Life Cycle Assessment of Solar Photovoltaics and Their End-of-Life

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Abstract

The rapid global uptake of solar photovoltaics promises the hope of affordable low-carbon electricity. Most production so far and for the foreseeable future has been of modules based on silicon wafer cells and, while there are further R&D outcomes still to be fully transferred to the silicon cell industry, the next major technology change is likely to be the addition of a thin-film top cell to form an efficient tandem device. The authors have applied life cycle assessment (LCA) to several of the current and potential mass manufactured solar cell technology choices, including different silicon wafer styles and silicon/thin-film tandems. We have demonstrated that the environmental benefits of some paths for efficiency improvements, particularly of the incorporation of atomic hydrogen into silicon wafers, more than compensate for the additional inputs required. Further, we have shown that the stability of top-cell materials for tandems is paramount, to avoid the premature demise of the underlying silicon bottom cell. The end-of-life has been assumed to be landfill in most of our preceding LCA studies but there is a growing global consciousness that the current rapid rise in uptake of photovoltaics, while offering hope of a more sustainable global energy supply, also implies a significant future waste stream. Europe is leading the world in requiring industry stewardship for photovoltaics (and batteries, inverters and other system components) and other jurisdictions, including Australia, are following. However, photovoltaic modules are difficult to dismantle or deconstruct for materials recovery by methods that are both financially and environmentally acceptable. We will use LCA to guide our research on module recycling by chemical, thermal and mechanical methods and their combinations, with an aim to maximize the value of separated materials.

Keywords: *Life Cycle Assessment; LCA; tandem solar cells; photovoltaic technologies.*

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1. INTRODUCTION

Photovoltaics (PV) have been a rapidly growing renewable energy technology, particularly in the last two decades. The world solar PV installed capacity was around 78 gigawatts by the end of 2016, which is 32 times more than in the year 2000 [1]. Silicon (Si) solar cells dominate the market share [2], because the technology is mature, robust, and the manufacturing costs are low and keep falling. However, the search for new PV materials and device designs is necessary to increase the cells' and modules' efficiency, in order to continue the cost reduction.

The focus on higher solar cell conversion efficiency and lower production costs is continuous [3] and potential enhancements for single-junction Si solar cells efficiency have been studied and implemented for several years. The benefits of the hydrogenation process, for example, have recently become better understood, offering improvements to the electrical performance of Si solar cells from different feedstocks [4, 5], including solar, electronic and upgraded metallurgical grade Si (SGS, EGS, UMG-Si, respectively).

However, the single-junction solar cell still has a limiting energy conversion efficiency of around 30% [6] with diminishing returns for the efforts invested as efficiencies approach that limit. Consequently, the concept of a two-cell tandem structure is being studied, where a top cell is used to boost the performance of the base Si cell [7]. Tandem stacks automatically partition the solar spectrum between the cells, improving the energy capture per incident photon. The upper cell absorbs light from the short-wavelength part of the spectrum and transmits longer wavelengths to the underlying cell, in this case, Si. Upper cells need to be made of materials with higher bandgap energy, to cause them to absorb only the high energy (short wavelength) photons. Thin-film materials have been implemented as part of a two-junction tandem stack, using Si as the bottom junction, which may be a pathway for an affordable efficiency breakthrough [7].

The main examples of industrialised thin-film PV technologies are amorphous and microcrystalline Si films, chalcogenide compounds such as cadmium telluride (CdTe), chalcogenides – like copper indium diselenide (CIS) and copper indium gallium diselenide (CIGS)[8] – and the recently emerging perovskite solar cells [9]. The possibility of a high band gap makes chalcogenides and perovskite technologies attractive materials for use in tandem solar cells on a Si base cell [10, 11]. In addition to the bandgap, candidate materials for top cells above silicon must satisfy several other practical requirements [12] for this role, including: thermal expansion coefficient, crystalline compatibility, n- and p-type dopability, low toxicity and stability. However, there is still no obvious candidate material satisfying all these requirements.

Besides these developments, there is also the concern with the environmental impacts from the production process, use phase and end-of-life (EoL) of PV solar cells and modules. Life Cycle Assessment (LCA) is a methodology used to analyse products or processes from an environmental perspective [13, 14] and is the tool chosen to support the selection of top cell materials for Si-based tandems cells.

This work's purpose is to compare global warming potential (GWP), human toxicity potential - cancer effects (HTP-CE), human toxicity potential – non-cancer effects (HTP-nCE), freshwater eutrophication potential (FEuP), freshwater ecotoxicity potential (FEcP), abiotic depletion potential (ADP) and energy payback time (EPBT) of Si and thin-film/Si tandem solar modules, including advanced Si technologies. We also pay attention to the advent of regulations and possible treatment options related to EoL PV waste.

2. METHODS

We have used LCA to assess different impact categories, including EPBT of thin-film/Si (CIGS/Si, copper zinc tin sulphur (CZTS)/Si, silver zinc tin sulphur (AZTS)/Si and perovskite/Si) tandem solar modules compared to Si solar modules (considering different Si technologies), using GaBi LCA software [15]. The functional unit is defined as 1kWh of generated electrical energy and the system boundaries are shown in Fig. 1. The analysis initiates with the raw materials necessary for the cells' production and finishes at the modules' EoL (landfill). Recycling is considered in more recent works [16].

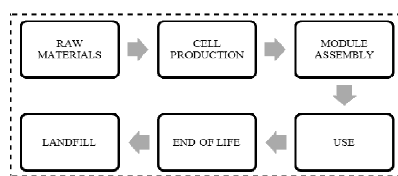

Fig. 1. System boundaries considered in this LCA.

Our results are based on a 20 year life-time for all modules. The recycling is very immature and inventory for recycling processes is still incomplete. Consequently, we are assuming that all EoL modules go to landfill. We discuss the development of alternatives in Sec. 3.4 of this paper. In all our calculations, we are assuming a performance ratio (i.e. the relationship between the theoretical and the real performances) [17] of 0.75, as is commonly assumed in LCAs for PV systems, and an insolation of 1700 kWh/m^2/year that is typical of southern European countries and representative of a world average [18].

We are not considering, here, the balance of system (BOS) components (e.g. inverters, mounting structures, cable and connectors) and the transport between processes. The BOS impacts are small when compared with the other components of a solar module, therefore they are not often included in LCS studies, and transportation is not a significant sources of environmental impact for PV systems [18], excluding EoL. However, it might add some significant impacts depending on the type of transport but we are not aware of any detailed studies of this aspect of the supply chain. Transport is, however, likely to cause significant impacts in EoL processing and we have begun to address this issue in recent work [16].

2.1. Chalcogenide/Si Tandem Solar Modules

The three chalcogenide/Si tandem solar technologies analysed are CIGS/Si, CZTS/Si and AZTS/Si (Fig. 2).

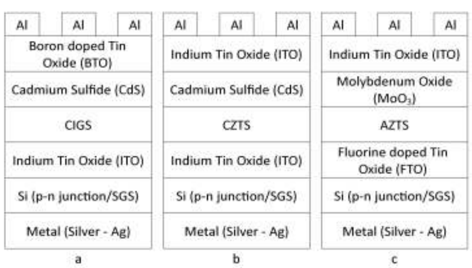

Fig. 2. CIGS/Si (a), CZTS/Si (b) and AZTS/Si (c) structures.

We assume an ideal quantum mechanical tunnelling junction to interconnect the two cells in these tandem structures and no electrical resistance or optical loss at the interface between the top and bottom cells. We also consider that, in practice, an adjustment of the thickness of the top cell (chalcogenide) would be made to match the currents generated in each cell but for the inventory we assume a layer thickness of 1µm for high bandgap CIGS [19] and 0.5µm for CZTS and AZTS [20-22].

2.2. Perovskite/Si Tandem Solar Modules

The LCA analysis for perovskite/Si tandem solar cells considers structures using silver (Ag), gold (Au) and aluminium (Al) as top electrodes and compares the impacts of these different materials, as related to the efficiency of the cells (Fig. 3).

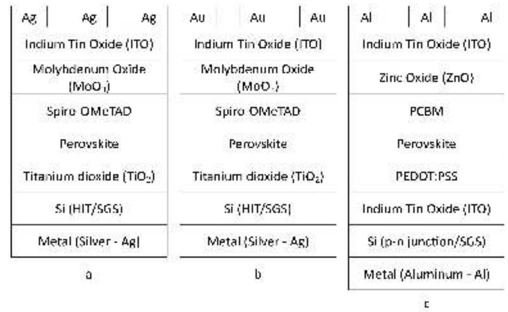

Fig. 3. Perovskite-Ag/Si (a), perovskite-Au/Si (b) and perovskite-Al/Si (c) structures.

Note that there is still considerable uncertainty in relation to eventual industrial production of perovskite and perovskite/Si tandem solar cells, mainly because stable forms of this material have not yet been developed. Hence, the disparity in expected lifetimes of perovskite top layer and Si base layer is a glaring problem [23].

2.3. Advanced Si Solar Modules

There are many different production processes for Si solar cells that aim to improve cells and module performances [3]. The current industry standard process is the screen-printed aluminium back surface field (Al-BSF) [24], but the passivated emitter and rear cell (PERC) technology is expected to replace Al-BSF as the dominant technology in the future (approximately 60% share by 2027) [3].

Si solar cells a “stable” but still experience degradation processes due to multiple mechanisms (e.g. light induced degradation (LID) [25]). The interactions of impurities and defects within silicon with hydrogen have been intensely studied as a possible solution to LID degradation, in particular [26]. As a result, the hydrogenation process has recently become better understood and more controllable and now offers improvements to the electrical performance of silicon solar cells from different feedstocks [4, 5].

3. RESULTS AND DISCUSSION

Based on the LCA methodology [27] and published inventories [18, 23, 28] we discuss the calculated impacts from the production (including raw materials, use phase and EoL) of CIGS/Si, CZTS/Si, AZTS/Si [28], perovskite-Au/Si, perovskite-Ag/Si and perovskite-Al/Si [23] tandem modules compared with Si [29, 30]. None of these options have yet found market acceptance for a range of technical and financial reasons and that additional research is necessary to identify the ideal material to partner with silicon in future high-efficiency, stable and affordable modules.

3.1. Chalcogenide/Si Tandem Solar Modules

The GWP impact assessment (Fig. 4) shows that the CZTS/Si and AZTS/Si tandem structures have slightly better outcomes than pn-junction Si using solar grade silicon (SGS) feedstock, not considering possible uncertainties in the inventory data, and that the most harmful impact comes from the production of SGS, due to the intensive use of electricity during its treatment process. Because of that, attention should be paid to the Si layer [28]. Better results could be achieved if the energy used during the production process (especially during Si treatment processes) can be reduced and/or generated from renewable sources.

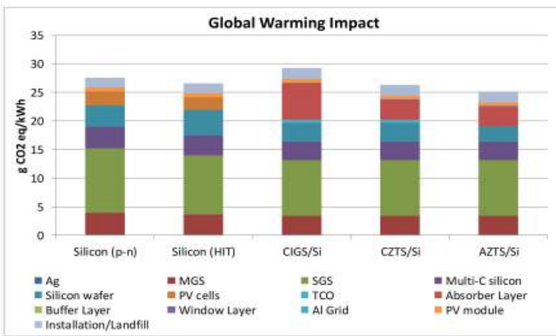

Fig. 4. Global warming impact results for CIGS/Si, CZTS/Si, AZTS/Si compared with Si.

For HTP, FEcP and FEuP the main impacts come from the CdS layer, mainly due to the toxicity of Cd. Much work has been done in regards to Cd in environmental studies for CIGS [31-34] but finding a nontoxic and more transparent material as a replacement is still a work in progress [28].

Because the recycling process is not considered in this LCA, the ADP result is related to the use of of metals and other materials in solar cells. The recycling of toxic elements and scarce metals is similarly very important to reduce the environmental impacts, particularly in the ADP category [28]. Specifically for CIGS, indium is a key element and its scarcity is a concern for scaling up module production to industrial level [10].

3.2. Perovskite/Si Tandem Solar Modules

For the perovskite/Si tandem structures we are using two alternative types of Si cell as the bottom cell: p-n junction and heterojunction with intrinsic thin layer (HIT) [35].

The perovskite/Si tandem devices have poorer environmental outcomes than those for silicon cells, mainly because of the short lifetime considered, which is 1 year. The analysis is based on valid and realistic assumptions, but there is still considerable uncertainty in relation to the stability of future perovskite solar cells. Considering the LCA results for all impacts analysed, it can be concluded that the top cell's lifetime has a major influence on the environmental impacts of the tandem device.

A longer lifetime for perovskite technology is still a major challenge. To model the environmental impacts of a possible industrial process for the tandem technologies chosen, we analysed six different environmental categories, including GWP (Fig. 5), for perovskite-Au/Si, perovskite-Ag/Si and perovskite-Al/Si. In this analysis we are considering that the tandem solar cells could last for 20 years, assuming that the perovskite layer fails after one year and then becomes transparent and electrically conductive, allowing the Si cell to continue operating for the next 19 years.

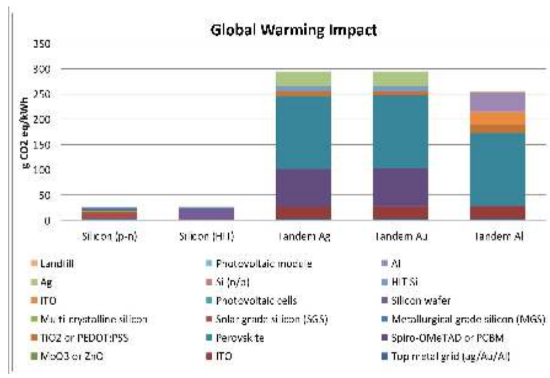

Fig. 5. Global warming impact results for perovskite-Ag/Si, perovskite-Au/Si and, perovskite-Al/Si compared with Si (assuming that the perovskite layer lasts for 1 year and the Si cell continues operating for the next 19 years).

The analysis has shown that all perovskite/Si tandem solar cells have significant GWP impacts, even when the tandem life approaches 20 years, considering that the perovskite layer only lasts for one year and then becomes transparent and conductive. Further analysis from this study shown most of the impacts assessed, including the GWP, of the tandem structures can be lower when compared with silicon HIT if the perovskite was stable and could continue to operate for 20 years [23].

There are also significant environmental impacts from the Si layer so attention should be paid to the SGS treatment process in order to reduce the energy usage during this process [23].

In most of the cases considered, perovskite/Si tandem devices have poorer environmental outcomes than those for silicon cells. However, our study showed that the perovskite/Si tandem can have lower HTP-nCE impact compared with Si p-n junction and lower GWP (Fig. 6), HTP-nCE (Fig. 7) and FEcP

(Fig. 8) compared with Si HIT, but only when the perovskite life approaches 20 years [23], which is still a very challenging condition.

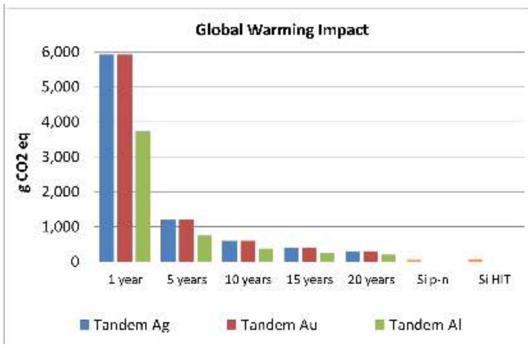

Fig. 6. Global warming impact results for perovskite/Si (up to 20 years lifetime) compared with Si.

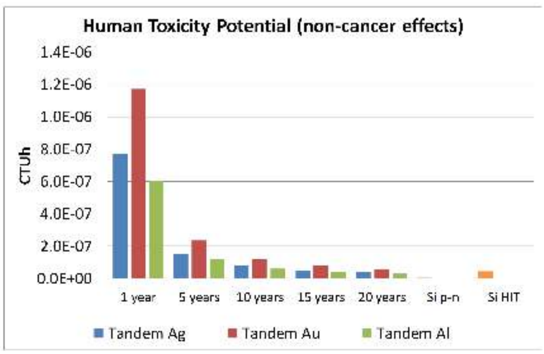

Fig. 7. Human toxicity (non-cancer) potential results for perovskite/Si (up to 20 years lifetime) compared with Si.

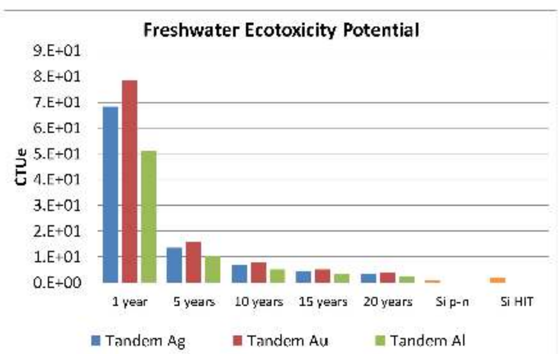

Fig. 8. Freshwater ecotoxicity results for perovskite/Si (20 years lifetime) compared with Si.

3.3. Advanced Si Solar Modules

Our studies have made it clear that the Si layer of a Si-based tandem cell tends to dominate the environmental impacts [28] from chalcogenide/Si and perovskite/Si tandem solar modules. Because of that, a detailed LCA studies were conducted for PERC Si technology [30] and for the application of the hydrogenation process on Si solar cells [29]. These are alternative processes for the Si technologies that allow the enhancement of Si cells performance for low investment.

In both studies, the results demonstrate that better environmental outcomes can be achieved when the performance of the cells and modules is increased by the processes analysed, for which environmental costs are low. The use of PERC technology with UMG-Si feedstock shows improved environmental outcomes (Fig. 9). Also, the EPBT analysis demonstrates the importance of higher efficiency modules, not only for the best environmental results but also for the effective use of energy input [30].

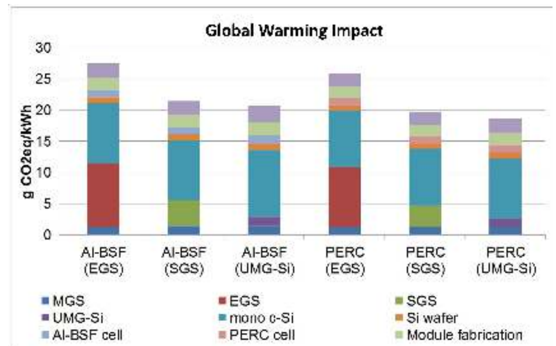

Fig. 9. Global warming impact results for PERC Si technology considering different SI feedstocks.

Considering the hydrogenation process, better environmental outcomes can be achieved, mainly as a result of the high efficiencies produced by this process [29]. Fig. 10 shows the GWP results for the hydrogenation process.

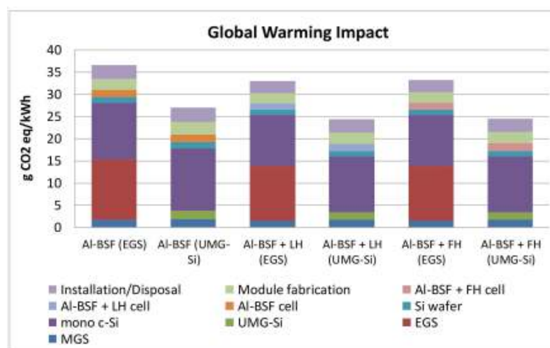

Fig. 10. Global warming impact results for the hydrogenation process in Si technology considering different Si feedstocks.

A key finding of the environmental analysis of advanced Si technologies is that the improvements in the modules' efficiency (PERC and hydrogenation) and the use of less energy (UMG-Si) result in lower environmental impacts than the use of Al-BSF cells and SGS or EGS feedstock [29, 30].

3.4. EoL regulations

The majority of LCA studies focus on the production process of PV technologies because of the lack of data for the EoL possibilities, e.g. landfill and incineration. Also, due to their long lifetime (up to 25-30 years or more) there are not yet considerable quantities of PV waste, which contributed with the lack of waste legislation around the world [36].

The presence of toxic materials and heavy metals, e.g. lead and tin, in the EoL PV waste can result in significant environmental pollution issues if not managed correctly. Besides, valuable metals like silver and copper represent a value opportunity if recovered. Hence, landfill may not be the best option since it does not recover potentially valuable materials from PV modules.

The European Union (EU) provides the most comprehensive legislative framework for extended producer responsibility of PV modules. This regulation is measure through the Waste Electrical and Electronic Equipment (WEEE) Directive 2012/19/EU [37], which aims to preserve, protect and improve the quality of the environment, to protect human health and to utilise natural resources prudently and rationally [37]. However, countries such as China [38], Japan [39], India [40], Australia [41] and USA [42], which have an expanding PV market, are still lacking in specific regulation for PV EoL modules and are still treating this waste under a general regulatory framework for hazardous and non-hazardous solid waste.

Fortunately, there are signs of change. The Japan Photovoltaic Energy Association (JPEA), for example, has published, in late 2017, a guideline on how to properly dispose EoL PV modules [43]. In the USA the PV waste is managed by the Resource Conservation and Recovery Act, which regulates hazardous and non-hazardous waste management [13]. However, some stated go beyond this regulation. California, for example, has additional threshold limits for hazardous materials classification [44]. Also, to better deal with the PV waste issue, the Australian government has recognized the significance of guaranteeing that regulations are in place with this special type of waste. The State of Victoria is leading the creation a framework that will seek to reduce the environmental impacts caused throughout the lifecycle of photovoltaic systems [45].

In addition to the definition of mandatory requirements for PV waste treatment there should be a continuous focus on scientific evidences on the potential impacts and benefits related to the treatment of PV residues [46], as, for now, only about 10% of EoL PV modules are recycled worldwide.

3.5. EoL management

It is well known that today most of the PV modules go to the landfill and the reason for that is mainly because the regulation in most of the countries is not yet established, as already mentioned, and also because the recycling processes are not yet economically favourable [46]. It has been shown that, for the current PV recycling technologies, silicon-based modules do not have sufficient valuable materials [23] to make recycling financially viable. Although there is a scientific interest in recycling, and a few the mandatory regulations already in place in Europe, for example, the number of waste PV modules currently still is small since most PV plants were built recently and have not yet exceeded their lifetimes. Consequently, the amount of PV waste being taken to recycling facilities is currently insignificant compared to the amount of other electronic waste [47], which results in little commercial interest in investing into PV module recycling technologies because the waste streams are too small to justify it [48]. In addition, there remains great uncertainty about likely commercial recycling technologies. However, preliminary studies predicted that panel recycling will represent an estimated $15 billion (American dollars) opportunity by 2050 [46]. Thus, it is critical to handle the disposal of PV waste.

There are different PV waste approaches, which are landfill, incineration, reuse and recycling, and each one of them has particular characteristics and can offer different environmental benefits or disadvantages on the PV modules' overall impacts.

Aiming to reduce the environmental impacts and to recover some of the value materials from PV waste, methods for recycling solar modules are being developed worldwide. There is still a lot of room for improvement in these processes, as current recycling methods are mostly based on downcycling processes, recovering only a portion of the materials and value.

Recycling processes for thin-film PV technologies processes are under development in countries including Italy, Japan and South Korea. Even up to 90% recovery of materials from CdTe solar modules, made by FirstSolar [49], their value is still not sufficient compared to the production costs, so these processes are not yet competitive [50]. However, is has been shown that more complex processes can achieve recovery rates up to 95% and high commercial value materials can be recovered but, currently, these processes as still being tested at laboratory scale [51].

Commercially available in Europe and created by PC Cycle, the recycling process for silicon based modules can recover a maximum amount of 80% materials from the EoL modules [52]. Fortunately, the same company recently has achieved a recycling rate of 96% for c-Si PV modules using a new process that combines mechanical and thermal treatments [53].

Generally, the first step to recycle PV modules is to mechanically separate the aluminium frame and the junction box. After that, the challenge is to delaminate or remove the encapsulant material, which is normally ethylene-vinyl-acetate (EVA) for Si based solar modules. There are several techniques that can be used in this phase [46], including thermal [54, 55], and chemical (organic and inorganic) [56-58] and mechanical recycling processes [59].

Based on available data from literature we estimated the environmental impacts of different EoL scenarios for Si-based PV modules [16], excluding transport. It is important to notice that the results presented are not completely representative because of the lack of data for some processes. A summary of all results is calculated (Fig. 11) using the ReCiPe method, which harmonizes the environmental impacts calculated [60].

Our LCA study has shown that low environmental impacts can be achieved through recycling methods, when compared to landfill, reuse and incineration scenarios [16]. The incineration process presents worse impacts compared with the other EoL scenarios studied, assuming an analysis where the thermal energy and electricity produced by the incineration process is neglected. However, it is possible that transport impacts may prove to be significant.

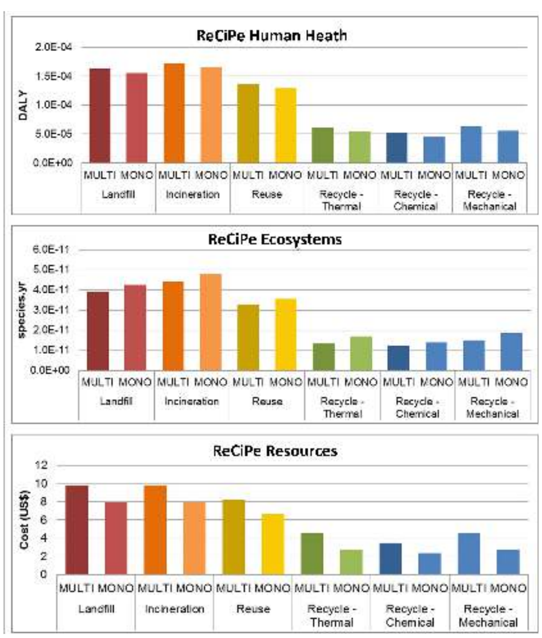

Fig. 11. ReCiPe results (effects on Human Health) in disability-adjusted life year (DALY), for effects on Ecosystem in species per year (species.yr) and for effects on Resources in US Dollars (US$) considering multi- and mono-crystalline silicon modules.

4. CONCLUSIONS

Considering the environmental analysis of CIGS/Si, CZTS/Si, AZTS/Si, perovskite-Au/Si, perovskite-Ag/Si and perovskite-Al/Si tandem technologies, the main conclusion of our study is that Si-based tandem modules can marginally reduce environmental impacts relative to Si modules but only under conditions of similar lifetime to that of Si, while also satisfying a wide range of physical and optoelectronic restrictions. Further research is required to identify more stable top cells that can enhance the silicon efficiency without increasing the environmental impacts during the production process.

The impacts from the silicon layer on the tandem structures analysed are significant and mainly generated by the use of primary electricity from non-renewable sources. However, our LCA study has shown that lower environmental impacts can be achieved by enhancing the performance of Si based solar cells and modules through the implementation of the PERC technology and further improvements from the hydrogenation process.

Current and near-future regulations will demand better management of EOL of PV modules, internalising this cost and linking environmental and financial costs. This will drive the development of improved recycling techniques with lower costs and improved materials recovery.

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