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Peer-reviewed author version

MARTULLI, Alessandro; Rajagopalan, Neethi; Gota, Fabrizio; Meyer, Toby; Paetzold, Ulrich Wilhelm; Claes, Steven; Salone, Alberto; Verboven, Jordy; MALINA, Robert; VERMANG, Bart & LIZIN, Sebastien (2022) Towards market commercialization: lifecycle economic and environmental evaluation of scalable perovskite solar cells. In: Progress in photovoltaics (Print),.

DOI: 10.1002/pip.3623
Handle: http://hdl.handle.net/1942/38120

Towards market commercialization: lifecycle economic and environmental evaluation of scalable perovskite solar cells

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ABSTRACT

Many economic and environmental studies on novel perovskite solar cells (PSCs), published ex-post the development stage to investigate the market competitiveness, have focused on laboratory-scale PSC architectures that are not amenable for upscaling. In this paper, we evaluate the market potential and environmental sustainability of a scalable carbon-electrode-based PSC by benchmarking it to the market dominating c-Si photovoltaics and CIGS thin film photovoltaics. The analysis covers the PSCs full lifecycle, at the module and system levels (residential and utility scale), and is based on realistic annual energy output data derived from energy yield calculations. We find that this PSC can produce electricity at low cost (3-6 €cents/kWh), with lowest energy payback (0.6-0.8 years) and greenhouse gas emissions (15-25 g CO_2 eq/kWh) compared to grid-connected PV market alternatives, assuming 25 years of lifetime, expected PV system cost reductions, and PSC module recycling and refurbishment.

1 INTRODUCTION

Decarbonizing the energy system is one of the goals to limit the global warming to 1.5°C by 2050 [1]. A power sector that mostly relies on renewable energy sources is a critical component for reaching these targets, and solar energy can be a crucial source in the future power system because of the carbon-free electricity generated through photovoltaic (PV) technologies [2, 3].

The rapid increase in PCE from less than 4 percent to 25.5 percent in the last 10 years [4] has further induced economic interest in the perovskite technology, now considered one of the most promising technologies for next generation photovoltaics [5]. The successful commercialization of innovative PV technologies predominantly depends on the "solar cell golden triangle" which comprises three crucial performance indicators: efficiency, lifetime, and cost; besides, also environmental sustainability and manufacturability have considerable importance [6]. Different PSCs configurations have been developed to address the technical and commercialization requirements. Given the heterogeneity of PSCs configurations and production techniques, it is essential to assess the available options in technical, economic, and environmental terms to evaluate the PSCs commercial potential and identify critical factors to be optimized throughout the technology development. Few research groups have examined PSCs' economic and environmental aspects through cost analyses or techno-economic analysis (TEA) [7-15] and life cycle assessments (LCA) [16-24]. In general, cost and environmental impact assessment studies have highlighted the potential of perovskite PV to be competitive with already-established PV technologies, such as c-Si and copper-indium-gallium-selenide (CIGS). In both types of studies, the results nevertheless vary widely depending on the type of configuration considered, the module components included, the chosen process sequence, and the methodological assumptions. A review of LCA literature on perovskite PV showed that the wide divergence of LCA studies' results is mainly due to the significant differences in process energy consumption. The resulting cumulative energy demand (CED) and the global warming potential (GWP) of single-junction perovskite PV have respectively been found to be in the range of 265-13000 MJ/m² and 16-1700 kgCO2eq/m² [25]. Similarly, a wide range of values has been found for economic indicators, with module cost in the range of 0.17-0.73 US$/W and levelized cost of electricity in the range of 3.5 – 18.6 US$cents/kWh [7-13].

Existing assessments have two fundamental limitations. Firstly, most studies on the economic and environmental performance have dealt with perovskite configurations that are not amenable for commercialization. Some studies have focused on the configurations that only meet the technical performance requirements (such as high PCE), and a consequence are composed of expensive materials and are using deposition techniques that are not suitable for industrial applications [7, 11]. Consequently, the debate on the best PSC candidate configurations and its processing route for commercialization and deposition techniques is still ongoing. In other cases, the analyzed configuration was optimized exclusively for environmental or financial sustainability [8-10]. A recent study by Leccisi and Fthenakis analyzed the environmental impact of perovskite PVs by focusing on scalable configurations; The CED and GWP resulted in low values in the range 265-548 MJ/m² and 16-40 kgCO2eq/m² [21]. Nevertheless, this study focused on environmental aspects, and the cost aspects have been considered only qualitatively. The study by Rao et al., focused only on technoeconomic aspects of another potential perovskite PV candidate for large-scale manufacturing. This study, however, resulted in higher module costs (0.53-0.9 US/W) than previously assessed perovskite configurations [13]. A more exhaustive evaluation of emerging PV technologies' large-scale market deployment potential should incorporate cost, efficiency, lifetime, scalability, and environmental performance.

Secondly, environmental and economic assessments in existing studies were carried out separately, which does not allow a comprehensive evaluation of the financial and environmental aspects of the technology developed and the identification, where present, of environmental and economic trade-offs. In particular, scope and system boundary assumptions represent relevant limitations of the previous studies. Cost studies were limited to assessing the manufacturing and electricity generation costs (such as LCOE) during the use-phase of PV systems and neglected the end-of-life. Similarly, few LCAs have considered the end-of-life implications [26]. Moreover, such analysis has been limited to the device-level, even when considering scalable architectures, such as the carbon-based one [27]. In particular, the performance of PSCs was assessed without including PV system analysis, thus excluding the eventual deployment of perovskite modules for electricity generation of PV systems. Moreover, the method employed to estimate energy generated by perovskite PVs among economic and environmental studies was inconsistent.

In this paper, we focus on a scalable perovskite single-junction PV configuration, produced on a large-scale, and evaluate the economic and environmental sustainability by deriving a set of performance indicators. To this end we integrate TEA and LCA methodology, and include the end-of-life stage in the analysis. We present findings both at the PV module level and the PV system level and investigate the impact that recycling has on said outcomes. Finally, we benchmark the chosen PSC architecture with commercially available PV technologies such as c-Si (mono-Si) and CIGS to examine its large-scale production and commercialization potential. The analysis is supported by an energy yield (EY) model that simulates the annual power output under realistic irradiation conditions at different climatic conditions to reproduce the technology performance more accurately compared to estimates based only on local irradiation data.

2 METHODS

2.1 DEVICE CONFIGURATION, AND ENVIRONMENTAL AND ECONOMIC INDICATORS

We selected a monolithic perovskite solar cell device with a carbon electrode. One of the most critical obstacles for the commercialization of PSCs is the long-term stability; PSCs should guarantee a stable electricity production for over a lifetime that is comparable to outdoor installations of Si PV modules [28]. In this regard, carbon-based perovskites have shown significant stability improvements compared to alternative PSC configurations. Replacing expensive metal electrodes such as gold with carbon has proven to be a successful strategy for achieving high PCEs and improving cell stability and duration [29]. The carbon-based PSC showed the longest stability measurements, around 9000 – 10000h under AM1.5 spectrum at 55°C [30, 31]. A particular issue for bringing perovskite PV production to the market is the rapid degradation under reverse-bias conditions [32, 33]. Recently, the carbon-based perovskite configuration has demonstrated long-term stability under reverse-bias-induced degradation and the tests on carbon-based perovskite modules (56.8 cm^2 aperture area) demonstrated prolonged outdoors endurance (IEC 61215-2:2016 standard test procedures) [34]. Hence, this cell architecture can be considered a promising candidate of perovskite configuration that might satisfy the most relevant commercialization requirements of efficiency, cost, stability, and scalability. Figure 1 provides the reference structure of the monolithic perovskite device being assessed. The PCE considered in this study is 14.4 percent for a module size of 1.43 m^2.

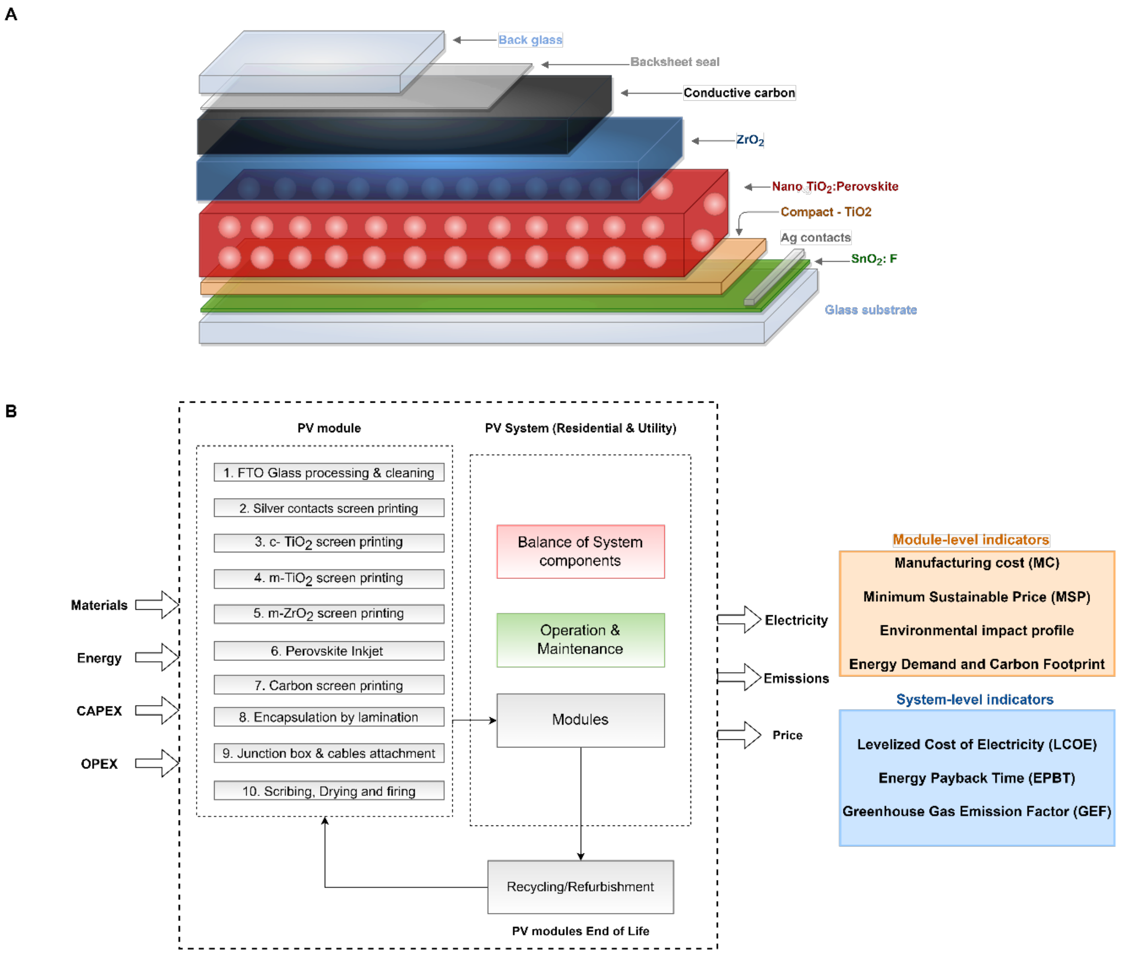

Figure 1: A) Structure of monolithic perovskite solar cell with a carbon electrode; B) System boundary of manufacturing a carbon-based perovskite PV module, PV system installation and use, and PV modules recycling/refurbishment.

To evaluate the economic and environmental sustainability of the PSCs, we introduce a method for emerging PV technology assessments; we integrate the life-cycle assessment (LCA) with the techno-economic analysis (TEA) to quantify financial and environmental key indicators through the environmental-techno economic assessment (ETEA). With this method, we compute environmental and economic indicators based on the same system boundaries and functional unit. Then, we compare the indicators for the carbon-based perovskite PV to c-Si and CIGS and previous perovskite environmental and economic assessments. Firstly, we evaluate the environmental and economic performance of the carbon-based perovskite at the PV module level by assuming a manufacturing plant based in Europe. Secondly, the environmental and economic competitiveness of perovskite devices is evaluated at a PV system level. The process environmental profile, the manufacturing costs (MC) and minimum sustainable price (MSP) are provided at the module level. Moreover, energy demand and carbon footprint values are compared to previous perovskite PV studies as well as established PV technologies, such as c-Si and CIGS. All indicators are based on 1m^2, which is the functional unit of this study. Consequently, we assume that the produced modules are installed at optimal tilt in a PV system with the balance of system (BOS) components. Here, the indicators include levelized cost of electricity (LCOE), energy payback time (EPBT), and greenhouse gas emission factor (GEF). The assumed areas are 30 m^2 and 0.5 km^2 for the residential and utility scale, respectively. For the LCOE, we employ the MSP to compute the costs of the modules composing the PV system; besides, we consider the current (2020) and future (2030) system cost scenario, divided into power dependent, area dependent costs and soft costs.

We compute the economic and environmental indicators at residential and utility-scale PV systems over 25 years of lifetime. In this case we assume that the selected PSC technology will further improve its stability by achieving a lifetime comparable to competing technology. Nevertheless, we assume that perovskite modules will degrade faster than traditional PVs, as described in section 2.4. Regarding the

BOS, the inverter is assumed to have a lifetime of 15 years. All the other components are considered to have the same life expectancy as PV modules. These assumptions follow the Methodology Guidelines on LCA of PV [35]. Energy yield (EY) calculations are performed considering outdoor conditions of the device under study, and the results (Table 1) are used as input for the indicators.

The recycling and refurbishment of the perovskite PV modules are also included, and the effect of this process on the module and system-level indicators is studied. The PSC architecture considered in this study was proven to be easily recyclable once end-of-life is reached. The recycling process was demonstrated on laboratory scale devices where the main composing layers were processed and raw precursor materials could be successfully obtained from used solar cells. These materials were then used to produce new PSCs without compromising performance [36]. We assume the perovskite PV manufacturer implements such a refurbishment process, and we evaluate the economic and environmental indicators for different levels of recovery rate and performance of the refurbished PV modules.

2.2 ENERGY YIELD

To accurately assess the performance of the carbon-based perovskite PV, energy yield (EY) calculations are performed considering outdoor conditions of the device under study. The EY analysis calculates the annual energy output of the carbon-based perovskite device under realistic irradiation conditions modelled using the state-of-the-art energy yield platform open-source software "EYcalc" developed by KIT [37, 38]. The energy yield modeling platform is composed of 4 different modules: (i) irradiance module, (ii) optics module, (iii) electrics module, (iv) energy yield core module. The irradiance module computes the irradiance of selected locations with a time resolution of one hour. The irradiance is angularly and spectrally resolved, taking into account the meteorological conditions and the cloud coverage of the selected location. The meteorological data from National Renewable Energy Laboratory (NREL) are used. The optics module calculates the angularly and spectrally resolved absorptance for each layer of the solar cell stack. To this end, a combination of transfer-matrix-method (TMM) for thin, coherent layers and series expansion of the Lambert-Beer law for thick, optically incoherent layers is used. The irradiance obtained from module (i) and the absorptance obtained from module (ii) is then given as an input to the energy yield core module, which then computes the photogenerated current density in the absorber materials with a time resolution of one hour. The electrics module then uses the time-resolved photogenerated currents to compute the maximum power point (MPP) for each hour of the year using a one diode analytical model. In order to estimate the temperature of the cells, we use the Nominal Operating Cell Temperature (NOCT) model [39], assuming a NOCT of 48°C, while the insolation on the cell and the ambient air temperature are extracted from TMY3 data [40].Then, we use temperature coefficients to update the current density – voltage (J-V) characteristic in the electrical simulations.

After modeling the carbon-based perovskite, the CIGS, and c-Si PV in standard test conditions, energy yield simulations in realistic irradiation conditions are performed. Three locations, representing very different climatic conditions, are selected: Miami (tropical), Phoenix (desert), and Seattle (temperate oceanic). The EY results are given in Table 1 for the three selected locations, and the performance of the carbon-based perovskite device is compared to the c-Si and CIGS performance.

2.3 PV MODULE-LEVEL INDICATORS

We construct a bottom-up ETEA model based on the perovskite device manufacturing shown in Figure 1. The environmental performance of the carbon-based perovskite modules is evaluated by assessing the environmental impacts of the inventory input. In this study, the impact assessment is conducted using the Environmental Footprint (EF) 3.0 (adapted). This method is the one recommended by the European Commission and uses the ILCD recommended method as the default basis for the EF method [41]. According to Fazio et al [42] the characterization factors of Recipe method mapped to the ILCD flows only cover 15% of them and thus not an improvement over the default method. Hence the choice to use EF 3.0 (adapted) method. The EF method 3.0 life cycle impact assessment method released in 2018 has undergone several revisions with updated characterization factors and default methods, to address the critical point previously raised [43]. The database used for this study is ecoinvent 3.8 within SimaPro

9.1 software. The EF 3.0 (adapted) evaluates 16 impact categories, including global warming, human health impact (cancer and non-cancer), freshwater ecotoxicity, resource use fossils, and minerals. The manufacturing phase is modeled using this method, and consequently, the environmental profile of the processing steps is provided. Furthermore, regarding the environmental analysis, the values of energy requirements (MJ/m^2) and carbon footprint (kgCO$_2$/m^2) of the carbon-based perovskite module are derived and benchmarked with previous LCA studies results on perovskite, CIGS and c-Si.

The economic performance of the carbon-based perovskite modules is first assessed by calculating the cost per unit area (€/m2), defined as manufacturing cost (MC), and it includes the sum of the costs incurred in each processing as in Equation 1.

$$Manufacturing\ cost = \sum_i M_i + E_i + O_i + R_i \quad [\frac{€}{m^2}] \qquad \text{Equation 1}$$

Here the manufacturing cost includes cost per unit area for material (M_i), equipment (E_i), operations (O_i, utilities, insurance, and labor) and repair and maintenance (R_i) for each i processing step. The cost incurred for raw materials is determined by the device configuration, the materials composing the various layers, and the related processing technique. The equipment cost includes the purchase cost of the individual machinery used in each manufacturing step and the facility cost. The mass data of the input materials and price data regarding materials, equipment, and facility were obtained mostly from a perovskite PV manufacturer and, where missing from available literature data.

From a PV manufacturer's perspective, the MC is not sufficient to establish the price at which the PV modules can potentially be sold in the market since the indicator does not account for financing costs and the price evolution throughout the investment lifetime. For this reason, from the MC, we also compute the module minimum sustainable price (MSP), which provides the lowest price value for a PV manufacturer to be financially sustainable and achieve a defined rate of returns. This indicator is defined as the sum of the manufacturing cost (MC), the overhead cost (OH), and the weighted average cost of capital ($WACC$), divided by the module PCE and the irradiance power density at standard test conditions ($P_0 = 1000\ W\ m^{-2}$ under AM1.5 illumination) [8, 10, 44, 45]:

$$MSP = \frac{MC+OH+WACC}{PCE\ x\ P_0} \quad [\frac{€}{Wp}] \qquad \text{Equation 2}$$

The methodology employed to estimate the MSP differs across the various cost assessments of PV technologies; some studies computed the cost per watt peak by accounting for only the production costs and the module PCE, disregarding the financing costs and the necessary selling price for the PV manufacturer to be economically sustainable [7] . On the other hand, some studies simplified the calculation by assuming the financing costs equal to a fixed percentage of the manufacturing costs [8, 10]. Here, we use the previously developed method for calculating the MSP of silicon manufacturing [45]. A more detailed description of the MC and MSP calculation inputs can be found in the Supplemental Information, in sections 1.1 and 1.2.

2.4 PV-SYSTEM LEVEL ANALYSIS

The environmental techno-economic performance of carbon-based perovskite PV is also evaluated at the system level, assuming the deployment of perovskite modules for PV systems. We analyze two different PV system scales, residential and utility, to reflect the differences in costs, energy requirements, and GHG emissions. We then compare the environmental-techno-economic performance of the perovskite PV systems with traditional alternatives such as c-Si and CIGS. We assume a constant area of 30 m2 for residential-scale systems and 0.5 km2 for utility-scale systems to perform the calculations. Moreover, EY calculations for the three PV technologies estimate the energy generated at three different climatic locations, which allows a realistic computation of the ETEA indicators at the system level. Besides, we include losses due to inverter and wiring, assuming these account for 10% reduction in energy generation.

The PV systems' environmental performance is assessed by computing two indicators: energy payback time (EPBT) and greenhouse gas emission Factor (GEF). The EPBT indicates the time required for the system assessed to generate the same quantity of energy needed to produce the system itself. Hence, for PV systems, it is defined as the ratio between the primary energy demand and the annual electricity generated by the system (E_{agen}) [46]. Besides the primary energy demand for manufacturing the materials and the PV modules (E_{mod}), the energy demand for BOS (including inverter) (E_{bos}) and operation and maintenance ($E_{O\&M}$) are considered.

$$EPBT = \frac{E_{mod}+E_{bos}+E_{O\&M}}{E_{agen}} \quad [yr] \qquad \textit{Equation 3}$$

$$GEF = \frac{GHG_{mod}+GHG_{sys}+GHG_{O\&M}}{\sum_{i=0}^{N} \mathrm{E_i}(1-\mathrm{d})^{\mathrm{i}}} \quad [\frac{g\ CO2\ eq}{kWh}] \qquad \textit{Equation 4}$$

Another relevant environmental sustainability indicator is the GEF which estimates the lifecycle GHG emissions (g CO_2 equivalent) per kWh of electricity generated (E_i) by the PV system throughout its lifetime (N). d is a mutual parameter for the system indicators and represents the annual degradation rate. We consider that c-Si and CIGS PV systems degrade at the same rate annually by 0.2%, as reported for currently installed PV systems [47] and assume that carbon-perovskite PVs degrade faster at a rate of 0.50% per year.

To evaluate the potential cost of generating electricity through a PV system of carbon-based perovskite PV modules, we compute the levelized cost of electricity (LCOE). The LCOE is generally defined as the ratio between the cost of a PV system throughout its lifetime to the total energy that that system can generate during the lifespan, as in Equation 5 [48]:

$$LCOE = \frac{\sum_{i=0}^{N} \frac{C_i}{(1+D)^i}}{\sum_{i=0}^{N} \frac{E_i(1-d)^i}{(1+D)^i}} \quad [\frac{€}{kWh}] \qquad \textit{Equation 5}$$

Where C_i represents the system cost (€) and E_i the electricity generated in the i-th year, D is the discount rate and N is the total lifetime of the PV system.
A mutual parameter for system-level indicators is the system lifetime. We consider that the PV system lifespan is equal for the three technologies (25 years), so we assume that the perovskite technology will be able to overcome the stability and duration issues that currently represent a significant barrier towards commercialization. Furthermore, besides the modules, it is critical to consider PV systems elements such as inverters and balance of system components (BOS) and the yearly operation and maintenance (O&M) activities that contribute to the energy requirements, GHG emissions, and cost, thus having a considerable effect on the EPBT, GEF and LCOE indicators. The energy requirements and GHG emissions data for inverters and BOS are extracted from the available EcoInvent database. As for the cost, we assume power, area dependent and soft system costs. As our focus is a European PV system application, we adopt the up-to-date estimates and assume system costs reduction by 2030. The system costs considered in this study represent the average among 21 EU countries [49]. Future system costs are computed considering the forecasts regarding worldwide PV cumulative capacity by 2030 [50, 51] and information related to learning rates of inverters and BOS components. In this way, we determine the residential and utility-scale LCOE at current and future system costs. The MSP of the carbon-based perovskite PV module is used as input to account for the cost of the modules of the PV systems, whereas the current estimates of module price are employed for c-Si and CIGS. A detailed description of the EPBT, GEF, and LCOE assumptions and input data is provided in the Supplemental Information.

2.5 END-OF-LIFE ANALYSIS

The PSC architecture addressed in this study was proven to be easily recyclable once end-of-life is reached. The recycling process was demonstrated on laboratory scale devices where the main composing layers were processed, and raw precursor materials could be successfully obtained from degraded solar cells. These materials were then used to produce new PSCs without compromising performance [36]. Ideally, by implementing this recycling procedure, refurbished solar PV devices can be produced by employing raw materials extracted and re-processed from used PV modules. In that case, the operational costs related to materials, environmental impacts, and energy demand may be considerably affected.

For this reason, we address the end-of-life phase and, in particular, the effects of the implementation of a technically feasible recycling process. We then show the impact of perovskite PV modules end-of-life processing on the economic and environmental indicators. We assume that the PV manufacturer is also responsible for collecting the dismissed PV modules. Recycling allows the manufacturer to recover materials that can be used for the production of successive modules. In this regard, we define the materials and process-related costs and environmental impacts of recycling and then consider the benefits of the recycling process in terms of avoided material purchase and manufacturing steps to calculate the economic and environmental indicators. We include the collection costs of dismissed PV modules which account for logistic operations to transport the PV waste to the recycling facility [52, 53]. Hashmi et al. [36] claimed that the refurbishment procedure for carbon-based perovskite PVs could fully recover the materials without compromising performance. However, we adopt a more conservative approach in modeling the recycling performance. Besides the best-case scenario of full recovery (100 percent), our analysis also considers three levels of recovery for the materials that can be recycled: a low (50 percent), middle (70 percent), and high-rate (90 percent). Moreover, we consider three cases with the resulting refurbished PV modules that do not retain the technical performance of new modules. In this sense, we consider a high (-30 percent), medium (-20 percent), and low (-10 percent) reduction in the technical performance of the refurbished PV modules. We assume the PCE to represent the performance, and we then consider its relative decrease when computing the MSP. For the system level indicators, thus for LCOE, EPBT, and GEF, the factor influencing the performance is the EY, and its relative reduction is assumed. We compute the relevant indicators for each case and analyze the recycling effects on the perovskite PV environmental and techno-economic performance. However, not all recycled material components can be employed to produce new modules; for these components, we assume that once recycled, they are sold in the market for different applications at a reduced price compared to their initial purchase. The details of the recycling process modeled can be found in the Supplemental Information.

3 RESULTS AND DISCUSSION

3.1 PV MODULE-LEVEL INDICATORS

Figure 2 shows the environmental profile (1 m^2), the manufacturing and material cost breakdown of the carbon-based perovskite module. The profile displays the impact of each manufacturing step on the 16 normalized impact categories considered by the impact assessment method employed for this analysis. The total manufacturing cost is 31.32 €/m^2, of which materials costs account for 66 percent, whereas other operational expenditures (labor, energy, and insurance) are responsible for 24 percent. Equipment and maintenance costs do not significantly impact total module manufacturing costs, which account for 7 percent and 3 percent, respectively. In almost all impact categories, the glass presents the highest environmental burden, accounting for approximately 50-60 percent in the majority. The substrate influence is also evident from an economic perspective since the dominant input affects the materials cost, and thus, the manufacturing step involving the glass processing is the most costly. The silver contacts are primarily responsible for the impact on resource use (minerals and metals). Considerable influence comes from the junction box and cabling of the module in several impact categories (such as human toxicity, ecotoxicity – freshwater). Regarding the other layers, carbon electrode deposition has the highest impact on ozone depletion. The use of lead is seen as an environmental concern to be considered during the commercialization of PSCs because of its harmful effects on the human body [54]. However, our analysis, in line with previous studies, shows that the absorber layer does not seem to be particularly influential on the environmental profile and the manufacturing cost of the perovskite configuration assessed. A more cumbersome barrier is represented by the "RoHS Directive" that restricts the use of Pb to 0.1% in homogenous materials in the European market [55]. Nevertheless, the effects of Pb used in the carbon-based perovskite can be mitigated by adopting efficient recycling processes as described in Section 3.3.

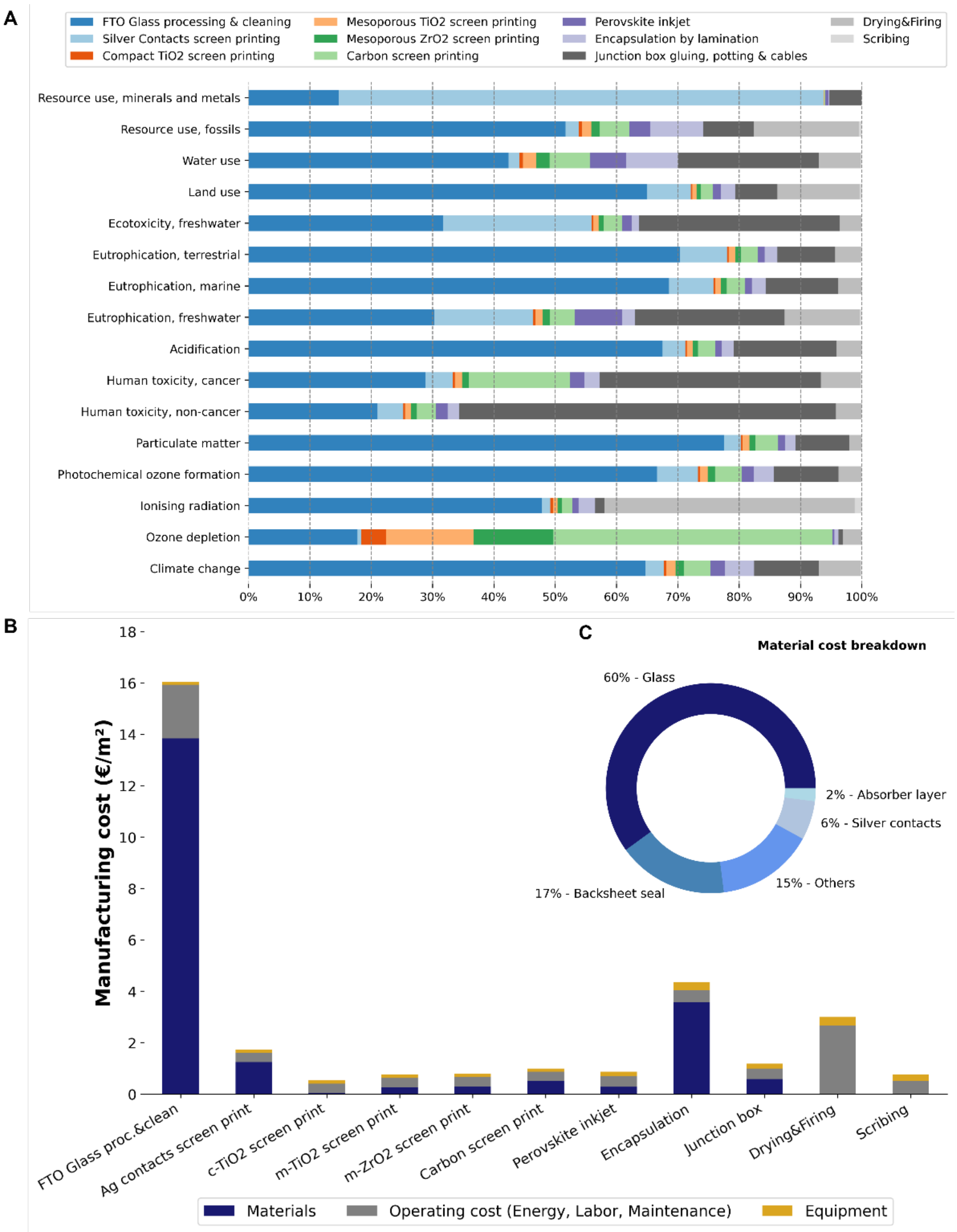

Figure 2: A) Environmental profile of carbon-based perovskite module (1 m^2), B) step by step manufacturing cost and C) material cost breakdown.

Table 6 in Supplemental Information summarizes the energy demand and carbon footprint values found by the various studies on perovskite PV devices, along with the results derived in this analysis for the carbon-based perovskite. The findings present considerable variation in the literature due to the variety of configurations analysed and the modelling assumptions. The energy requirement of the carbon-based perovskite is found to be 736 MJ/m^2 and it is in line with other configuration results. The carbon footprint is found to be 28 kgCO$_2$eq./m^2 which is closer to the lowest literature values literature concerning solution processed perovskite PV configurations. Other studies found significantly higher energy demand and carbon footprint values (above 100 kgCO$_2$eq./m^2) which could be related to the processing energy requirements, which were 1080 kWh (solution) - 1460 kWh (vacuum) in Espinosa et al. [18] and 31 700 kWh/m^2 in Serrano-Lujan et al. [22]. The carbon-based perovskite presents also significant advantages compared to traditional PVs as energy demand is estimated to be 2577 and 1520 MJ/ m^2 whereas the carbon footprint is 143 and 94 kgCO$_2$eq./m^2, respectively for mono c-Si and CIGS PV modules [21].
The obtained manufacturing costs are used as input for computing the MSP, which is found to be 0.27 €/Wp (0.31 US$/Wp). This value falls in the wide range of MSP results obtained for other perovskite PV configurations. (Table 8 Supplemental Information). However, the perovskite configurations assessed by previous studies are diverse, which means that the costs involved and the assumed module efficiencies vary. Moreover, the methodology employed to estimate the MSP differs across the assessments. The carbon-based perovskite PV module MSP is comparable to the current selling price for CIGS PV modules (0.25-0.30 US$/Wp) and slightly higher than mainstream c-Si PV modules currently sold on average at 0.25-0.28 €/Wp (0.28-0.31 US$/Wp). CIGS and c-Si technologies achieve higher PCEs than the rated carbon-based perovskite efficiency, but the low operational and capital costs involved with the production of perovskite PV modules partly offset the performance gap and thus reach a comparable cost per watt peak.

The results of the economic and environmental indicators at the PV module level demonstrate the potential of the carbon electrode-based perovskite PV. This configuration optimizes the economic and environmental performance by minimizing the costs and environmental impacts of the several composing layers, except for the glass substrate. The manufacturing cost and MSP of the carbon-based perovskite are computed for the reference production size of 100 MW and the processing time is assumed to be approximately 2 m^2/min. The obtained results are conservative estimates since the module cost could further decrease as the production increases towards larger scales. Moreover, it is reasonable to assume that the fast and low-temperature solution deposition techniques could allow higher production throughput and thus contribute to further reducing the manufacturing cost and MSP. These processing techniques also ensure low process electricity consumption, resulting in low energy-related-costs and emissions and thus facilitating large-scale production.

3.2 PV SYSTEM-LEVEL INDICATORS

We extend the analysis to the system-level and estimate the relevant indicators for the eventual deployment of this technology for residential and utility-scale electricity production over 25 years of lifetime.

Figure 3 provides the EPBT and GEF results for the carbon-based perovskite at three locations where the energy yield has been computed for residential and utility-scale PV systems. The perovskite PV system outperforms the c-Si (mono-Si) and CIGS PV systems used for comparison. The perovskite PV systems can operate with a payback time lower than one year in desert and tropical climates where the higher levels of energy yield contribute to offset the energy requirements for the modules, the PV systems components, and annual operation and maintenance activities. On average, at the three locations, the carbon-based perovskite has 18 percent and 8 percent lower EPBT than c-Si and CIGS, respectively, at the residential and utility scale.

Similarly, the GEF of the carbon-based perovskite produces the lowest value of g CO2 eq for kWh of electricity generated in contrast to the c-Si and CIGS PV systems at the residential and utility scales. This is due mainly due to the lower climate change impact of 1 m^2 of the perovskite module (28 kg CO$_2$

eq.) compared to the CIGS module (94 kg CO_2 eq.) and the c-Si module (143 kg CO_2 eq.). Although the perovskite device produces considerably lower energy yield, the larger decrease in emissions counterbalances the poorer electricity generation per unit area compared to the other two PV technologies. The significant reduction seen for the EPBT is more pronounced for the GEF since, on average, the perovskite systems have 23 percent and 19 percent lower GEF than c-Si and CIGS, respectively. These results show the considerable advantage for electricity generation in terms of energy demand and carbon emissions of carbon-based perovskite PVs.

Table 1: EY results for three selected locations (Desert, Oceanic, Tropical) and related residential and utility-scale system capacities of carbon-based perovskite, c-Si, and CIGS.

		Annual Energy Yield (kWh/m^2)			**System capacity (kW)**	
	PCE (25°C)	**Desert**	**Oceanic**	**Tropical**	**Residential scale (30 m^2)**	**Utility scale (0.5 km^2)**
Carbon-based Perovskite	14.4%	306	184	247	4.3	72k
c-Si	22.8%	451	295	375	6.8	114k
CIGS	19.2%	366	242	307	5.7	96k

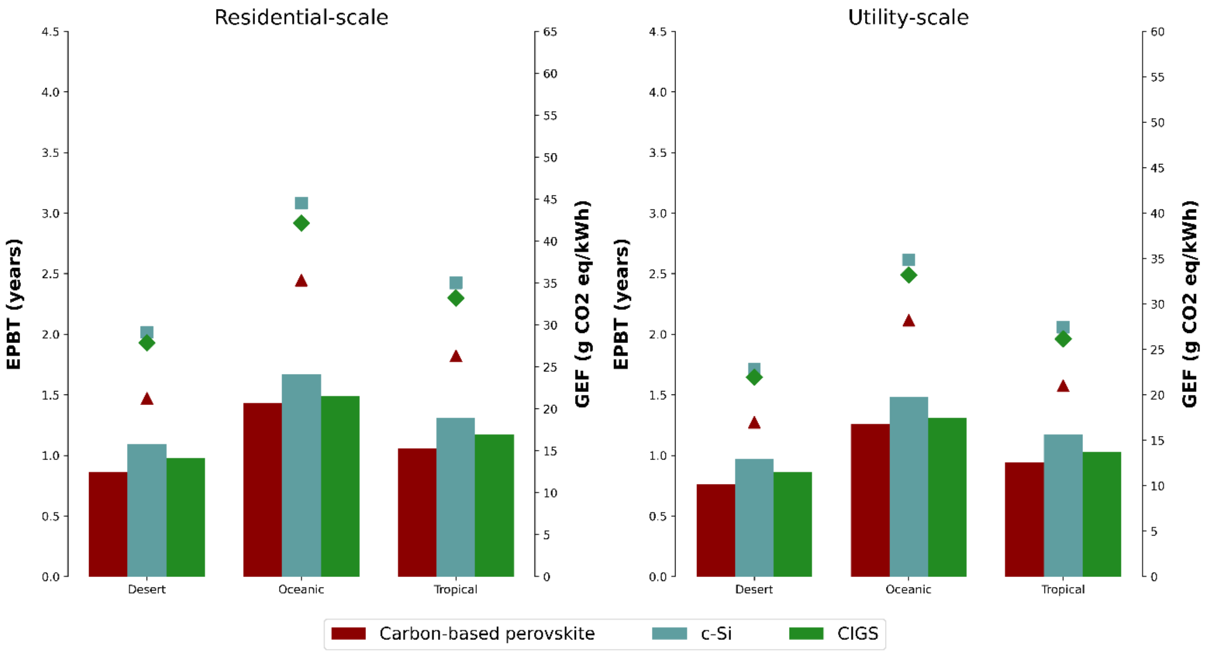

Figure 3: EPBT (bars) and GEF (scatter) results for carbon-based perovskite, c-Si, and CIGS PV at three climatic locations for residential scale and utility scale systems

The economic feasibility at the system level is measured through the LCOE indicator. This is calculated at current and future forecast system cost (2030), as in Figure 4. For 2030, we assume a reduction in selling prices of c-Si and CIGS PV modules due to learning effects. On the other hand, we do not consider price reductions for the perovskite PV modules since this technology is not yet mature, and it is reasonable to expect a few years before it could be deployed on a large scale.

In contrast with the system level environmental indicators, the LCOE of carbon-based perovskite PVs exhibit higher values than the benchmarked alternatives. Perovskite PV systems in general present a worse performance than c-Si and CIGS in all locations at the residential-scale. For residential-scale plants, the system component costs represent a relevant fraction of the total cost, and the reduced plant area does not enable large energy harvest to outweigh the high system-related costs. In this context, the mature technologies are capable of reducing the area dependent system costs due to their higher PCEs and thus better energy yield. In fact, the highest difference is noticeable in the oceanic location where the EY differences between the PV technologies are more remarked. On average, the LCOE of carbon-based perovskite PV systems is 23 percent and 10 percent higher than c-Si and CIGS at the residential-scale. A similar picture emerges for the current utility-scale systems, although the gap of the carbon-based perovskite with c-Si and CIGS is shorter. In this case, c-Si has an LCOE 15 percent higher than carbon-based perovskite, on average at three locations. Compared to CIGS, the LCOE of perovskite PVs is found to be 4 higher and, in desert and tropical locations, the performance of both technologies is approximately the same.

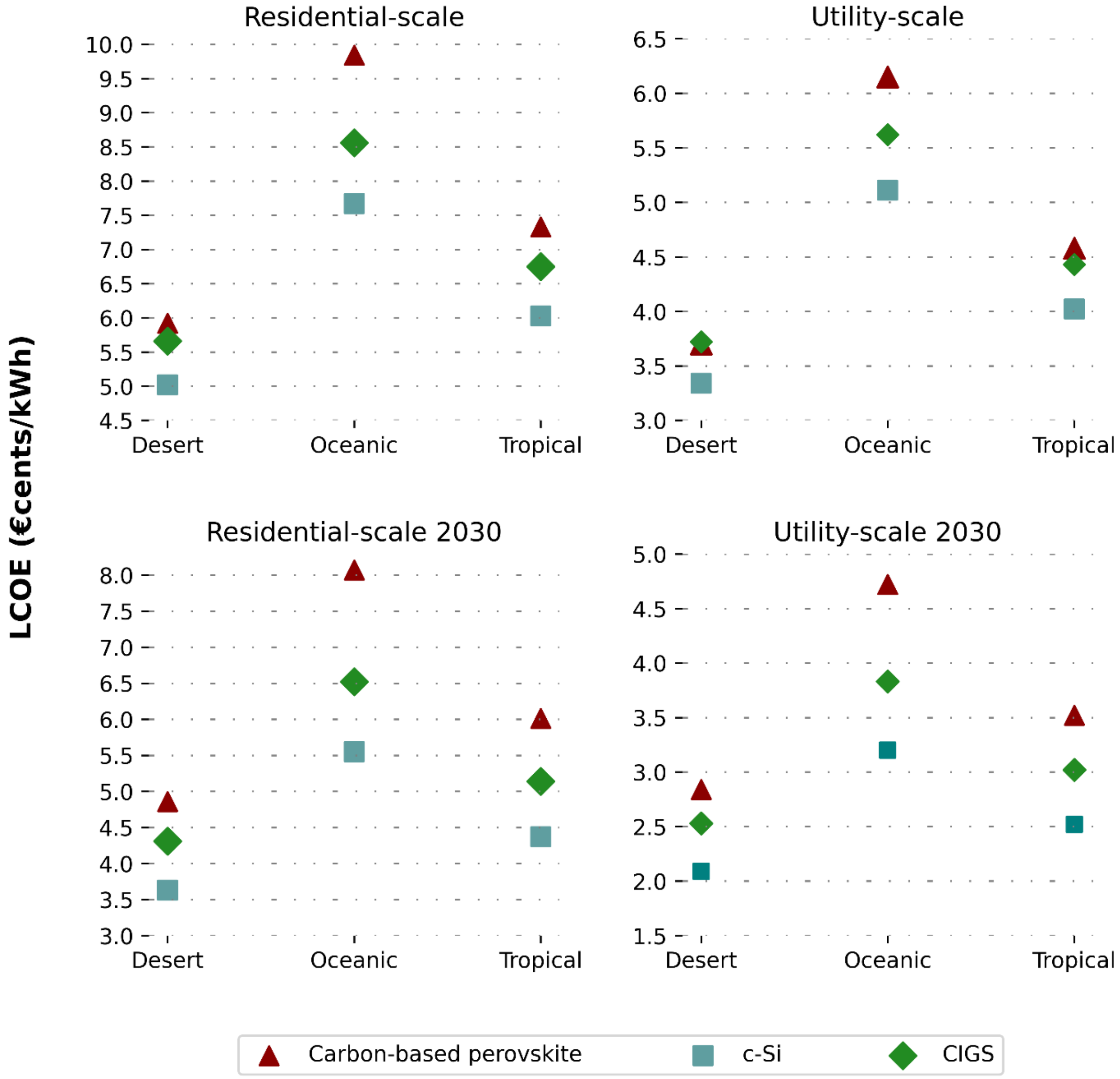

Figure 4: LCOE of carbon-based perovskite, c-Si, and CIGS PV systems at three climatic locations (desert, oceanic, tropical) for residential scale and utility scale at current and 2030 system costs.

The 2030 scenario reveals how the cost gap perovskite PV systems is expected to further exacerbate. This is due to the forecasted system cost reductions and the assumed decrease of module prices for c-Si and CIGS. The equal decrease of system costs produces a decline of the LCOE values at the utility scale and the residential scale, but its degree varies among the three technologies. The LCOE of residential scale perovskite PV systems is expected to diminish by 18 percent, whereas the LCOE of c-Si and CIGS are expected to diminish by 28 percent and 24 percent by 2030, respectively. In contrast, for the utility scale PV systems, the expected decrease is 23 percent, 37 percent, and 32 percent for perovskite, c-Si, and CIGS, respectively. As a result, the carbon-based perovskite residential and utility scale LCOE is, on average at three locations, 40-42 percent and 17-19 percent higher than c-Si and CIGS, respectively. This shows that with module and system cost reductions, the better EY performance of c-Si and CIGS technologies represent a significant advantage, and perovskite PVs will need to lower the production costs further and improve the EY to remain competitive in the future. In this regard, besides the stability and duration issue that still needs to be fully solved, the performance may be the most relevant aspect to improve. The perovskite configuration's rated PCE is around 14%; it is not unlikely to expect increases in PCE as the development of perovskite PVs is rapidly progressing, and cell efficiencies of around 20% can be envisaged. This would consequently enhance the energy yield and thus considerably lower the LCOE. On the other hand, the production costs already result in very low values compared to alternative PV technologies. Nevertheless, a further decrease in manufacturing cost may be achieved by the fast and low-temperature processing techniques (e.g. screen printing, slot-die coating, blade coating, inkjet printing) that would provide higher throughput values than this study's conservative assumption (industry expert validated), and thus lower module prices.

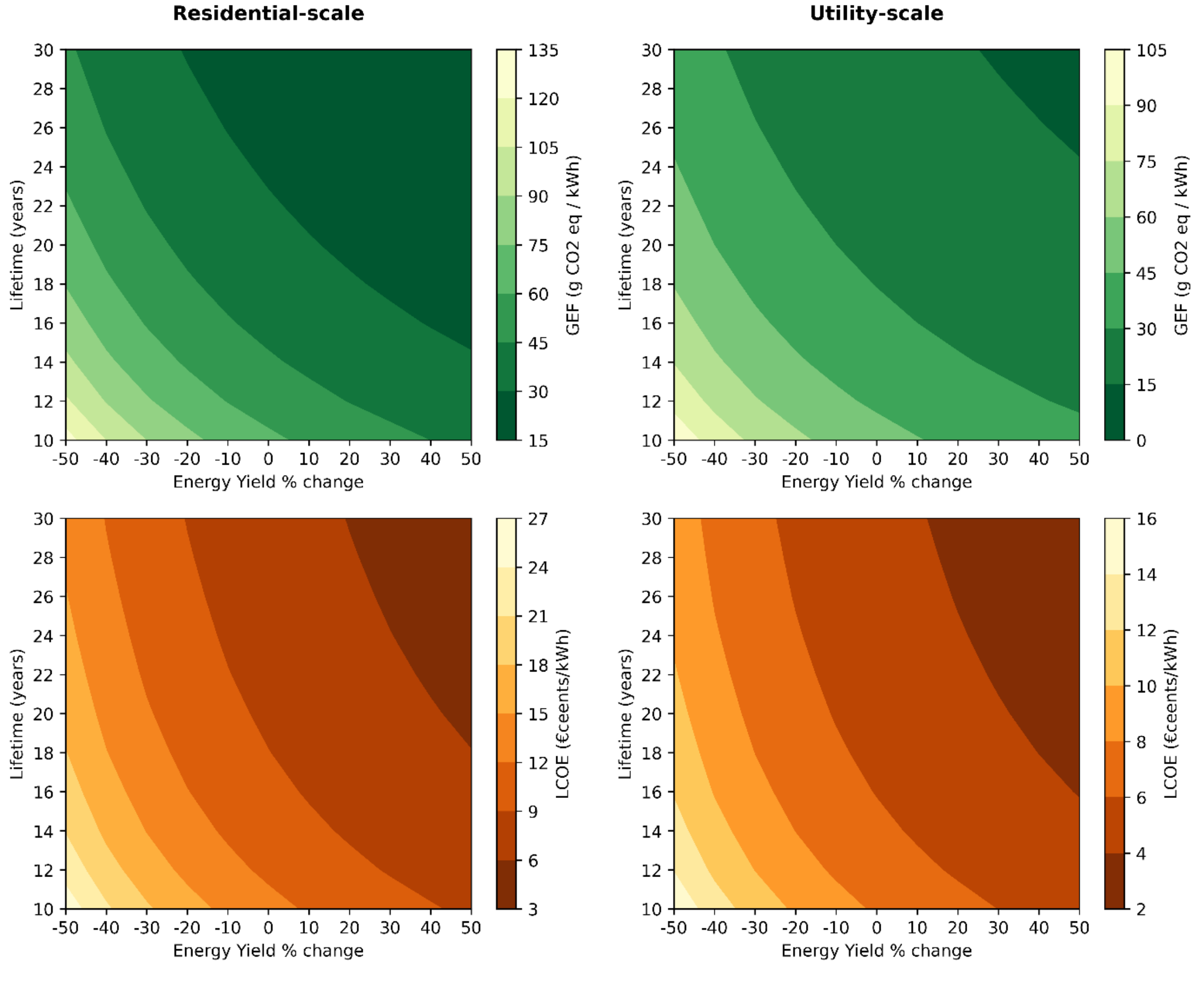

Figure 5: Carbon-based perovskite LCOE and GEF sensitivity for changes in lifetime and EY for residential and utility scale systems (average of three locations).

The influence of lifetime and EY on the LCOE and GEF indicators is illustrated in Figure 5 for residential and utility scale systems averaged at the three locations. The contour plots highlight the potential of carbon-based perovskite to become an economically and environmentally sustainable competitive PV technology. Achieving EY values higher than 20 percent (approximately 294 kWh/m^2 on average at the three locations), carbon-based perovskite PVs might reach very low average LCOE (3 - 6 €cents/kWh) even for moderate lifetime values (>20 years). With an EY performance similar to c-Si (374 kWh/m^2 on average at the three locations) and lifetime >20 years, the average LCOE would result in the range of 2-4 €cents/kWh. This would make carbon-based perovskite PV considerably more economically attractive than alternative PVs. For comparison, the LCOE of utility-scale PV systems in Europe is 2.5-6 €cents/kWh and is forecasted to be in the range of 1.5-4 €cents/kWh by 2040 [47]. Analogous trends can be seen for the GEF, although it seems unlikely that this indicator would decrease below the 15 gCO$_2$/kWh at the utility scale since the carbon-based perovskite would need to reach very high values of EY (+50 percent) and lifetime (>26 years).

3.3 END-OF-LIFE CONSIDERATIONS

Figure 6 shows how the economic and environmental indicators change for different values of recovery rate achieved by the recycling process and different levels of technical performance obtained by the refurbished PV modules. In this regard, we assume that performance depends on PCE and EY; as an example, -30 percent performance corresponds to a 30 percent relative reduction in module PCE (relevant for the MSP) and relative EY (relevant for LCOE, EPBT, and GEF). The end-of-life recycling/refurbishment benefits are only observed with high recovery levels (>90 percent) and low performance reduction (-10 percent to 0). Full end-of-life recovery does not positively influence the economic and environmental performance if the refurbished PV module technical performance is negatively affected. The indicators' sensitivity differs between the MSP/LCOE and the EPBT/GEF. The environmental indicators, provided high levels of recovery (>90%), improve even with a slightly reduced technical performance of the refurbished PV modules. The EPBT can be decreased up to 23% and the GEF up to 13% with full recovery and no performance reduction; This is due to the recycling process that allows significant savings in materials and energy employed in the production phase. In contrast, the MSP and LCOE would only benefit from high recovery levels and unaffected technical performance. For full recovery and performance unaffected, the MSP and LCOE would decrease by 14% and 4%, respectively. Furthermore, for low and medium (50-70%) levels of recovery and unchanged performance, the environmental indicators are positively influenced in contrast to the economic indicators that slightly increase. Hence, a trade-off between economic and environmental indicators optimization exists, thus, it is essential to integrate the economic and environmental evaluation to identify similar trade-offs where present.

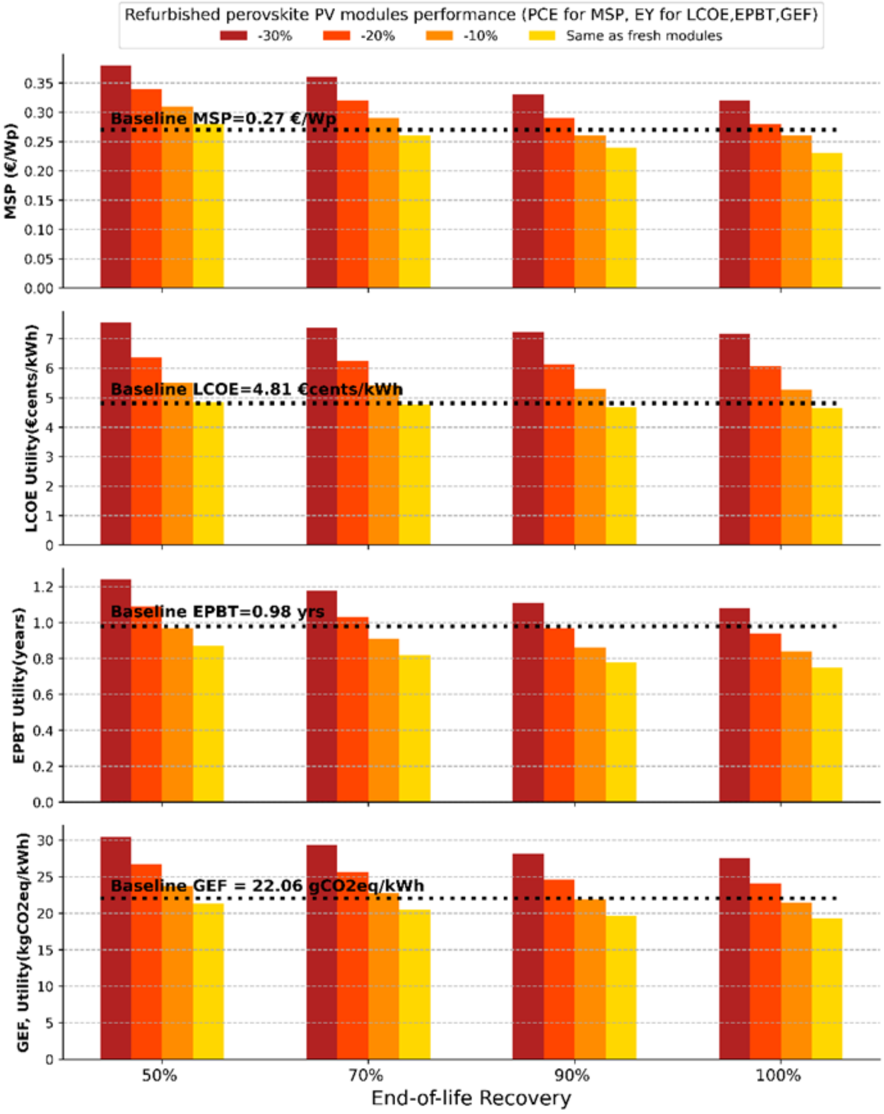

Figure 6: Indicators change at different levels of recovery rates. LCOE, EPBT, and GEF represent the average at three locations for utility-scale PV systems.

We then consider the total effect of relative PCE improvements, EY increase, and at least a 90 percent recovery rate of the recycling process for the system-level indicators (Figure 7). We assume a relative PCE increase of 20 percent (≈17.3 percent), a relative EY increase of 20%, and an end-of-life recovery rate of >90 percent. The PCE considered in this study is moderate and underestimated compared to the high values demonstrated on a smaller-scale device at a laboratory scale. Therefore, it is reasonable to expect that the MSP value found in this study represents a conservative perovskite performance since higher PCEs can also be reached in the future on large-area devices. With the simultaneous relative PCE increase and 90 percent recovery rate, MSP can be reduced by 19 percent, achieving 0.22 €/Wp. This corresponds to approximately 20 percent less than the average price currently paid for c-Si PV modules.

Values are reported for residential and utility-scale systems and represent average results at the three climatic zones considered. The LCOE would experience remarkable reductions for both scales by reaching values less than 5.5 €cents/kWh. In this case, we also consider system cost reductions expected by 2030. The average LCOE decreases considerably (more than 28 percent), and the gap of carbon-based perovskite with c-Si and CIGS is curtailed; the perovskite LCOE, in this case, is 26 percent and 5 percent higher than the corresponding c-Si and CIGS LCOE and, computed with 2050 system costs at utility scale. At the residential scale, the carbon-perovskite has 23 percent higher LCOE than c-Si and 4 percent lower LCOE than CIGS. Therefore, the simultaneous technical performance enhancement (PCE and EY) and the successful implementation of end-of-life recycling procedure indicate that perovskite PVs can reasonably reduce their gap with alternative PV technologies. In that scenario, c-Si PVs would still remain the most cost-competitive technology for electricity generation, provided that no further technological improvement to perovskite PVs are carried out. The perovskite PVs seem to be more cost-competitive with other thin-film technologies such as CIGS than traditional PV modules based on c-Si. Nevertheless, the perovskite PVs development is progressing fast and it is reasonable to expect module PCEs improvements in the coming years; this would further increase the energy yield, thus reduce the LCOE values and reduce the cost competitiveness gap with traditional c-Si modules. On the other hand, in contrast to the LCOE, the environmental indicators highlight the potential of the carbon-based perovskite PVs. Similar reductions are observed for the EPBT, with payback times below 0.9 years, and this corresponds to approximately 30 percent reduction compared to the baseline at both scales; this would further expand the energy payback benefit compared to traditional PVs. A smaller reduction is shown for the GEF, which could decrease below 20 g CO_2 eq/kWh at utility-scale (approximately 24 percent reduction) and thus perform considerably better than c-Si (29 g CO_2 eq/kWh) and CIGS (26 g CO_2 eq/kWh).

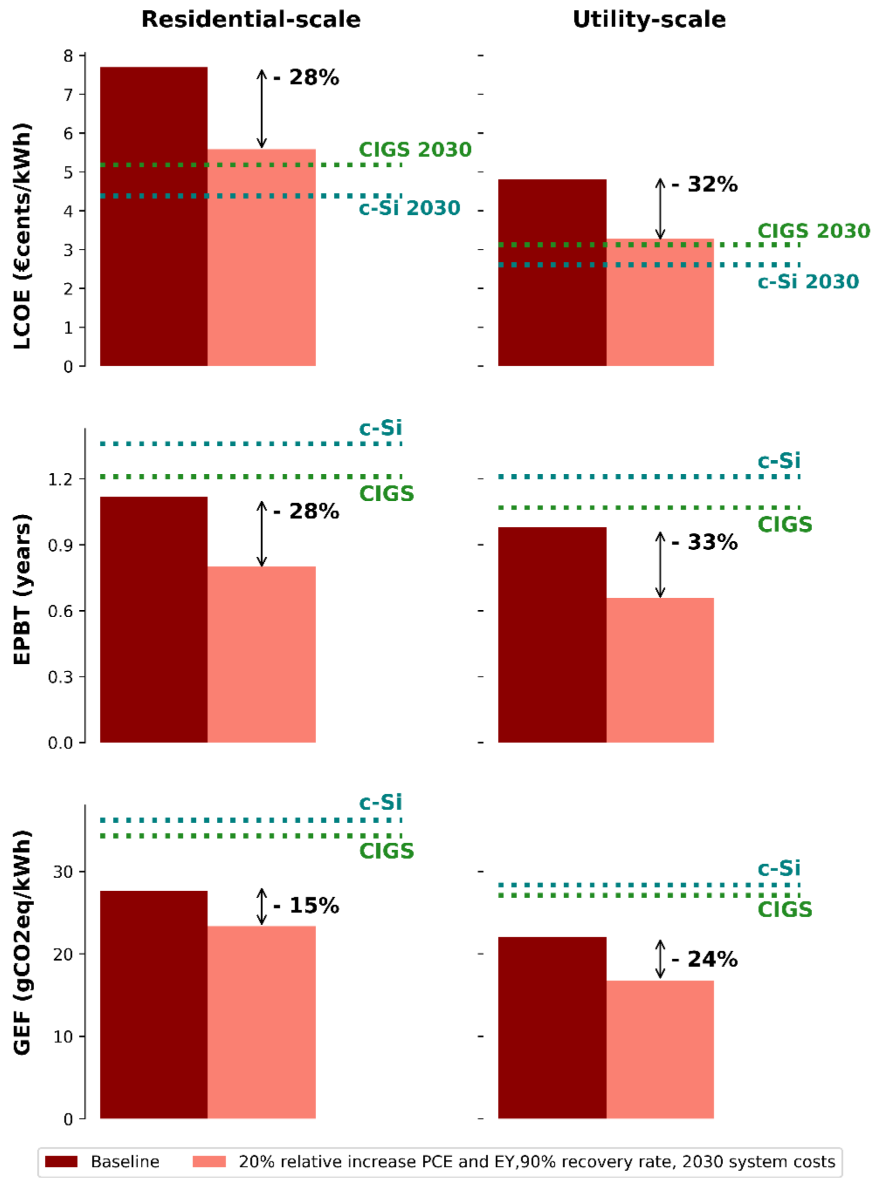

Figure 7: LCOE, EPBT, and GEF carbon-based perovskite values with a 20% relative increase in PCE and EY, 90% recovery rate and 2030 system costs (relevant for LCOE only) compared to baseline. c-Si (mono) and CIGS LCOE values are computed at 2030 system costs.

4 CONCLUSIONS

This study quantified the economic and environmental performance of a carbon-electrode-based perovskite PV configuration throughout its full lifecycle ex-ante. This configuration is considered promising as it has shown encouraging results for both efficiency and stability in laboratory-scale devices. In addition, it is composed of low-cost materials that can be deposited by employing fast and low-energy demanding manufacturing techniques. Hence, it is a suitable candidate to evaluate the competitiveness of large-scale perovskite manufacturing (100 MW). The analysis focused on quantifying economic and environmental indicators at module and system level, while for the latter assuming a lifetime of 25 years.

With regards to economic indicators, at module level, the carbon-based perovskite configuration was found to offer promising results since its minimum sustainable price was estimated to be 0.27 €/Wp. This is in line with previously assessed perovskite PV configurations that are not amenable to upscaling.

It indicates that carbon-based perovskite PV modules can be sold at a comparable price of c-Si and CIGS modules currently available in the market (0.20-40 €/Wp). Nevertheless, the LCOE computed at system-level and across three climatic zones revealed that perovskite PVs generate electricity at on average a 7 and 20 percent higher cost compared to c-Si and CIGS both at residential and utility-scale given current system costs. This is mainly the due to the higher rated PCEs of CIGS and c-Si, and thus better yield, which increases the system's output and consequently decreases the overall system cost. In locations with higher insolation (e.g. desert) perovskite's LCOE was closest to that of a CIGS system. This gap between LCOEs across PV technologies would further increase by projecting the LCOE values to 2030 by considering reduced module and system costs. Yet, we demonstrate that the successful implementation of recycling processes, as well as technical improvements (e.g., PCE and EY), can close this gap by generating an LCOE in the range of 3.5-5.5 €cents/kWh, depending on the system scale. This implies that this perovskite architecture can generate electricity at a comparable price to CIGS (3-5.5 €cents/kWh) given further system cost reductions and learning effects that will significantly reduce the LCOE of conventional technologies. With regards to environmental indicators, both at module and system-level, a comparative advantage of carbon-based perovskite PVs was established.

The EPBT and GEF were on average across the three climatic zones found to be 18 percent and 8 percent and 23 and 19 percent lower than respectively c-Si and CIGS. The carbon-based perovskite energy payback period was estimated to amount to less than one year with room for further improvement. These results demonstrate the climatic benefit of a large- scale market deployment of carbon-based perovskite photovoltaics.

In order to limit global warming to 1.5°C by 2050, electricity generation from renewable energy sources would need to be significantly expanded. IRENA [1] estimates that solar PV, along with wind energy, would lead the transition and, to reach the 1.5°C scenario, should generate approximately 23000 TWh of electricity yearly. Currently, only 650 TWh of electricity is generated by solar PVs. If this expansion was fully conducted through use of perovskite PV, approximately 167 megaton of CO_2 eq. could be saved compared to the use of c-Si technologies, which amounts to 23 percent reduction of the lifecycle GHG emissions of the expansion with c-Si technologies.

ACKNOWLEDGEMENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 850937.

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