenditures in year n)	
	r (discount rate)	
	E_n (energy generated in year n)	
	S_n (rated energy output in year n)	
	d (degradation rate)	
PV financial (eqn (7))	I (initial investment)	The PV system undergoes a time-dependent exponential degradation
	N (number of years)	
	n (year)	
	D_{PV} (present value of depreciation)	
	INT (interest paid)	
	T (tax rate)	
	r (discount rate)	
	LP (loan payment)	
	O & M_n (operation and maintenance cost in year n)	
	RV (residual value)	
	E_0 (energy generated in year 0)	
	d (degradation rate)	

This definition can be expanded by considering further financial parameters, as demonstrated by eqn (7).

$$\mathrm{LCOE_{PV}} = \frac{I - \sum_{n=1}^{N} \frac{D_{PV} + \mathrm{INT}}{(1+r)^n} T + \sum_{n=1}^{N} \frac{\mathrm{LP}}{(1+r)^n} + \sum_{n=1}^{N} \frac{\mathrm{O\ \&\ M}_n}{(1+r)^n}(1-T) - \frac{\mathrm{RV}}{(1+r)^n}}{\sum_{n=1}^{N} \frac{E_0(1-d)^n}{(1+r)^n}} \quad (7)$$

where INT is the interest paid, LP is the loan payment, and RV is the residual value.[17] Although this level of detail adds complexity to the calculations, most of these parameters are well-defined by several financial models and usually do not add uncertainties. Table 1 compares the different variables and assumptions adopted for each model considered above.

Conversely, when addressing LCOE calculations for perovskite PVs, several factors relating to large-scale efficiency, stability, and manufacturing costs can only be assumed. Sofia *et al.* compared the LCOE of two types of perovskite/silicon tandem cells, adopting a d of 0.5%, which is typical of Si PVs, hence supposing huge advances in the stability of PSCs.[18] Moreover, to account for future changes in material prices and operation costs, they determined a reduced system cost scenario based on the predictions of the economic viability that they previously performed on thin-film tandem PVs.[19] Differently, Cai *et al.* assumed a discount rate of 5% to calculate the LCOE of fully printable perovskite solar modules.[16] Moreover, they presented the trend of the LCOE *versus* the device's lifetime for different module efficiencies, to evaluate the impact that stability and PCE have on the LCOE. Similarly, to elucidate the impact of the system degradation, Hosseinian *et al.* produced maps of LCOE as a function of the deployment time,[20] which is assumed equivalent to T_{85}, defined as the time (expressed in years) at which the PCE of the solar device reaches 85% of its initial value. Finally, a completely different approach was adopted by Zafoschnig *et al.*, who employed a performance ratio of 80% to account for the system degradation without involving d in their calculations.[13]

Thus, the abundance of models and assumptions renders the determination of the LCOE for PSCs very challenging. Indeed, the variety of reported values, produced by different models, hinders the comparison between commercial and emerging PV technologies. Arranging data from several references (see Table S1, ESI†), we collected the calculated LCOE for perovskite solar devices reported from 2016 to the present day (Fig. 1). LCOE values are differentiated based on the assumed lifetime of the PV system and further categorized according to the adopted PCE, location of installation, and estimated annual insolation. Interestingly, the number of works reporting LCOE calculations has been growing over the years, especially since 2020. Moreover, although the majority of analyses assume PCEs between 16 and 20%, from 2022 the performance range is extended up to 27%, which is beyond the promising advances achieved at the laboratory scale. Similarly, the lifetime adopted in the estimations increased from less than 20 years to 25 years

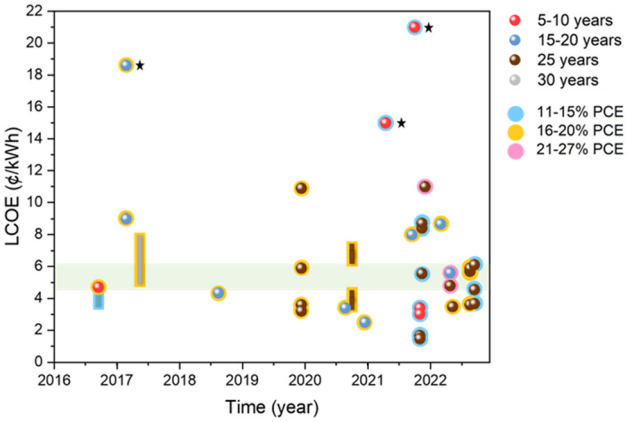

Fig. 1 LCOE predictions for perovskite photovoltaics over the last seven years. The data are divided according to the stability of the perovskite modules (red, blue, brown, and grey dots, ranging from 5 to 30 years) and their efficiencies (pink, yellow, and light blue contours). The rectangles report the spreading of the LCOE when a single value is not given. Outlier values are marked with a star. The green-shaded area visualizes the 95% interval of confidence for the true LCOE value for perovskite devices, which is between 4.53 and 6.12 c$ per kW h.

since 2020, revealing the ambition of the research community to attain comparable stability to crystalline silicon technologies. To analyze the dataset, we first applied a statistical dispersion approach to identify potential outliers, as described in the Supporting Information. Then, we determined the 95% interval of confidence for the remaining values. The LCOE value was found to lay between 4.52 and 6.11 c$ per kW h with 95% probability, as it is highlighted by the green-shaded area in Fig. 1. Nevertheless, despite similar lifetime and PCE inputs, a huge spread of LCOE values was reported in 2021, due to different calculation and assumption approaches. This highlights the importance of determining a common method to account for uncertainties when addressing the LCOE calculation of perovskite PV systems. Furthermore, the refinement of the assumptions regarding manufacturing costs and financial parameters is a critical factor for enabling a more reliable determination of LCOE values.

The Impact of the performances

With regards to the energy output, assumptions must be adopted when calculating the LCOE of perovskite PVs, since the scaling-up of the technology produces efficiency and cell-to-module (CTM) losses that cannot be unequivocally predicted yet. Indeed, the vast majority of PSCs are produced as laboratory prototypes with small active areas. The currently certified record efficiency of 25.7% is attained on a 0.096 cm^2 area cell and the largest active area recorded for a perovskite solar module is 802 cm^2 with a PCE of 17.8%.[21] Since conventional solar panel dimensions are usually between one and two square meters, further progress in the scale-up field is required, generating uncertainties in the prediction of the performance of future perovskite solar panels. Indeed, every technology that wants to increase its technology readiness level (TRL) towards commercialization must face the transition from the laboratory

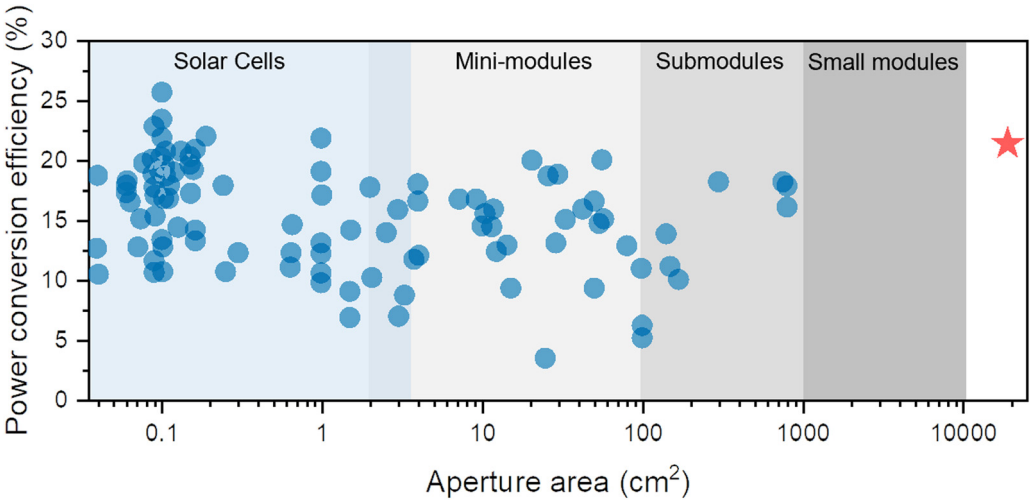

Fig. 2 Scaling-up process of perovskite photovoltaics. The graph reports the efficiency of perovskite solar cells and modules as a function of the aperture area. The red star represents the performance and dimension of a commercial silicon module as of 2022. Data edited from Ritzer *et al.*[22]

scale to the pilot line, and then to the production line. For perovskite PVs, this starts with the scaling up of the active area. Fig. 2 shows the trend of the PCE with respect to the logarithm of the active area of perovskite single junction modules. These data demonstrate that the PCE for standard modules (10 000 cm^2) will be significantly lower than the record performance on small-area single cells. To reach a competitive position in the PV market, perovskite modules should target entry commercialization with PCE of 17%–20% for 10 000 cm^2 or more, which should be further improved in the future following the development trends. A large part of these losses is due to the perovskite deposition technique that is required to coat large-area substrates. For solution deposition, highly performing devices are always achieved by spin-coating the perovskite solution and on small active areas (<1 cm^2). Conversely, for large-area modules, vacuum deposition methods are usually combined with slot-die coating and blade coating, among others. Unfortunately, these techniques still lack performance when compared to solution depositions. Apart from the scaling-up process, PSCs efficiency is further threatened by CTM losses, which are typical of any solar technology and may vary according to the module configuration and design. For example, in thin-film modules (such as perovskite single junctions and all-perovskite tandem modules) the CTM losses regard the p1, p2, and p3 patterning that defines the non-PV active area of the module. Moreover, the area required for the edge sealing (roughly 1 cm, running around the glass edge) and the tabbing of the junction box terminals must be also considered. Overall, these losses in performance have a negative impact on the determination of the LCOE for perovskite PVs, which is worsened by the lack of information regarding the performances of standard-sized modules.

To evaluate the influence that the system performances have on the LCOE value, a sensitivity analysis must be conducted. An example was presented by Darling *et al.*,[17] who studied and compared three hypothetical 20 MW utility-scale PV systems

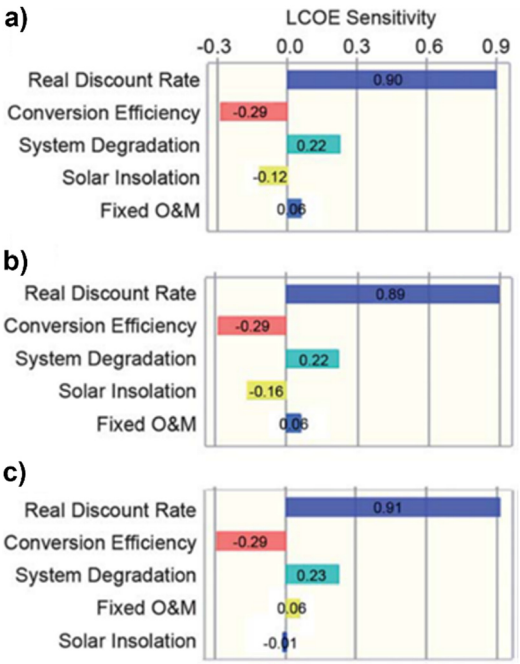

Fig. 3 Sensitivity analysis of the LCOE over *r*, *E*, *d*, solar irradiation, and *O & M* costs, performed on 20 MW utility-scale PV systems located in (a) Boston, (b) Chicago and (c) Sacramento. Reprinted with permission from.[17]

located in Boston, Chicago, and Sacramento (Fig. 3a, b, and c). The sensitivity analysis correlates the LCOE to *r*, *E*, *d*, solar irradiation, and *O&M* costs. The correlation is positive if an increase in the input parameter results in higher values of LCOE, while it is negative if the increase in the LCOE value is the consequence of a decrease in the input parameter. The magnitude of the correlation indicates how strongly the parameter influences the LCOE. It is worth noting that the authors did not include manufacturing and installation costs in their calculations. As displayed in Fig. 3, the conversion efficiency is

the second most significant contribution in all three case studies, underlining its importance in the definition of the LCOE.

It is important to mention that future performance analyses should take into account potential technological improvements in the large area perovskite modules. In the near future, perovskite modules may benefit from thin-film module improvements that are already present in other technologies. For example, a fourth patterning process (p4) can be included to minimize the effect of partial shading. Similarly, perovskite modules will benefit from a large implementation of bypass diodes, to reduce the negative effects of reverse biasing and partial shadowing. These improvements at the module level will be parallel to improvements in module design aimed to minimize the gFF, for example with a narrower gap in the scribing process.

The role of stability

As much as PSCs shine for their efficiency, they quickly fade away concerning stability. Nowadays, mainstream silicon manufacturers are extending the warranties of their products beyond 30 years, with T_{80} degradation rates. Conversely, perovskites are well-known for their fast degradation, either in the photo-absorber or in the extraction layers, often accelerated in presence of atmospheric agents and temperature. In 2021, Nieto-Díaz *et al.* proposed a thorough investigation of the effects of performance degradation on the LCOE.[23] Firstly, they collected a large dataset of literature data regarding the stability of perovskite devices with different architectures. From the dataset, they identified two coefficients to express the degradation: a fast "burn-in" coefficient (B) that quickly reduces the initial efficiency up to 60% in the initial hours, and a linear degradation coefficient (D) that affects the stability on the long term (Fig. 4a). The spread in the dataset's distribution of the two coefficients (Fig. 4b) reflects the high level of uncertainty regarding a proper evaluation of the perovskite stability. Secondly, they implemented the two coefficients into LCOE calculations, providing the variation of the LCOE as a function of D for two different values of B (10% and 40%, Fig. 4c). Such a large variation in the LCOE points out the paramount importance of precisely quantifying the stability of PSCs. Although, more and more studies are exploring perovskite outdoor stability, from these experiments we can only extrapolate their predicted long-term lifetime. For a more accurate evaluation, we need statistical analyses on accelerated tests, to compare them with the results on c-Si products. In this regard, the recent progress on the back end research developed new encapsulation strategies that allowed the perovskite to succeed in the internationally recognized IEC 62715-6-1 accelerated stability test.[8,24,25]

The challenge of the manufacturing

Despite the fact that most perovskite system expenses, such as installation, system, and maintenance costs, can be derived from other PV technologies, the quantification of realistic manufacturing costs remains a complex challenge. Two issues complicate the evaluation of the production costs of perovskite modules. Firstly, there is still not a general consensus regarding the deposition approach since both solution and vacuum depositions have good potential. Likely, early production lines will be based on a combined system: a solution deposition for the first transport layer and the perovskite, followed by a vacuum deposition of the second transport layer and the contact. This leads to the second issue: the lack of an industrial reference for production lines. At the time of writing, it is still not possible to acquire industrial perovskite manufacturing lines (>20 MW) without excluding high levels of customization and relative added costs. In Fig. 5a, we collected the calculated manufacturing costs, expressed in \$ per m^2, for perovskite modules from 2016 to 2022. From our selection, we excluded those reports that included gold or very expensive transport layers, resulting in manufacturing costs >150 \$ per m^2. Several studies proposed values between 20–40 \$ per m^2, which are significantly lower than those reported for c-Si (50–80 \$ per m^2). Moreover, we noted that the p–i–n configuration has an average lower cost than the n–i–p configuration. To assess which component of the module has the highest impact in the total cost of a perovskite solar module we analyzed several cost breakdowns taken from the literature. Where possible, we included the glass substrate, the transport layers with the

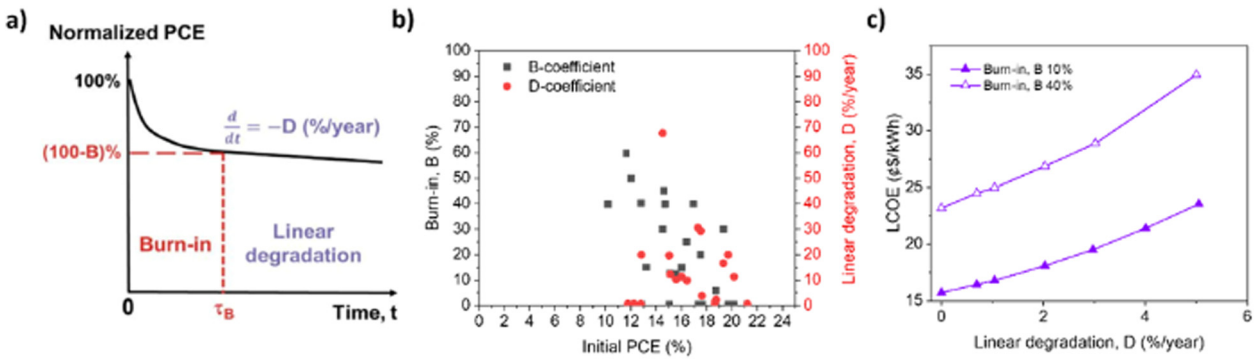

Fig. 4 The degradation of perovskite photovoltaics and their impact on the LCOE. (a) The typical degradation of a perovskite solar cell, is characterized by a fast burn-in coefficient (B) and a slow linear degradation coefficient (D). The figure is taken from.[30] (b) Trend of B and D coefficients for different perovskite solar cells with different architectures, adapted from.[30] Two LCOE calculations as a function of D and B coefficients adapted from.[30]

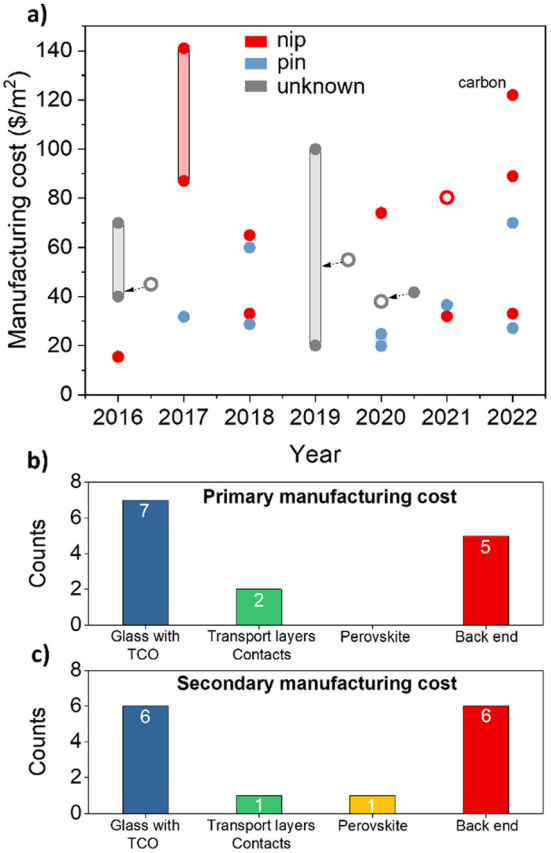

Fig. 5 Manufacturing cost of perovskite solar modules. (a) Manufacturing cost expressed in $ per m_2 for perovskite solar modules from 2016 to 2022. (b) Number of publications that have identified each material as the first highest cost in their cost breakdown. (c) Number of publications that have identified each material as the second highest cost in their cost breakdown. Graphs (b) and (c) are extrapolated from (a) when the details of the cost breakdown are provided.

contacts, the perovskite, and the back end (which includes the rear glass encapsulation, the edge sealing, the junction box application, and the framing). Results are displayed in Fig. 5b and c. The glass substrate with the transparent conductive oxide (TCO) and the back end are identified as the first and second highest cost for a perovskite solar module. Conversely, the perovskite and the transport layers are considered by several works among the less expensive components in the manufacturing process. Finally, reusing and recycling critical components of perovskite solar modules can effectively reduce the cost of manufacturing, hence reducing the LCOE, as demonstrated by Tian *et al.*[26]

Besides the difficulties regarding the evaluation of a realistic cost for manufacturing, another question arises regarding the mass and volume of chemicals and solvents needed to reach mass production and their availability. Therefore, we estimated the amount of precursor materials that are required for the production of 20 MWp of perovskite modules. We considered a module efficiency of 20% with a geometrical Fill Factor (gFF) of 83%, which is among the state of the art of research publications.[27] For the device configuration, we considered both n–i–p and p–i–n, excluding the top electrode and the conductive glass substrate from our analysis. Table S2 (ESI†) summarizes the estimated quantity of materials required to produce 20 MWp of perovskite modules. For instance, assuming 500 nm of film thickness and negligible material losses from slot-die deposition, we calculated that 66.22 kg of methylammonium iodide (MAI) and 192 kg of lead iodide (PbI_2) are required to realize the methylammonium lead iodide ($MAPbI_3$) perovskite active layer. To prepare the precursor solution, a volume of 0.35 m^3 of DMF is also needed. Similar estimations are reported for the production of ETLs and HTLs, considering several deposition techniques. In our analysis, we also considered the quantity of precursors, solvents, and chemicals that will scale up with an increased production capacity, while fixing the efficiency of the perovskite solar modules and their gFF. Fig. S1 (ESI†) displays this linear correlation for production capacities up to 1 TWp. We calculated, for example, that the amount of PbI2 required for the production of 1 TWp of $MAPbI_3$ solar panels with an efficiency of 20% is around 10kt, which is less than 0.1% of the global production of lead in 2016 (11 144 000 *t*), most of which comes from recycling processes. We then analyzed the same scenario for MAI, which is produced from methylamine. In this case, the amount of methylamine needed to produce the 3.3 kt of MAI is about 1.6kt, which is less than 1% of the BASF methylamine production in 2009. These data confirm the availability of the perovskite precursors to achieve 1TWp production in the next years. Nevertheless, a critical point must be highlighted: the current trend of replacing methylammonium with formamidinium or cesium cations may have an impact on the cost and availability of the precursors.

Future perspective

Perovskite PVs are transitioning from research to early industrialization. In this process, more attention will be given to the competitiveness of perovskite technology in the PV market.

Therefore, we expect a growing interest in refining models for producing more precise values of the LCOE. Furthermore, it is urgent to univocally determine those input variables which are still missing, such as outdoor performances and stability. Indeed, the validation of perovskite modules outdoors is already providing realistic energy yield predictions that will largely benefit more accurate calculations.[28]

Testing the modules in real environmental conditions has already shown the relevant impact of elevated temperatures on the module performances. In this direction,[29] Xu *et al.* proposed an innovative model to assess the economic impact of thermal effects on the LCOE prediction for different solar technologies, perovskites included.[30] The next challenge regards the stability of perovskite PVs. We have seen that degradation rates are the parameters that mostly affect the LCOE predictions. Only over the last few years, the academic research started to consider the challenge of stability as important as performance. The improvements at the device level and

in the encapsulation allowed for the first internationally recognized stability tests. The outcome of these tests is of great value to refine the degradation rates in the LCOE. Finally, we expect that during this early industrialization stage a standard production line for perovskite PVs will emerge, thus completing the cost estimation of this technology. After that, we will witness strategies that aim to further reduce the LCOE below 2 c$ per kW h. In this direction, improving performance and stability are imperative. In particular, improving the stability is even more important, considering the new commercial standards of 25 years or more for the residential and utility markets. But other strategies can be adopted to further reduce the LCOE by looking at the manufacturing costs. Indium-free electrodes can be adopted to reduce the impact of the cost of the transparent electrode. Due to its scarcity, indium is a relatively costly element. Alternatives formulations of indium-free are currently being explored also for the mass production of silicon heterojunction solar cells. For perovskite modules, fluorinated tin oxide (FTO) and aluminum-doped zinc oxide (AZO) are possible alternatives. Concerning the utilization of expensive metals as rear electrodes, it is possible to replace silver with less expensive copper. However, the metal consumption for thin-film modules can be further reduced if sputtering replaces thermal evaporation. This is a significant advantage over silicon technology, where screen-printed silver contacts require a much higher amount of metal, justifying the need for plating and copper adoption. Aside from these technical considerations, the driving factor to further reduce the LCOE will be determined by the mass production of the perovskite modules. Similarly to what we have seen and what we are witnessing for silicon technology, increasing the production capacity translates into a steady reduction of manufacturing costs, significantly benefitting the LCOE.

Conclusions

In conclusion, we have discussed the leading role of the LCOE to set a competitive position for perovskite PVs in the market. We showed that there is still a large uncertainty regarding the exact value of perovskite LCOE, even though several studies reported the LCOE in a range between 3–6 c$ per kW h. This uncertainty stems from a lack of information regarding the real performances of the modules, the degradation rate, and the manufacturing costs for industrial production.

For the performances, the scaling-up process from small-area single devices to large-area modules is the big challenge for the next years. Similarly, the improvement of the stability, minimizing the degradation rate, is fundamental to preserve a cutting edge in applications that share the market with the mainstream silicon technologies. Lastly, we have seen that the lack of information regarding the manufacturing cost is partially compensated by the cheap depositions and the abundancy of the perovskite's precursors. Overall, in the next few years the LCOE calculations will be important to set the agenda for an early commercialization or a pivotal strategy towards other applications of halide perovskites.

Author contributions

Conceptualization, data curation, analysis, writing original draft: MD.B., V.L., R.M. Funding acquisition, supervision, writing review: G.G.

Conflicts of interest

The authors declare that there are no conflicts of interest.

Acknowledgements

The authors acknowledge the ''HY-NANO'' project that received funding from the European Research Council (ERC) Starting Grant 2018 under the European Union's Horizon 2020 research and innovation program (Grant Agreement No. 802862) and the Fondazione Cariplo Economia Circolare 2021 Project ''Green flexible hybrid perovskite solar module for the market: from smart lead manipulation to recycling'' (FLHYPER, no 20201067), funded under the ''Circular Economy-2020'' call. R. M. and G. G. acknowledge the PhD Fellowship from Eni S.p.A.

Notes and references

1 Levelized cost of electricity for solar photovoltaic and electrical energy storage - ScienceDirect, **https://www.sciencedirect.com/science/article/pii/S030626191631933X**, (accessed 1 August 2022).
2 M. De Bastiani, M. Babics, E. Aydin, A. S. Subbiah, L. Xu and S. De Wolf, *Solar RRL*, 2022, **6**, 2100493.
3 R. Montecucco, E. Quadrivi, R. Po and G. Grancini, *Adv. Energy Mater.*, 2021, **11**, 2100672.
4 M. Kim, J. Jeong, H. Lu, T. K. Lee, F. T. Eickemeyer, Y. Liu, I. W. Choi, S. J. Choi, Y. Jo, H.-B. Kim, S.-I. Mo, Y.-K. Kim, H. Lee, N. G. An, S. Cho, W. R. Tress, S. M. Zakeeruddin, A. Hagfeldt, J. Y. Kim, M. Grätzel and D. S. Kim, *Science*, 2022, **375**, 302–306.
5 K. Yoshikawa, H. Kawasaki, W. Yoshida, T. Irie, K. Konishi, K. Nakano, T. Uto, D. Adachi, M. Kanematsu, H. Uzu and K. Yamamoto, *Nat. Energy*, 2017, **2**, 1–8.
6 Best Research-Cell Efficiency Chart, **https://www.nrel.gov/pv/cell-efficiency.html**, (accessed 1 January 2021).
7 P. Kajal, B. Verma, S. G. R. Vadaga and S. Powar, *Global Challenges*, 2022, **6**, 2100070.
8 Damp heat–stable perovskite solar cells with tailored-dimensionality 2D/3D heterojunctions, **https://www.science.org/doi/full/10.1126/science.abm5784**, (accessed 1 August 2022).
9 Japan's NEDO and Panasonic achieve 16.09% efficiency for large-area perovskite solar cell module | Perovskite-Info, **https://www.perovskite-info.com/japan-s-nedo-and-panasonic-achieve-1609-efficiency-large-area-perovskite-solar**, (accessed 2 August 2022).

10 X. Zhao, T. Liu, Q. C. Burlingame, T. Liu, R. Holley, G. Cheng, N. Yao, F. Gao and Y.-L. Loo, *Science*, 2022, **377**, 307–310.
11 J. Jeong, M. Kim, J. Seo, H. Lu, P. Ahlawat, A. Mishra, Y. Yang, M. A. Hope, F. T. Eickemeyer, M. Kim, Y. J. Yoon, I. W. Choi, B. P. Darwich, S. J. Choi, Y. Jo, J. H. Lee, B. Walker, S. M. Zakeeruddin, L. Emsley, U. Rothlisberger, A. Hagfeldt, D. S. Kim, M. Grätzel and J. Y. Kim, *Nature*, 2021, **592**, 381–385.
12 G. Grancini, C. Roldán-Carmona, I. Zimmermann, E. Mosconi, X. Lee, D. Martineau, S. Narbey, F. Ostwald, F. De Angelis, M. Graetzel and M. K. Nazeeruddin, *Nat. Commun.*, 2017, **8**, 15684.
13 L. A. Zafoschnig, S. Nold and J. C. Goldschmidt, *IEEE J. Photovolt.*, 2020, **10**, 1632–1641.
14 J. Aldersey-Williams and T. Rubert, *Energy Policy*, 2019, **124**, 169–179.
15 J. Foster, L. Wagner and A. Bratanova, LCOE models: A comparison of the theoretical frameworks and key assumptions, (accessed 20 September 2022).
16 M. Cai, Y. Wu, H. Chen, X. Yang, Y. Qiang and L. Han, *Adv. Sci.*, 2017, **4**, 1600269.
17 S. B. Darling, F. You, T. Veselka and A. Velosa, *Energy Environ. Sci.*, 2011, **4**, 3133–3139.
18 S. E. Sofia, H. Wang, A. Bruno, J. Luis Cruz-Campa, T. Buonassisi and I. Marius Peters, *Sustainable Energy Fuels*, 2020, **4**, 852–862.
19 S. E. Sofia, J. P. Mailoa, D. N. Weiss, B. J. Stanbery, T. Buonassisi and I. M. Peters, *Nat. Energy*, 2018, **3**, 387–394.
20 R. Hosseinian Ahangharnejhad, A. B. Phillips, Z. Song, I. Celik, K. Ghimire, P. Koirala, R. J. Ellingson, R. W. Collins, N. J. Podraza, Y. Yan and M. J. Heben, *Sustainable Energy Fuels*, 2022, **6**, 2718–2726.
21 Champion Photovoltaic Module Efficiency Chart, **https://www.nrel.gov/pv/module-efficiency.html**, (accessed 13 January 2021).
22 D. B. Ritzer, T. Abzieher, A. Basibüyük, T. Feeney, F. Laufer, S. Ternes, B. S. Richards, S. Bergfeld and U. W. Paetzold, *Prog. Photovoltaics Res. Appl.*, 2022, **30**, 360–373.
23 B. A. Nieto-Díaz, A. F. Crossland and C. Groves, *Appl. Energy*, 2021, **299**, 117302.
24 J. Liu, M. De Bastiani, E. Aydin, G. T. Harrison, Y. Gao, R. R. Pradhan, M. K. Eswaran, M. Mandal, W. Yan, A. Seitkhan, M. Babics, A. S. Subbiah, E. Ugur, F. Xu, L. Xu, M. Wang, A. Ur Rehman, A. Razzaq, J. Kang, R. Azmi, A. A. Said, F. H. Isikgor, T. G. Allen, D. Andrienko, U. Schwingenschlögl, F. Laquai and S. De Wolf, *Science*, 2022, **377**, 302–306.
25 Z. Li, B. Li, X. Wu, S. A. Sheppard, S. Zhang, D. Gao, N. J. Long and Z. Zhu, *Science*, 2022, **376**, 416–420.
26 X. Tian, S. D. Stranks and F. You, *Nat. Sustainable*, 2021, **4**, 821–829.
27 M. A. Green, E. D. Dunlop, J. Hohl-Ebinger, M. Yoshita, N. Kopidakis, K. Bothe, D. Hinken, M. Rauer and X. Hao, *Prog. Photovoltaics Res. Appl.*, 2022, **30**, 687–701.
28 A. Di Carlo, F. Bonaccorso, E. Kymakis and T. Watson, *Nat. Energy*, 2022, **7**, 580–581.
29 E. Aydin, T. G. Allen, M. De Bastiani, L. Xu, J. Ávila, M. Salvador, E. Van Kerschaver and S. De Wolf, *Nat. Energy*, 2020, **5**, 851–859.
30 L. Xu, W. Liu, H. Liu, C. Ke, M. Wang, C. Zhang, E. Aydin, M. Al-Aswad, K. Kotsovos, I. Gereige, A. Al-Saggaf, A. Jamal, X. Yang, P. Wang, F. Laquai, T. G. Allen and S. De Wolf, *Joule*, 2021, **5**, 631–645.