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Life cycle assessment on PERC solar modules

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ABSTRACT

The screen-printed aluminium back surface field (Al-BSF) technology is the current industry standard process for crystalline silicon solar cells but, due to the search for higher efficiency, much attention has been paid to the passivated emitter and rear cell (PERC), which is gaining significant share in the world market. We undertake an environmental analysis comparing Al-BSF and PERC monocrystalline solar modules. Through the life cycle assessment (LCA) method we calculate the global warming, human toxicity (cancer and non-cancer effects), freshwater eutrophication, freshwater ecotoxicity, abiotic depletion potentials and energy payback time of these technologies considering solar, electronic and upgraded metallurgical grade silicon feedstock. The functional unit considered is 1 kWh of energy delivered over the modules' lifetime. As a result of this work, we showed that PERC technology generates a slight improvement in the environmental impacts when compared with Al-BSF. The use of electronic and upgraded metallurgical grade silicon results in lower environmental impacts in most cases, compared with the other technologies analysed, based on the assumptions made in this LCA.

1. Introduction

Photovoltaic (PV) researchers and industry are persistently looking for technologies that can reduce costs and enhance efficiencies for solar cells and modules [1], and frequent developments are being reported for alternative PV materials. Nevertheless, crystalline silicon (c-Si) wafer based technology still dominates the PV market (above 90% share) [2].

There are many variations of existing production processes that aim to improve c-Si cell and module performance [3]. The screen-printed aluminium back surface field (Al-BSF) [4] is the current industry standard process but the passivated emitter and rear cell (PERC) technology [5] is gaining significant share in the world market and is expected to displace Al-BSF as the dominant technology in the future (estimated around 60% share in 2027) [3].

The PERC process has already been industrialized [5], and in 2016 the efficiency of a p-type monocrystalline cell using this technology achieved 20.6% [6]. However, efficiency improvements are not the only focus for the PV industry and solar cell manufacturers also aim to produce lower cost modules that show more stable performance during operation. One possibility to promote those aims is the use of low-cost silicon feedstock, such as upgraded metallurgical silicon (UMG-Si). This refinement process has the benefits of being cheaper in comparison to solar (SGS) and electronic grade silicon (EGS) production processes and has a significantly lower (around 80% compared with the EGS purification process [7]) energy consumption. However, UMG-Si produces lower quality wafers than SGS and EGS, mainly due to impurities [8].

The development of PV technologies should be complemented by environmental analyses. Life cycle assessment (LCA) is a methodology that assesses the impacts associated with all the stages of a product's life cycle from raw material extraction to the end of its life [9]. LCA has previously been applied to silicon solar cell manufacturing by several authors [10–13] but, to the best of author's knowledge, not for monocrystalline PERC solar modules.

In this work we undertake a comparison of 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 monocrystalline Al-BSF and PERC (considering EGS, SGS and UMG-Si feedstocks) solar modules through the LCA method.

2. Materials and methods

The LCA system boundaries include the impacts from the raw materials necessary for the cells' and modules' production until their end

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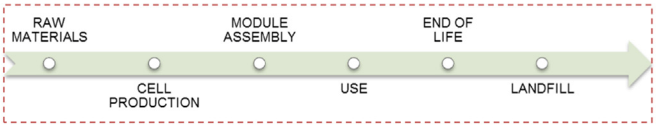

Fig. 1. LCA system boundaries.

of life (Fig. 1). However, the balance-of-system (BOS) components and recycling processes are not considered in our analysis, because of the scarce inventory data available [14]. It would be expected that inclusion of BOS components would increase the environmental advantage of PERC over Al-BSF, as a result of PERC's higher efficiency. Recycling is a potentially important factor for the LCA [15] and should be explored in future work, when research has led to potentially commercial processes. Transportation is also not considered because it has been shown to not be a significant source of environmental impacts of PV systems [16]. The functional unit (FU) is defined as 1 kWh of generated direct current electrical energy from the PV module over its lifetime.

We calculate, supported by the LCA software, GaBi [17], the environmental impacts of these modules based on the area required for a solar module to produce 1 kWh of electricity, considering its assumed efficiency and lifetime (Table 1), the insolation (assumed to be 1700 kWh/m^2/year, which is representative of southern Europe [10]) and performance ratio (in this study set as 0.75 [10] for all cases). It is important to emphasize that changes in these assumptions would change the final environmental impacts results.

It is important to note that a module with a low degradation rate can be expected to produce more electrical power over its lifetime for the same initial power rating than will one with a high degradation rate. Light-induced degradation (LID) impacts the performance of solar cells, and it is a significant cause of performance reduction for cells made on p-type Czochralski (Cz) grown silicon [18]. Higher degradation occurs in PERC compared to Al-BSF, mainly due to the stronger dependence of efficiency on bulk lifetime in high-efficiency solar cell structures [19,20]. The LID degradation process in PERC is strong in the first year of exposure and then slows [21], although researchers have also used linear degradation simplifications [22]. We are assuming in our calculations the worst case for PERC, in which all the degradation occurs in the first year. We estimate the resulting average lifetime efficiency and use that as if it applied, throughout its life, as indicated in Table S1 (SM). We assume 0.5% abs. [23] degradation per year over a 25-year lifetime for Al-BSF technology from initial efficiencies as shown in Table 1.

The GaBi software [17] is used to calculate the environmental impacts through the inclusion of external data (life cycle inventory, LCI) and the use of the software's internal database (in this case, the Ecoinvent database [24]). The PVPS Task 12 report [10], with content adapted from de Wild-Scholten [25] and Fthenakis et al. [26], provides data for the standard monocrystalline Al-BSF processes (assuming the efficiencies shown in Table 1). Considering a generic p-type monocrystalline PERC implementation [5], we estimate the LCI based on information from equipment manufacturers indicating the throughput and electricity usage [27] (efficiencies shown in Table 1) and the inventory data from Table S2 (SM). The process data for UMG-Si, shown in Table S3 (SM), were collected from the literature [28] and are based on a pilot plant which can be considered very similar to an industrial plant regarding equipment dimensions [29]. For comparison reasons, we are considering China as the manufacturing location for all cells and modules studied. Table 2 shows the process steps for all technologies studied in this LCA.

Table 1
Efficiency values and lifetime of the Si solar cells and modules assumed.

Technology	Initial cell efficiency	Initial module efficiency	Lifetime
Al-BSF (EGS feedstock)	20.0% [3]	18.0%	25 years
Al-BSF (SGS feedstock)	19.0% [70]	17.1%	25 years
Al-BSF (UMG-Si feedstock)	18.3% [71]	16.5%[a]	25 years
PERC (EGS feedstock)	21.2% [3]	19.1%	25 years
PERC (SGS feedstock)	20.2%	18.2%	25 years
PERC (UMG-Si feedstock)	20.0% [71]	18.0%[a]	25 years

[a] Assumed efficiencies for this LCA study, based on a 90% abs. ratio from cell to module efficiency.

Table 2
Al-BSF and PERC production process steps.

Aluminium back surface field (Al-BSF)	Passivated emitter and rear cell (PERC)	LCI Data source
Treatment of metallurgical grade silicon (MGS) to achieve a purity of 99%.		[24]
The EGS is produced by the fluidized bed process.		[10,24,28,72]
The SGS is produced by the Siemens process.		
UMG-Si produced with liquid MGS and then it is purified and solidified.		
The crystal growth (mono c-Si) is produced via Czochralski (CZ) process.		[24,73]
The Si wafer production consists in sawing and cleaning the wafers.		[24]
The photovoltaic cells production step.		[24]
-	Rear Passivation Layers	[27,74]
-	Dielectric Openings	[5,27]
Rear Screen print Ag/Al, front Screen Print Ag and standard Firing		[10,24]
Module fabrication		[10,24]
Installation stage considers materials and packaging.		[24]
Disposal of inert material to landfill with no direct emissions.		[24]

The analysed impact categories are chosen according to the recommendations of the European Commission's Joint Research Centre [30]. For GWP we are using the method developed by the Intergovernmental Panel on Climate Change (IPCC), which assesses the science related to climate change [31]. As solar energy is considered a green source of energy, this set of environmental impacts is the most common for LCAs on PV technologies [10,12,32].

The toxicity of materials (HTP-CE, HTP-nCE, and FEcP) is assessed using the USEtox model, a scientific method for characterizing human and ecological impacts of toxic chemicals [33]. These impacts are chosen because solar cell and module production processes involve toxic substances, heavy metals and other hazardous materials with effects on human health, fauna and flora [34].

ADP is based on the relationship between the annual extraction rates and the reserves of resources [30,35]. The use of non-renewable materials to produce solar cells and modules is an issue to be analysed for the decreasing global availability of these natural resources and, hence, it is important to include this environmental impact in this study.

3. Results and discussion

We are analysing the impacts of monocrystalline Al-BSF and PERC solar modules considering EGS, SGS and UMG-Si feedstocks through the LCA methodology described above.

3.1. Global warming potential

The GWP results (Fig. 2) show that the most significant impacts arise from the growth of monocrystalline silicon ingots by the Czochralski (CZ) process, (labelled as mono c-Si in Fig. 2) which represents approximately 35%, 45% and 51% of the impact for EGS, SGS and UMG-Si, respectively. In this process, the solid silicon is placed in a