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# Beyond silicon: Thin-film tandem as an opportunity for photovoltaics supply chain diversification and faster power system decarbonization out to 2050

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## ABSTRACT

In the last decade, the manufacturing capacity of silicon, the dominant PV technology, has increasingly been concentrated in China. This coincided with PV cost reduction, while, at the same time, posing risks to PV supply chain security. Recent advancements of novel perovskite tandem PV technologies as an alternative to traditional silicon-based PV provide opportunities for diversification of the PV manufacturing capacity and for increasing the GHG emission benefit of solar PV. Against this background, we estimate the current and future cost-competitiveness and GHG emissions of a set of already commercialized as well as emerging PV technologies for different production locations (China, USA, EU), both at residential and utility-scale. We find EU and USA-manufactured thin-film tandems to have 2–4 % and 0.5–2 % higher costs per kWh and 37–40 % and 32–35 % less GHG emissions per kWh at residential and utility-scale, respectively. Our projections indicate that they will also retain competitive costs (up to 2 % higher) and a 20 % GHG emissions advantage per kWh in 2050.

## 1. Introduction

Over the last decade, photovoltaics (PV) deployment has grown significantly to reach 1 TW of global cumulative PV capacity installed [1]. By 2050, capacity is expected to surpass 40 TW [2–4]. Single-junction (SJ) silicon solar modules are the dominant PV technology, accounting for 95 % of the PV market [5]. Between 2014 and 2021, China invested more than USD 50 billion in scaling up the domestic manufacturing capacity of silicon PVs [6]. Currently, China holds over 75 % of the production capacity in all stages of manufacturing PV modules, and almost half of its modules are sold to Europe [7]. This, along with technological learning, has contributed to cost reductions of over 80 % per kWh of electricity generated in the last decade [8], which came at the expense of relocating PV manufacturing capacity away from other locations, especially Europe and the United States (USA). In 2021, 89 % of European solar PV modules were imported from China [9]. Approximately 50 % of modules in the USA are imported from China, Singapore, Taiwan, and Vietnam [10].

The COVID-19 pandemic and the Ukraine war have recently shown that global supply chains are vulnerable to shocks and that import dependency can threaten security of supply, thereby limiting availability and increasing prices [11,12]. For instance, after experiencing declines for many years, PV module prices increased by approximately 25 % between 2020 and 2022 due to the increase in material input prices and

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supply chain disruptions [13,14].

Supply chain and market concentration-related price increases are an impediment to the rapid decarbonization of the energy system required to reach climate goals. This is widely realized by policymakers. For example, in 2022, the International Energy Agency called for a diversification of the PV supply chain [6]. In the USA, the Inflation Reduction Act contains provisions to stimulate domestic PV manufacturing capacity ramp-up through investment credits [15]. Similar plans have been announced in the European Union (EU) [16].

As traditional SJ PV technologies approach the theoretical efficiency limit of 30 % [17], one pathway to long-term cost competitiveness for a domestic PV module manufacturing sector may lie in the earlier development and deployment of novel, advantageous technologies [18], such as PV tandem configurations. Perovskites have been growingly applied as top-cell in such tandem configurations due to their advantageous bandgap tunability [19] and rapid increase in power conversion efficiency (PCE) in the last decade. Perovskite tandem configurations combining bottom-cell based on silicon technologies have shown PCEs surpassing 30 % [20]. Yet, thin-film tandems coupling perovskite with CI(G)S bottom-cell have also been demonstrated with promising efficiencies above 25 % [21–23]. Moreover, thin-film tandems employing perovskite as top and bottom cell, with efficiencies above 25 % have also emerged recently [24,25]. The latter results, combined with established thin-film R&D centers and equipment suppliers in the EU and the USA [26], may provide an opportunity to build new thin-film tandem PV module manufacturing capacity to provide the additional supply needed due to expected growth of demand for solar PV. Consequently, this would contribute to diversifying the PV supply chain and the PV products available in the market.

Previous analyses determined the conditions under which specific tandem PVs can compete with traditional SJ PVs [27–34]. However, these studies did not provide an analysis that considers both a range of SJ and tandem technologies and jointly covers cost and environmental impact aspects. Wikoff et al. [35] addressed the embodied carbon of single-junction c-Si and cadmium-telluride (CdTe) PV technologies in the EU, USA, China and India. However, regional (dis)advantages and a perspective out to 2050 for tandem technologies were not addressed.

Against this background, the goal of this paper is to define the conditions under which thin-film tandem PVs, containing a perovskite top cell and a CIS bottom cell, can be economically and environmentally competitive with the market-dominant silicon PVs manufactured in China. To obtain a harmonized study, we quantify the costs and the lifecycle GHG emissions of different single-junction and tandem PV technologies when manufactured either in the EU, China, or the USA as if production of the modules were to take place now and out to 2050. For SJs, we consider PERC, HJT, CIGS, and perovskite PV modules. For the tandems, beside perovskite/CIS we also focus on devices in a 2-terminal (2T) and 4-terminal (4T) architecture of perovskite//silicon (PERC or HJT) modules. We start by quantifying present-day cost metrics for both the production of SJ and tandem modules as well as their deployment in PV systems across the three geographical areas considered (EU, China, and the USA) for the same climatic conditions and production scale. Since location also affects environmental impact, we proceed by quantifying the lifecycle greenhouse gas (GHG) emissions associated with module production and the accompanying PV systems. Our results benefit from the output of an energy yield model that quantifies PV modules' yield under realistic climate conditions. In a final step, we project the selected cost and GHG emissions indicators to 2050. We account for growing worldwide solar capacity, cost reductions, power conversion efficiency (PCE) improvements, and changes in countries' energy mixes.

## 2. Methods

### 2.1. Device architecture and steps in the production process

The PV device architectures under consideration for manufacturing are shown in Fig. 1. Due to the wide range of possible choices in cell architectures and fabrication methods employed, we focus on PV configurations that are representative of industrial-scale production to reflect the purpose of this study. The selected SJ configurations comprise two alternative silicon-based technologies, passivated emitter and rear cell (PERC) and silicon heterojunction (HJT). We specifically focus on these two silicon SJ technologies due to their strong presence in the market and the best efficiency performance. PERC is the market-dominant c-Si PV technology that currently accounts for about 85 % of the world market share, whereas HJT is the most-efficient silicon PV technology [20]. HJTs currently account for only 2 % of the market and are expected to grow in the following years [36]. The PERC technology substituted the mainstream Al-BSF solar cell in the last decade by overcoming the recombination losses at the rear side, leading to higher PCEs; the theoretical limit of PERC's PCE is around 25 % due to bandgap narrowing, Auger, and contact recombination losses [37]. The HJT technology reduces contact recombination losses by using passivated contact layers (e.g., a-Si: H) between the c-Si wafer and doped silicon films; this approach has demonstrated high efficiencies of around 26 % [38]. HJTs are the ideal bottom cell for high-efficiency tandem devices; a tandem configuration that combines a perovskite top cell with an HJT bottom cell currently holds the PCE record [39]. Nevertheless, as highlighted by the first cost studies, tandems with HJT bottom cells may not be the most suitable from a cost perspective [27,32] due to the higher associated costs with HJT production.

As an alternative to PV technology entailing silicon, we consider SJ thin-films, being CIGS and perovskites, and thin-film tandem devices, being the 2T and 4T architectures for a perovskite/CIS tandem. As our focus is on thin-film tandems employing the perovskite and CIGS technologies, we exclude another relevant thin-film PV technology, cadmium-telluride (CdTe), currently present in the market. Moreover, among thin-film tandem technologies, we limit the analysis to perovskite/CIS devices, thus excluding the all-perovskite tandem PV technology. The development of a 2T perovskite/CIS tandem has only recently been described. Its appeal derives from using a CIS bottom cell that perfectly couples the p-i-n perovskite top cell, which allows for optimal bandgap tunability and therefore increases the efficiency. The obtained PCE is close to 25 %, and values close to or above 30 % are expected to be reached. Additionally, this device demonstrated a more stable PCE [23]. A detailed description of the manufacturing process of each of the devices shown in Fig. 1 can be found in the Supporting Information. All devices are fabricated on glass substrates encapsulated with EVA and glass. For the module assembly components, such as the substrates and encapsulation, the same deposition methods and materials used for silicon-based devices are assumed to be used for all thin-film devices. Below, for brevity, we describe the manufacturing process for the thin-film perovskite/CIS tandem architectures, as these are the most novel devices.

In its 2T configuration, the perovskite/CIS tandem consists of a p-i-n top cell deposited on the CIS bottom cell having ZnO and CdS, respectively as a window layer and buffer layer, with the CIS absorber deposited on the molybdenum rear contact. The CIS and perovskite cells are connected through a recombination junction layer composed of AZO. The top cell uses NiOx and a thin layer of 2PACz as the hole transport layer, which is deposited on ITO. The electron transport layer is composed of SnO2 and C60. The 4-terminal device employs the same materials as the 2-terminal, although it does not include a recombination junction and comprises an EVA spacer layer between the top and bottom cells.

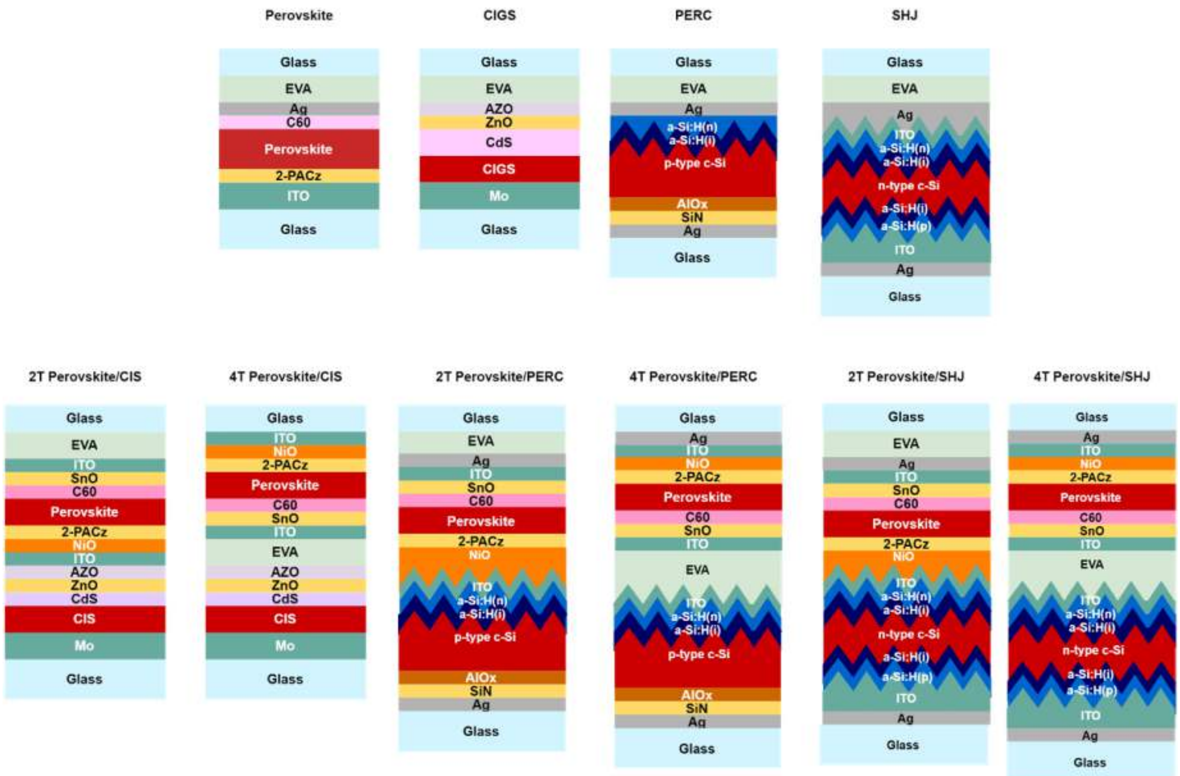


**Fig. 1.** Configurations of PV technology assessed in this study.

#### 2.1.1. *Estimating energy yield*

The energy yield (EY) analysis calculates the annual energy output for each device under realistic irradiation conditions modeled using the state-of-the-art energy yield platform open-source software "EYcalc" developed by KIT [40,41]. Four modules are integrated to create the EY platform: (i) an irradiance module, (ii) an optics module, (iii) an electrics module, and (iv) an energy yield core module. The irradiance module computes the irradiance at selected locations with a time resolution of 1 h. The irradiance is angularly and spectrally resolved, considering the meteorological conditions and the cloud coverage at the selected location. Meteorological data from the 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 the 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) are then given as an input to the energy yield core module to compute the photogenerated current density in the absorber materials with a time resolution of 1 h. Using a one-diode analytical model, the electrics module then uses the time-resolved photogenerated currents to compute the maximum power point (MPP) for each year's hour. In order to estimate the temperature of the cells, we use the Nominal Operating Cell Temperature (NOCT) model [42], assuming a NOCT of 48 °C (valid for an open rack configuration), while the insolation on the cell and the ambient air temperature is extracted from TMY3 data [43]. Ultimately temperature coefficients for the open circuit voltage (VOC) and short circuit current density (JSC) are used to update the electrical simulations' current density – voltage (J-V) characteristics as a function of the cell temperature, which, as previously mentioned, was computed via the NOCT model.

EY simulations in realistic irradiation conditions are performed for the ten devices under consideration. Three locations representing very different climatic conditions are selected: Phoenix (desert), Miami (tropical), and Seattle (temperate oceanic). The obtained EY results are given in Table 1 for the three selected locations. The PCE and EY figures presented in Table 1 include the losses attributed to module interconnections within the active area. These are obtained by considering 5 % active area losses for each technology on the initial outcomes of the simulations for the optical and energy yield simulations [44,45]. While the differences in EY for different locations are due to different solar spectra, temperature differences are not considered across the various locations. We use TMY3 data to calculate a solar spectrum for each hour of the year. The TMY3 dataset contains meteorological data about, among others, humidity, cloud coverage, dry-bulb temperature, pressure, precipitable water and aerosol optical depth, which vary for each location. On top of that, the different latitude and longitude of the locations lead to different irradiation conditions. Lastly, the different light absorption properties of each technology explain why certain

**Table 1**
PCE and EY values under three climatic conditions for PV devices under consideration.

| | PCE (%) | Average Energy Yield (kWh/m$^2$) | Energy Yield (kWh/m$^2$) | | |
|---|---|---|---|---|---|
| | | | Desert | Tropical | Oceanic |
| PERC | 21.8 | 370 | 461 | 372 | 278 |
| HJT | 22.8 | 377 | 451 | 375 | 295 |
| CIGS | 20.2 | 343 | 426.5 | 345 | 256.7 |
| Perovskite | 20.4 | 362 | 455.8 | 365.3 | 264.9 |
| 2T Perovskite/PERC | 29.3 | 489 | 618 | 495 | 355 |
| 4T Perovskite/PERC | 29.2 | 498 | 630 | 499 | 365 |
| 2T Perovskite/HJT | 29.6 | 503 | 636 | 504 | 368 |
| 4T Perovskite/HJT | 29.5 | 494 | 624 | 500 | 359 |
| 2T Perovskite/CIS | 28.8 | 483 | 610 | 487 | 353 |
| 4T Perovskite/CIS | 28.9 | 492 | 624 | 492 | 361 |

technologies perform better than others for specific solar spectrum conditions.

### 2.2. Estimating cost competitiveness and greenhouse gas emissions

To quantify and compare the cost competitiveness and GHG emissions for manufacturing the PV devices shown in Fig. 1 across the three locations, we apply the principles of an environmental-techno economic assessment (ETEA) [46,47]. This technology assessment method integrates a life-cycle assessment (LCA) with a techno-economic assessment (TEA) using the exact system boundaries. Here, we assess the PV devices from manufacturing to deployment in the PV systems without considering transportation between stages, as its impact is negligible [6]. The assessment comprises indicators computed at the PV module and system level. At the module-level, the cost competitiveness and GHG intensity are respectively determined by computing the minimum sustainable prices (MSP) in USD$ per watt) and the global warming potentials (GWP) in kgCO2-eq per watt) for each PV device being manufactured in each of the selected locations today. These two indicators do not include the evaluation of cost and GHG emissions derived from the use of the PV devices. The module-level analysis has thus a cradle-to-gate approach.

For each technology and region, we model manufacturing with an annual production capacity of 100 MW. We opt for this scale because, for the novel technologies, we assumed that additional capacity needs to be added, and the industry often uses this scale before ramping up its capacity. This additionally allows for an analysis that excludes the cost advantage coming from the scale. However, for the more established technologies, being PERC and HJT SJ, we also consider larger manufacturing capacities for a single plant to capture effects derived from manufacturing silicon PV cells and modules at larger scales. In particular, the indicators are also computed for 1 GW and 500 MW production of PERC and HJT in China. We refrained from performing such an analysis to expand CIGS SJ manufacturing capacity as this would be a break in an ongoing trend of shutdowns [48]. Furthermore, we assume that the cost of capital is equally costly across the technologies [49] and the regions considered due to the implementation of the Inflation Reduction Act in the USA and the Green Deal Industrial Plan in the EU. Additionally, as the cost of capital for PV projects decreases over time, this would likely be similar across regions [50].

Cost differentials across regions are assumed to be related to labor, energy, and scale. Data regarding energy and labor cost differences are readily available in contrast to regional price differences for materials and equipment. For the latter, we consider that manufacturers based in China have a cost advantage compared to those based in the EU or the USA due to the larger scale of raw material and equipment manufacturing and associated concentration of supply chain activities. Specifically, we assume a 20 % cost advantage for acquiring equipment of silicon-based PVs manufactured in China [51] whereas, no equipment cost differences are accounted for thin-film PVs due to the available equipment manufacturers in the USA and the EU. We also assume 10 % price advantage for sourcing materials for all PV technologies manufactured in China [51], including 100 MW and large-scale silicon PV manufacturing (1 GW PERC and 500 MW HJT). We consider equivalent efficiency performance for PV technologies originating in the EU, USA and China as connections between equipment manufacturers and R&D institutes facilitate technology diffusion on a global scale [51,52].

Analogously, at system-level, we quantify the levelized cost of electricity (LCOE) in USD$cents per kWh and GHG emission factor (GEF) in kgCO2-eq per kWh for residential scale (30 $m^2$) and utility-scale (0.5 $km^2$). With the system-level analysis, we consider the effect of the energy yield performance of each PV technology considered in this study. Both indicators are computed over a period given by the years until the PV system provides 80 % of the actual energy output for a maximum of 25 years. The inverter's lifespan is taken at 15 years. All the other components are considered to have the same life expectancy as the PV modules.

The assumptions of this study follow the Methodology Guidelines on LCA of PV [53]. Additionally, we use the most recent global warming potential (GWP100) factors published by the IPCC [54]. Depending on where the PV system is deployed, we use balance of system (BOS) cost data for the EU, China, and the USA [8]. Besides the differences in system area, the utility-scale and residential-scale differ in terms of system component costs (Table 43 in Supporting Information). With regards to emissions of the PV system components, the mounting structure GHG associated emissions are modeled for the three regions (USA, EU and China); for the other components, a default global value from the environmental impact database employed (ecoinvent 3.9) is considered. Degradation rates are assumed equal across PV systems, due to the unavailability of such data for other than silicon PVs, with a rate of 0.88 %/year, 0.78 %/year, and 0.48 %/year respectively, for a desert, tropical and oceanic climate [55]. Given that such a degradation rate has not been demonstrated for perovskites, we also explore the LCOE and GEF as a function of the perovskite cell's degradation rate. For 4T tandem applications, we assume that the perovskite cell contributes to 65 % of the overall PCE and thus of the EY performance, based on recent findings that place the top-cell influence between 60 % and 70 % [56]. In contrast, for 2T tandems, we reckon that the perovskite's degradation rate determines the lifetime of the entire device, as for this device the two sub-cells are in series. Since our paper is about diversifying the PV supply chain, we compare the LCOE and GEF indicators for PV modules manufactured in the EU, USA, or China and installed in a PV system in the EU or USA.

We account for two types of uncertainty while quantifying the indicators mentioned above. Technical uncertainty is caused by divergence in layer thicknesses for the considered device stack architectures, the equipment type employed, and the consequent material and energy use. The input parameters' ranges are larger for the novel technologies, such as tandems or perovskite SJ devices, compared to market-available technologies, such as silicon-based and CIGS SJ, due to more standardized production routes. Technical uncertainty affects both the cost and GHG emission indicators. Price-related uncertainty is mainly related to materials and capital equipment cost variation. We, therefore, estimate these indicators' distribution by performing a Monte Carlo analysis with 50 000 iterations. In every iteration, for every uncertain input parameter, a value is randomly drawn from a triangular distribution created with the most likely, maximum, and minimum values found describing that specific parameter.

This method allows for the identification of ranges for indicators like ours that are dependent on multiple, uncertain input parameters. Besides, the approach to executing the MC we describe above allows for the identification of cost and environmental impact uncertainties using the minimal resources available (e.g. technical and price data) for developing the cost and environmental impact analysis [57].

In a final step, we extend our analysis by projecting the LCOE and GEF results to 2050. The selected time frame is based on the expectation that tandem technologies may begin to gain a portion of the photovoltaic market after 2030 [36]. Additionally, substantial efforts towards decarbonizing the countries' energy mixes target the year 2050 [58]. In doing so, we consider forecasts for cumulative PV capacity that estimate worldwide capacity to be 42 TW in 2050 [2,59]; we then estimate modules and BOS costs by employing a learning rate approach [60]. We assume that future cost reductions are related to the industry learning rate, and therefore, we disregard potential cost reductions due to an increase in manufacturing scale for each technology. Besides the learning rate, module cost reductions are affected by PV technologies market shares as shown in the Supporting Information (Table 59). When a specific PV technology is present in the market, the same learning rate is applied; this implies that novel configurations such as perovskite/CIS are assumed to have, once entering the market, the same learning rate as traditional crystalline silicon technologies (e.g., PERC) even though in reality this could be different. However, we decided to adopt this approach as there is no information about learning rates for tandem thin-film PV technologies yet.

Table 59 in the Supporting Information provides the assumed market shares for each technology. For perovskite/silicon tandem technologies, the module cost reductions are not only driven by the perovskite (tandem) share in the market but also by the PERC and HJT shares (depending on whether the tandem considered is perovskite/PERC or perovskite/HJT). Thus, the module cost fraction of perovskite/silicon tandems dependent on the PERC (or HJT) technology is assumed to decrease based on the PERC (or HJT) market share. The module cost fraction dependent on the perovskite technology is assumed to decrease based on the perovskite tandem market share. Perovskite/CIS module cost reductions, are only driven by the perovskite (tandem) market share.

Moreover, we account for expected PCE improvements by fitting a logistic function to the cell efficiencies data provided [20,61]. The percentage increase in PCE is then taken as a proxy for the expected relative increase in the EY values in each climatic location. Additionally, we consider changes in all three countries' electricity mixes developments according to scenarios of energy system transition pathways developed by the Lawrence Berkeley National Laboratory, NREL, and the EU Commission [62–64]. Mathematical formulae for computing the indicators, the model specification for the learning rate and logistic function, and the data used as input for their calculation can be found in Supporting Information.

## 3. Results and discussion

### 3.1. Module-level indicators

The resulting present-day MSPs and GWPs are shown in Fig. 2. As can be seen on the left-hand side of Fig. 2, SJ photovoltaics are found to have the lowest MSP with the perovskite device resulting in approximately 0.25–0.34 USD$/W, depending on the manufacturing location. Despite the lower efficiency than silicon SJ technologies, perovskite SJ can achieve low MSP due to the associated low manufacturing costs (energy and material related). Large-scale manufacturing (1 GW) of PERC PVs in China results in the lowest MSPs being, on average, at 0.27 USD$/W. Although tandems generally show higher MSPs, the thin-film-based, perovskite/CIS are likely to reach similar MSP values as HJT devices, ranging between 0.36 and 0.44 USD$/W. In contrast, perovskite/silicon tandems, if manufactured in Europe (EU) or the USA, have higher prices than thin-film tandems, with perovskite/HJT MSPs over 0.49 USD$/W and perovskite/PERC MSP above 0.45 USD$/W. Although the distribution of novel thin-film tandems MSPs, such as perovskite/CIS tandems, is noticeably wider than those of SJ, the probability of perovskite/CIS manufactured in the EU to having a lower MSP than the mean MSP of perovskite/PERC (0.39 USD$/W) and perovskite/HJT (0.43 USD $/W), manufactured in China, is 26 % and 48 %, respectively. USA-based manufacturing of thin-film-based tandems may result in lower costs compared to the perovskite/HJT tandem and may result in comparable costs with perovskite/PERC tandems with manufacturing based in China; in this case, the probability of perovskite/CIS manufactured in the USA to have a lower MSP than the mean MSP of perovskite/PERC manufactured in China is 51 %. As seen on the right-hand side of Fig. 2, when considering the GHG emissions, the differences are more clear-cut across the manufacturing locations with a clear advantage to European production. In this location, only the perovskite SJ device obtains lower GHG emissions per watt than the perovskite/CIS tandems (EU), which in turn presents GWP reduction of around 30 %, 32 %, 33 %, and 29 % compared to perovskite/HJT, perovskite/PERC, PERC SJ and HJT SJ. Furthermore, the mean GWP of perovskite/CIS tandems manufactured in the EU is approximately 58 % and 56 % lower than PERC and HJT SJ modules produced in China. The mean GWP of perovskite/CIS modules produced in the USA is 49 % and 48 % less than PERC and HJT modules made in China. In sum, contrasting results are thus found for the MSP and GWP across regions. Whereas Chinese PV module production is associated with the lowest price per watt, European and US-based manufacturing cause the lowest GHG emissions. The former can be explained by the lower material and capital costs assumed in this study for Chinese producers and the markedly lower labor costs. As for energy costs, EU-based manufacturers are greatly influenced by the high energy

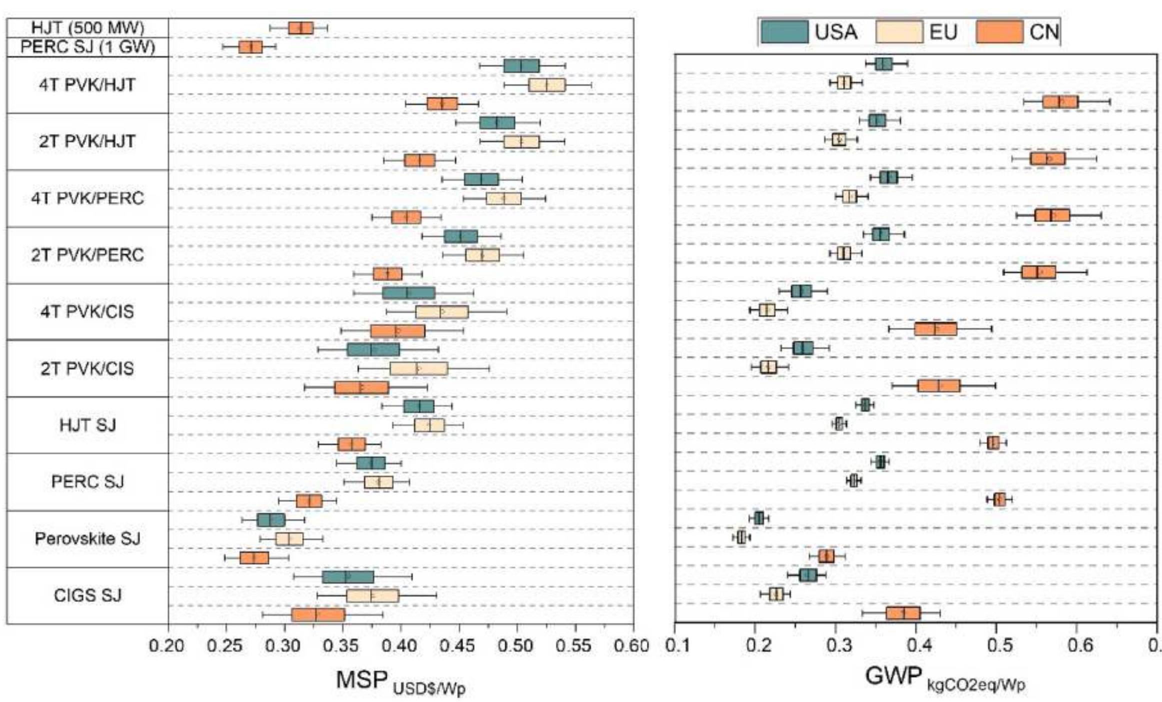


**Fig. 2.** Minimum Sustainable Price and GHG emissions associated with the production of each PV technology under consideration in the EU, China, and the US. Results are based on 100 MW manufacturing capacity; for comparison, MSPs corresponding to manufacturing capacities of 1 GW and 500 MW (in China), respectively, for PERC and HJT SJ, are provided.

prices, which started rising in the second half of 2021 [65]. This aspect not only results in higher costs for European PV modules but also enlarges this difference for technologies for which the energy costs have more relevance in the total manufacturing costs, such as thin-film PVs (tandem and SJ). The GWP differences are primarily due to the high carbon intensity of the Chinese electricity generation mix, which contributes to higher GWP values compared to the European counterparts.

### 3.2. System-level indicators

Building on the obtained module-level estimates, we present the estimated regional present-day LCOEs and GEFs for PV systems in Fig. 3. For each region, results pertaining to the utility-scale are presented on the left-hand side, whereas results applying to the residential scale are plotted on the right-hand side. The values shown for each technology result from an average of LCOE and GEF computed for the three climatic conditions (desert, tropical and oceanic). This cancels out the effect of where the PV system is installed on the presented metrics.

Generally, tandem PVs show the best economic performance at the residential scale. This can be explained by the larger influence of BOS costs for lower-capacity plants, as for these applications, tandems have a clear advantage due to their higher PCEs and hence the possibility to offset the higher residential system cost. The tandem residential cost advantage is more evident in areas characterized by higher system costs, such as the USA. At the utility scale, the tandem cost advantage is less marked, and except for the USA, where higher BOS costs are present, the perovskite SJ technology has the lowest LCOE. For the EU and USA, Perovskite/CIS PVs not only have the lowest LCOE at the residential scale but also present the lowest LCOEs among tandem PVs at the utility-scale. Furthermore, they obtain comparable values with the widely commercialized PERC SJ PVs. Additionally, we observe that perovskite/CIS are often found closer to the quadrant's bottom left corner, indicating the lowest LCOE and GEF. Perovskite/CIS tandems, manufactured in the EU, have about 23 % and 26 % lower GEF than PERC SJ manufactured in the EU, respectively, at the residential and utility-scale; The LCOE is 4 % and 1 % lower than PERC SJ respectively at the residential and utility-scale. The cost competitiveness of the thin film tandems is even more relevant for the systems produced in the USA; here, the LCOE

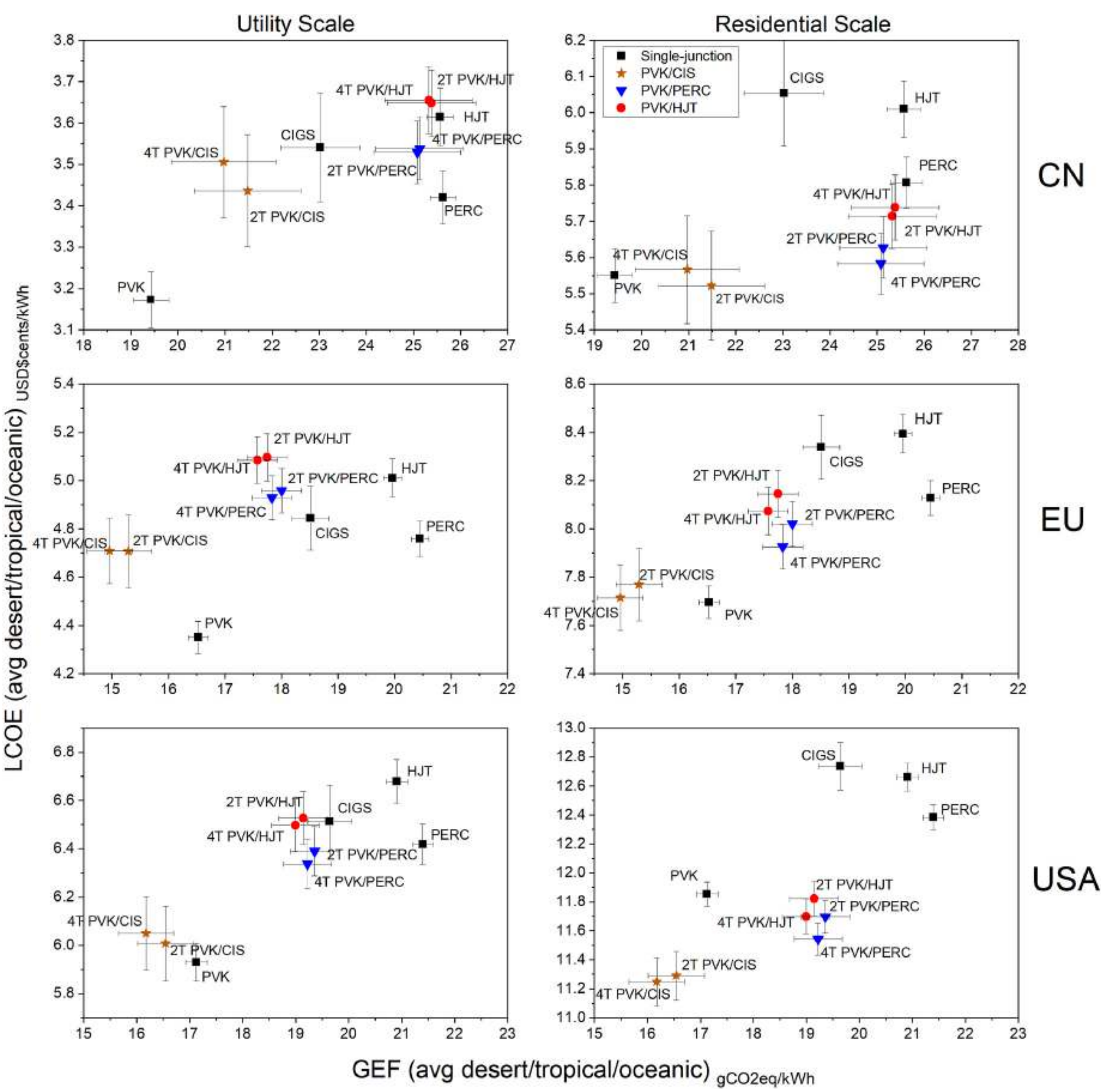


**Fig. 3.** LCOE and GEF for all technologies under study. Results show the utility and residential scale PV systems in the EU, the USA, and China. Each technology is assumed to be produced in the same region where it is deployed. Each LCOE and GEF point is representative of the average of three climatic conditions (desert, tropical and oceanic).

is 9 % and 6 % lower than PERC SJ (manufactured in the USA) at the residential and utility scale.

This confirms the potential of thin-film tandems to be cost-competitive with mature PV technologies, such as PERC, when disregarding the option to import modules. Furthermore, the potential contribution to reducing the GHG emissions of electricity generation is considerably higher for thin-film tandem PVs.

As for perovskite-based PV, despite recent advancements [66], stability represents a significant barrier to commercialization. For this reason, the LCOE and GEF are recalculated (Fig. 4) by varying degradation rates of perovskite-based PVs (SJ and tandems), between 0.50 %/year and 1.20 %/year. Degradation rates for PERC SJ PVs are the same as the baseline values assumed in this study, namely 0.88 %/year, 0.78 %/year, and 0.48 %/year respectively, for a desert, tropical and oceanic climate [55]. Generally, the findings suggest that all perovskite-based PVs should have an average yearly degradation rate below 0.80 %/year to have both a competitive LCOE and GEF with PERC SJ PVs. However, the maximum degradation value for competitive LCOE/GEF varies among the perovskite PV technologies. 4T Perovskite/CIS tandems have the highest limit for degradation rates, as for values approaching 1.00 %/year, the LCOE is only 3 % higher than PERC SJ. On the contrary, the GEF is always lower than that for PERC SJ. Among silicon-based tandems, the degradation analysis suggests that the use of PERC as bottom-cell is favored over that of HJT, given their cost and performance estimates.

Fig. 5 presents the results when considering imports. It depicts an LCOE and GEF comparison between EU-manufactured and Chinese-manufactured PV modules installed in an EU PV system, entailing EU BOS cost for both utility (left-hand side) and residential scale (right-hand side). This allows verifying whether installing thin-film PV modules made in the EU could be competitive with installing imported Chinese PV modules that currently dominate the European market. At the residential scale, EU-manufactured thin-film tandem PV systems may be cost-competitive with PV systems deploying SJ PVs produced in China. We can see that a PV system deployed in Europe utilizing EU-manufactured thin-film tandems' LCOE distribution overlaps with its counterpart utilizing PERC manufactured at large scale (1 GW) in China. This suggests thin-film tandems to be a promising alternative to silicon SJ PVs and an investment opportunity for EU-based PV manufacturers to develop and commercialize the technology, diversifying the supply chain. Nevertheless, emerging technologies such as perovskite SJ and perovskite/PERC manufactured in China, if installed in EU PV systems, would have a cost advantage compared to thin-film tandems manufactured in the EU. At the utility and residential scale, perovskite/PERC (China) PVs have an LCOE of 4 % and 2 % lower than perovskite/CIS (EU). Moreover, at the utility scale, PERC SJ (CN), with manufacturing capacities of 1 GW, presents the lowest LCOE among all PVs, approximately 9 % lower than perovskite/CIS made in the EU. In contrast, EU PV systems deploying perovskite/CIS manufactured in the EU would have a 40 % and 37 % lower GEF at the utility and residential scale compared to perovskite/PERC produced in China. Similar findings can be drawn from Fig. 6 for USA PV systems. In this case, at the utility-scale, USA-manufactured perovskite/CIS tandems exhibit more competitive LCOEs compared to PERC (1 GW) and perovskite/PERC tandems manufactured in China. Here, the perovskite/CIS LCOE is only 2 % higher than PERC (1 GW) and has approximately the same LCOE compared to perovskite/PERC tandems made in China.

### 3.3. Forecasted system-level indicators

The forecasted LCOEs and GEFs out to 2050 at residential and utility scales are shown in Figs. 7 and 8, respectively, for PV systems installed in the EU and the USA using domestic production or imports from China. As this paper's goal is to verify whether thin-film tandems manufactured in the EU and the USA provide room for supply chain diversification and faster decarbonization, we here focus on perovskite/CIS made in the EU and USA vs. silicon alternatives made in China. These objectives are motivated by the anticipated further increase of silicon PV production capacity in China to further benefit from economies of scale [13]. Thus, perovskite/CIS made in China is excluded even though it may represent a valid low-cost alternative, as can be seen in Figs. 5 and 6.

Despite the significant transitions towards low-carbon energy sources expected in the following decades for the Chinese energy mix, the mean GEF of perovskite/CIS tandem manufactured in the EU or USA will

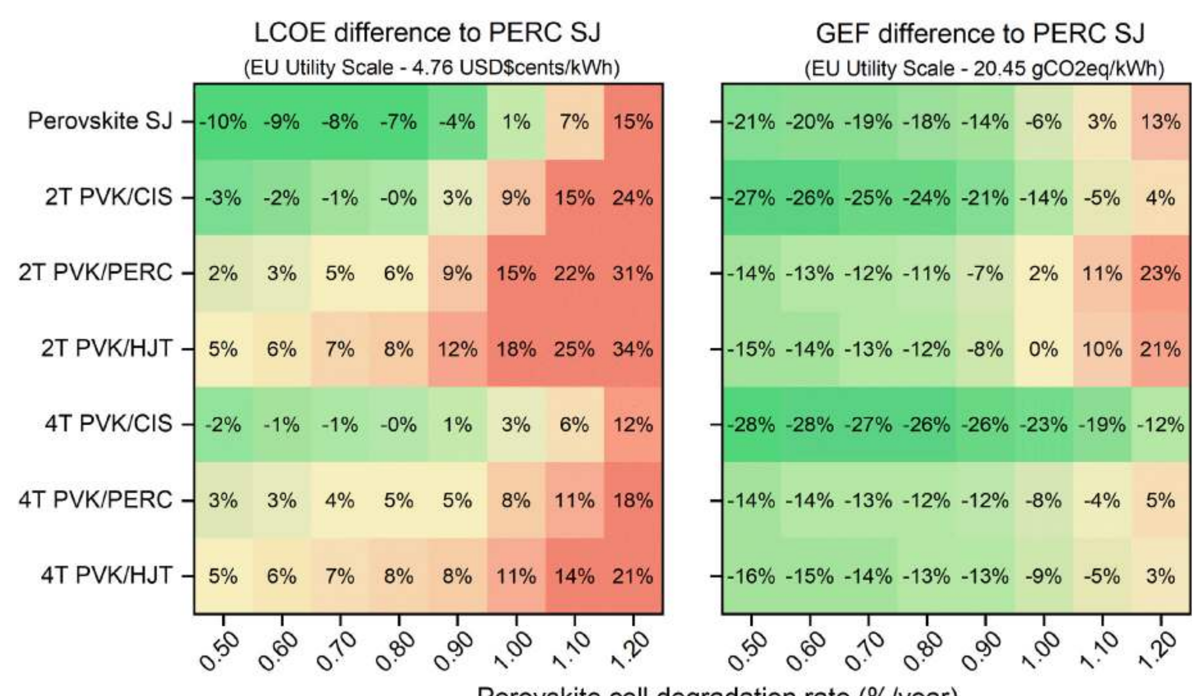


**Fig. 4.** Relative LCOE and GEF differences as a function of the perovskite cell degradation rate LCOE and GEF increase/decrease (utility-scale, average at three climatic locations) at various degradation rates, compared to PERC SJ.

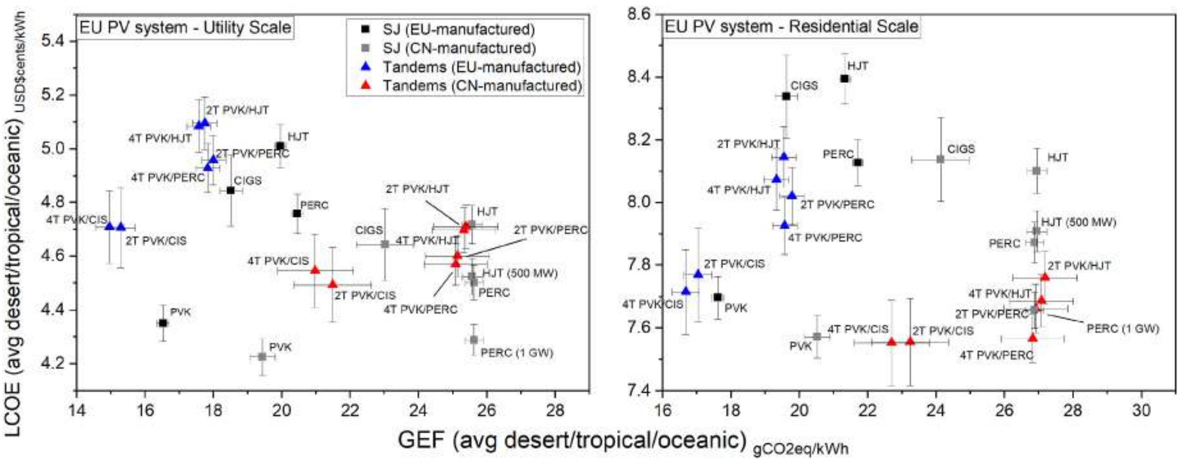


**Fig. 5.** LCOE and GEF for EU-PV systems, with modules manufactured in the EU and China. Values refer to 100 MW manufacturing capacity; for comparison, results for PERC 1 GW and HJT 500 MW (both in China) manufacturing capacity are provided.

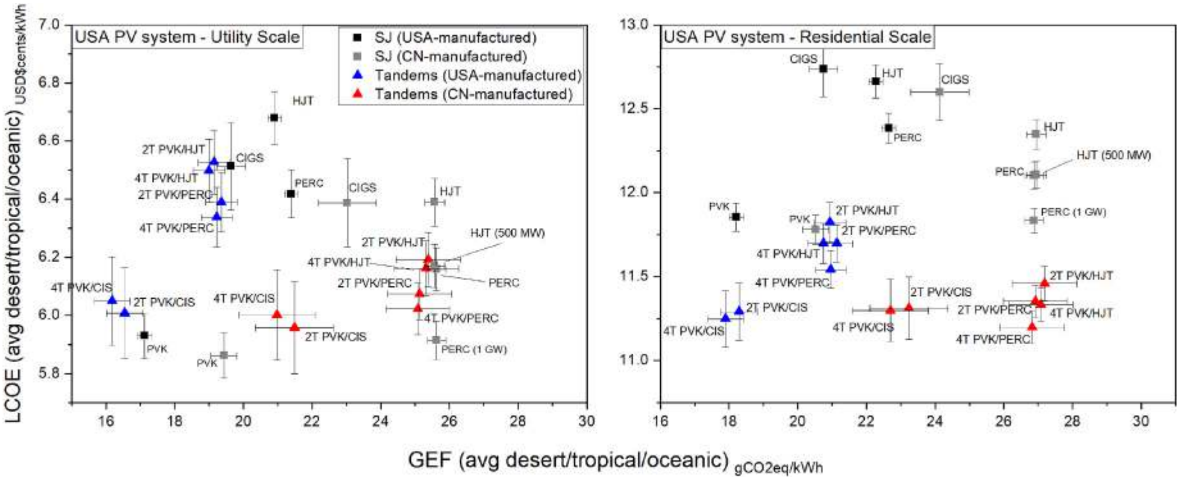


**Fig. 6.** LCOE and GEF for USA-PV systems, with modules manufactured in the USA and China. Values refer to 100 MW manufacturing capacity; results for PERC 1 GW and HJT 500 MW (both in China) manufacturing capacity are provided for comparison.

remain significantly lower than silicon SJ and tandem PV technologies produced in China. In 2050, for an EU PV system, the mean GEF of thin-film tandems would still be 34 % and 39 % lower than PERC SJ (manufactured in China) at the residential and utility-scale, respectively. The mean GEF of perovskite/CIS made in the EU is also lower, approximately 19 %, than silicon-based tandems manufactured in China. Similar GEF results are found for PV systems in the USA, with domestically manufactured perovskite/CIS tandems having 22 % and 19 % fewer emissions than perovskite/PERC made in China, respectively, at the utility-scale and residential scale.

For EU utility-scale PV systems, perovskite/HJT (CN) is expected to be the most cost-competitive technology in 2050 by gradually shrinking the gap in the following decades as market share and PCE increase. Silicon tandems (CN) are the most cost-competitive for EU residential-scale PV systems. Yet, with perovskite market share growth coming into effect after 2035, LCOE reductions are envisioned for EU-produced thin-film tandems out to 2050, causing them to catch up. For PV systems based in the USA, the cost disadvantage of locally manufactured thin-film tandems is less evident, making this technology more attractive to PV investors.

These results confirm the contrast between cost and GHG emission performance of PV modules. Technologies such as perovskite/CIS tandems could provide considerable GHG emissions benefits to the PV industry. Nevertheless, from a cost perspective, these would need to compete with cheaper PV technologies manufactured in China.

## 4. Conclusions

In the following decades, additional PV manufacturing capacity will need to be installed in the EU and the USA to meet the growing demand for solar PV. In this paper, we therefore compared the production of perovskite/CIS, perovskite/PERC, perovskite/HJT tandems and single-junction PVs such as PERC, HJT, perovskite, and CIGS based on economic and environmental indicators that were calculated for PV modules as if they were manufactured and installed today in the EU, the USA, and China under the same climatic conditions. It was presupposed that the performance of perovskite/CIS tandems obtained for lab-scale devices can be achieved with module-area devices while being manufactured using processing techniques that are amenable to upscaling. In addition, the results took as a given that perovskite-based devices achieve degradation rates lower than 1 %/year. These are requirements that have not yet been demonstrated and that may prove challenging to meet. We then sought to predict these indicators out to 2050. Our findings show that the development of production capacity for emerging thin-film tandems, in particular perovskite/CIS, could provide a cost-competitive way to enable PV supply chain diversification and faster way to achieve power system decarbonization for the EU and the USA.

The main findings that support this statement are the following.

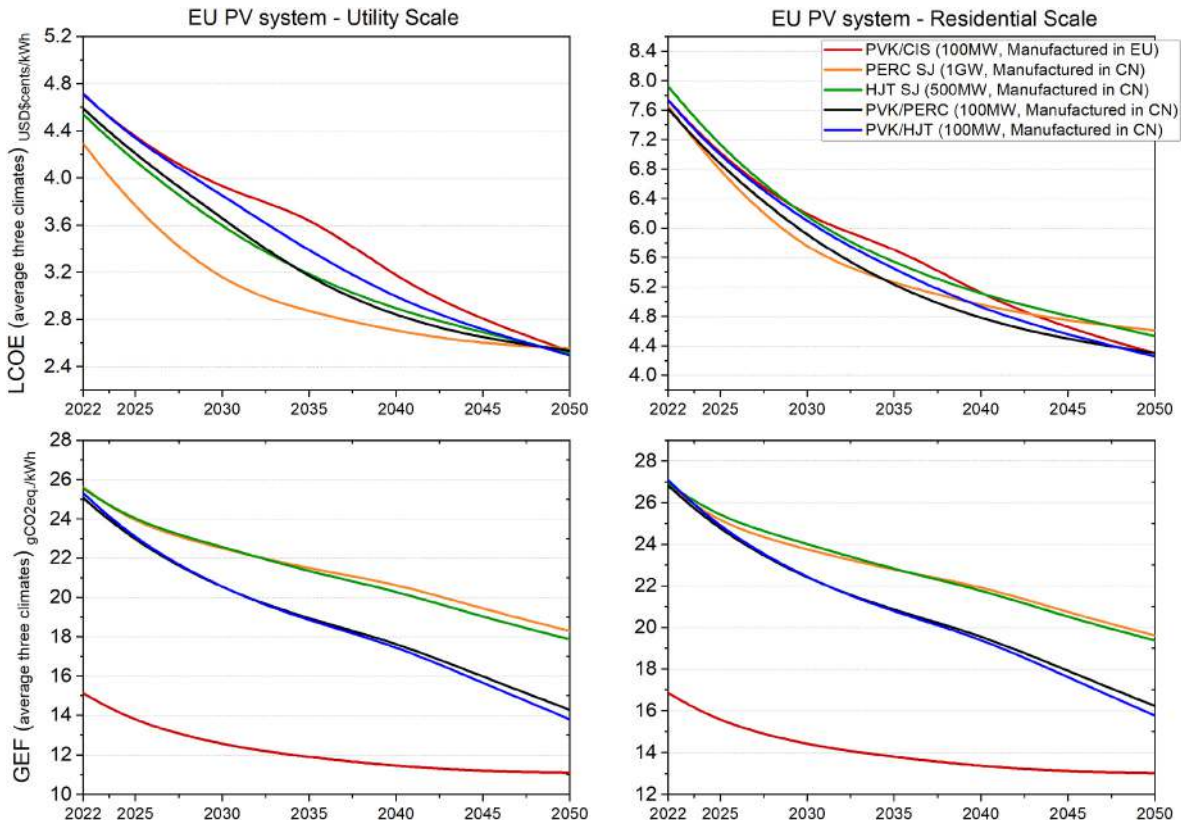


**Fig. 7.** Projected LCOE and GEF for EU PV systems (utility and residential scale) until 2050. As in Fig. 3, values are representative of averages at three climatic conditions. Perovskite/CIS tandems (with 100 MW manufacturing capacity) manufactured in the EU are compared to PERC SJ (with 1 GW manufacturing capacity), HJT SJ (with 500 MW manufacturing capacity), perovskite/PERC (with 100 MW manufacturing capacity), and perovskite/HJT PVs (with 100 MW manufacturing capacity) manufactured in China and imported to the EU.

First, perovskite/CIS modules showed one of the best GHG emission performances as the associated GHG emissions were quantified as low as 0.21 kgCO2eq./W if manufactured in the EU, approximately 56–58 % lower than PERC-HJT SJ PVs manufactured in China. Second, although having higher values than SJ PVs produced at GW scale in China, their module price at 100 MW scale, ranging between 0.36 and 0.44 USD$/W for 2T and 4T tandems, was found to be competitive with perovskite/HJT tandems manufactured in China for a same-sized plant. Third, for degradation rates lower than 1.0 %/year, perovskite/cis tandems manufactured in Europe entail the lowest GHG emissions per kWh across all PV systems. Fourth, their LCOE can be competitive with EU or USA-manufactured perovskite/PERC and PERC SJ. Fifth, although having a higher LCOE than PERC SJ made in China (9 %) when compared to perovskite/PERC tandems made in China, for the same manufacturing scale, the perovskite/CIS tandems made in the EU showed slightly higher LCOEs (2–4 %) while at the same time having GHG emission reductions of 37–40 %. When looking out to 2050, thin-film PV production in the EU and the USA continues to show lower GHG emissions than silicon PVs manufactured in China, even if the energy transition plans of China come to fruition. The LCOE results also exhibited that this carbon emission reduction brought by deploying diversified PV products could come at similar costs compared to perovskite/silicon tandems, provided strongly increasing market shares of thin-film tandem technologies.

Due to the current large-scale silicon PV deployment, silicon tandems are the usual suspect for bringing tandem PVs to the market. Nonetheless, our results indicate that an equivalent investment in expanding thin-film tandem manufacturing capacity could be cost-competitive, assuming a comparable lifespan, while also ensuring significantly lower GHG emissions.

We close by noting the limitations of this study. First, the module price reductions are based on forecasts of each PV technology market share until 2032, which are then extrapolated to 2050. Second, for projections out to 2050, the PCE (which impacts both the economic and the environmental metrics used) was extrapolated by fitting a logistic function to historical PV technology efficiency data. Higher future efficiency increases in specific tandem technologies (e.g., perovskite/HJT) would make these more attractive compared to others from both a cost and GHG impact perspective, which is not covered in our study. Furthermore, the learning rate is assumed to be equal among the various tandem technologies; differences in technologies' learning rates would affect the economic metrics. Finally, this work is limited to costs of production and GHG emissions and the trade-offs between the two. Future work could broaden the scope of the environmental impacts and use aggregation methods for the environmental impacts (e.g., multi-criteria analysis) to compare costs and environmental impacts more holistically.

## CRediT authorship contribution statement

**Alessandro Martulli:** Writing – review & editing, Writing – original draft, Visualization, Software, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Fabrizio Gota:** Writing – review & editing, Writing – original draft, Resources, Formal analysis, Data curation. **Neethi Rajagopalan:** Formal analysis, Data curation, Conceptualization. **Toby Meyer:** Validation, Resources, Data curation, Conceptualization. **Cesar Omar Ramirez Quiroz:** Validation, Resources, Data curation, Conceptualization. **Daniele Costa:** Writing – review & editing, Validation. **Ulrich W. Paetzold:** Writing – review & editing, Writing – original draft, Validation, Resources, Data curation, Conceptualization. **Robert Malina:** Writing – review & editing, Writing – original draft, Validation, Supervision, Conceptualization. **Bart**

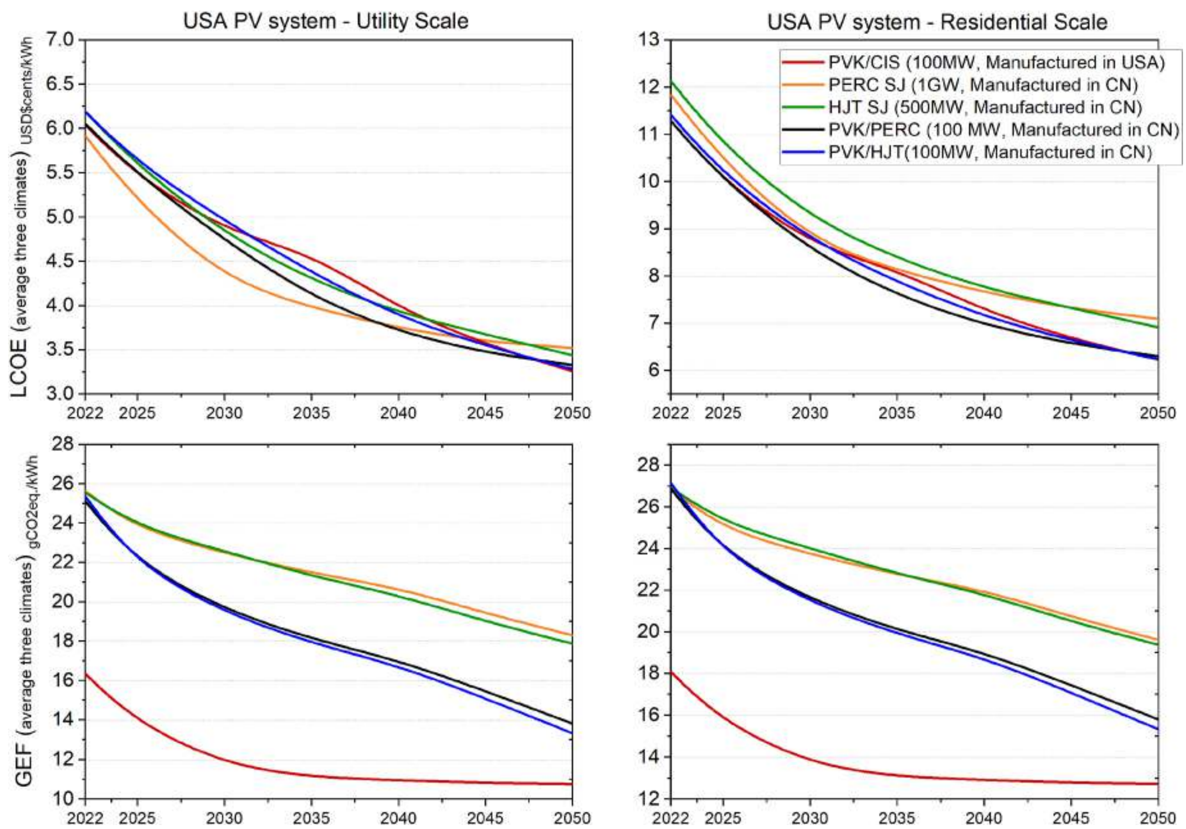


**Fig. 8.** Projected LCOE and GEF for USA PV systems (utility and residential scale) until 2050. As in Fig. 3, values are representative of averages at three climatic conditions. Perovskite/CIS tandems (with 100 MW manufacturing capacity) manufactured in the EU are compared to PERC SJ (with 1 GW manufacturing capacity), HJT SJ (with 500 MW manufacturing capacity), perovskite/PERC (with 100 MW manufacturing capacity), and perovskite/HJT (with 100 MW manufacturing capacity) PVs manufactured in China and imported to the USA.

**Vermang:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Sebastien Lizin:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Conceptualization.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.solmat.2024.113212.

### Data availability

Data is provided in Supporting Information file

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