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Life Cycle Assessment on Advanced Silicon Solar Modules

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Abstract

The development of new technologies and different processes for solar cells is studied worldwide. The screen-printed aluminium back surface field (Al-BSF) technology is the current industry standard process for silicon solar cells but much attention has been paid to the passivated emitter and rear cell (PERC) technology, and it is gaining significant share in the world market. Hydrogen has been shown the ability to interact with the impurities and defects within the silicon (EGS and UMG-Si), and hence the hydrogenation process has been studied as an important advanced process for silicon solar cells. Here we will undertake a comparison of global warming potential (GWP) and energy payback time (EPBT) of Al-BSF, PERC, PERC with laser hydrogenation (LaserH) and PERC with hydrogenation in a firing furnace (FurnH) processes trough the life cycle assessment (LCA) method. For the calculations, we consider the functional unit as being 1kWh of energy delivered, a performance ratio of 0.75 and an insolation of 1700 kWh/m2/year. As a result of this work, we showed that the UMG-Si combined with the hydrogenation methods result in better environmental outcomes considering the GWP and the EPBT and the assumptions made in this LCA. These results demonstrate that the hydrogenation process benefits the environmental impacts of the technologies studied in this LCA.

1. Introduction

Attention is being dedicated to the progress of new photovoltaic (PV) technologies. Besides that, for crystalline silicon c-Si wafer solar cells, especially, there are many variations in the existing production processes that are intended to improve module performance[1]. The screen-printed aluminium back surface field (Al-BSF) sequence[2] is the current industry standard process but the passivated emitter and rear cell (PERC) technology[3] is gaining significant share in the world market and it will probably mostly replace Al-BSF technology in the future[1].

The PERC process has already been implemented in industry[3]. In 2016 the efficiency of a p-type monocrystalline module using PERC cells achieved satisfactory efficiencies[4]. However, efficiency improvements are not the only focus on the PV industry and solar cell manufacturers also aim to produce lower-cost modules with stable performance during operation.

There are different routes and technologies related to silicon that have led to higher solar cell conversion efficiency or lower production costs. In recent years cost reduction has been a huge focus for the PV industry[1]. One possibility to reduce the overall costs of PV modules is the use of low-cost silicon feedstock, such as upgraded metallurgical silicon (UMG-Si). This metallurgical refinement process has the benefit of being carried out in the liquid phase of Si, resulting in a significantly less energy consumption in comparison to electronic grade silicon (EGS) production using the Siemens process[5], however, it produces lower quality wafers than the EGS[6] due to its purification process that generates large amounts of impurities, including boron, aluminium and phosphorus[7].

Additionally, both EGS and UMG-Si experience degradation processes due to multiple mechanisms. One example is degradation caused by the charge carriers generated by illumination (light induced degradation, LID) and it can severely impact the cells performance[8].

The interactions impurities and defects within silicon with hydrogen have been intensely studied for decades[9]. The hydrogenation process has recently become better understood and more controllable and offers improvements to the electrical performance of silicon solar cells from different feedstocks[10, 11].

The development of PV technologies should be complemented by environmental analyses of the production processes. Life cycle assessment (LCA) is a methodology that accesses the environmental impacts through the inputs and outputs associated with all the stages of a product's life cycle considering raw material extraction, materials processing, manufacture, distribution, use, repair and maintenance, and end of life[12]. LCA has previously been applied to silicon solar cell manufacturing by several authors[13-15].

In this work we will undertake a comparison of global warming potential (GWP) and EPBT of Al-BSF, PERC (considering EGS and UMG-Si feedstocks), PERC with laser hydrogenation (LaserH) and PERC with hydrogenation in a firing furnace (FurnH) processes through the LCA method. The LaserH and FurnH process will be further explained in the next sections of this work.

2. Materials and Methods

With the support of the LCA software GaBi[16], we calculate the environmental impacts based on the area required for a solar cell to produce 1 kWh with its assumed efficiency. Therefore, the functional unit for this LCA is 1 kWh of electricity generated.

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Table 1: Al-BSF, Passivated Emitter and Rear Cell (PERC), PERC with laser hydrogenation (LaserH) and PERC with hydrogenation in a firing furnace (FurnH) production process steps.

Process step \ Technology	Al-BSF	PERC EGS	PERC UMG	PERC + LaserH EGS	PERC + LaserH UMG	PERC + FurnH EGS	PERC + FurnH UMG
MGS	Y	Y	Y	Y	Y	Y	Y
EGS	Y	Y	N	Y	N	Y	N
UMG-Si	N	N	Y	N	Y	N	Y
mono c-Si	Y	Y	Y	Y	Y	Y	Y
Si wafer production	Y	Y	Y	Y	Y	Y	Y
Cell production	Y	Y	Y	Y	Y	Y	Y
Rear Passivation Layers	N	Y	Y	Y	Y	Y	Y
Dielectric Openings	N	Y	Y	Y	Y	Y	Y
Laser Hydrogenation	N	N	N	Y	Y	N	N
Hydrogenation in a firing furnace	N	N	N	N	N	Y	Y
Module fabrication	Y	Y	Y	Y	Y	Y	Y
Installation/Disposal	Y	Y	Y	Y	Y	Y	Y

Where:
Y= yes (this step is part of the process)
N = no (this step is not part of the process)
MGS = metallurgical grade silicon
EGS = electronic grade silicon
UMG-Si = upgraded metallurgical silicon

The inventory for metallurgical grade silicon (MGS), EGS, mono c-Si (Czochralski (CZ) process), Si wafer production, photovoltaic cells production (including front side passivation, rear etching and firing of contacts), module fabrication, installation stage and the disposal is from the Ecoinvent database[17], that is public available.

The UMG-Si production starts with liquid MGS, which is subjected to a segregation treatment which allows reduction of metal impurities. After that, it is remelted in an induction furnace and submitted to a second segregation process. The final step is the solidification and the UMG-Si is then transferred to the argon plasma purification unit[18]. This process can be used for multi and monocrystalline silicon. In order to reach higher cell efficiency for monocrystalline silicon, a high-purity feedstock is used to obtain an entire ingot that clearly demonstrates a very low total amount of impurities[18].

In the case of PERC technology this process also includes rear passivation layers and dielectric openings. It incorporates a rear contacting scheme that achieves the reduction of rear surface recombination by a combination of dielectric surface passivation and reduced metal/semiconductor contact area, with simultaneously increased rear surface reflection by use of a dielectrically displaced rear metal reflector[3]. For the laser throughput and electricity load associated with the dielectric openings we are using the technical data for a commercial laser workstation19 designed for high-precision applications in the photovoltaic, precision engineering, and electronic industries.

For this study we are considering two different advanced hydrogenation techniques that have been tested in PERC solar cells: LaserH and FurnH.

The LaserH process activates and then passivates defects on the Si solar cells using atomic hydrogen and high-intensity laser illumination[8]. This progress allows complete stabilisation from degradation mechanisms related to boron–oxygen reactions in solar cells[10].

The FurnH process controls the charge state of the hydrogen through in-furnace illumination in the contact firing step. For this LCA we are assuming a conventional industrial firing process[11].

It has been show that the hydrogenation process on monocrystalline PERC solar cells delivered both an as-produced efficiency gain as well as reducing light-induced degradation effects. For one studied manufacturer, the results showed that the process gave an initial average efficiency enhancement of 0.2% absolute and avoided annual degradation by 0.8% abs[20].

A module with no degradation can be expected to produce more electrical power over its lifetime for the same initial power rating than for one with degradation. The degradation process is considered in our calculations as being zero for the cells with hydrogenation processes. For other cells studied we are assuming an average efficiency considering 0.8% abs. degradation per year during 20 years.

To environmentally assess the impacts of these production processes, we are using the LCA methodology with the support of the software GaBi[16] and data from industry and literature. The complete inventory is shown in the supplementary material.

The assumed initial efficiencies end lifetimes of the studied cells and modules are shown in Table 2.

Table 2: Assumed initial efficiency values and lifetime of the Si solar cells studied in this LCA.

Technology	Cell efficiency	Module efficiency	Lifetime
Al-BSF	20.0% [1]	16% [1]	20 years
PERC (EGS feedstock)	21.2% [1]	17% [1]	20 years
PERC (UMG-Si feedstock)	20.0% [21]	16%*	20 years
PERC + LaserH (EGS feedstock)	21.4%*	18%*	20 years
PERC + LaserH (UMG-Si feedstock)	20.2%*	17%*	20 years
PERC + FurnH (EGS feedstock)	21.4%*	18%*	20 years
PERC + LaserH (UMG-Si feedstock)	20.2%*	17%*	20 years
* Assumed efficiencies for this LCA study.			

In this LCA we are analysing GWP and EPBT, because when "green" sources of energy, including PV, are environmentally assessed, GWP is the most common impact analysed. This impact is largely cited since it determinates the effectiveness of these technologies in reducing greenhouse gases emissions during the manufacturing processes, use phase and end of life[13, 15, 22].

The module area required to produce our functional unit of 1kWh is different for each cell technology, according Equation 1. The area for our functional unit, A, of 1kWh is given by:

$$A = \frac{\varepsilon}{\eta . I . y . PR} \quad [1]$$

where ε is the energy generated, η is the efficiency of the cell, I is the insolation (1700 kWh/m^2/year), y is the lifetime (years) and PR is the performance ratio (0.75).

3. Results and Discussion

3.1. Global Warming Potential (GWP)

The LCA methodology described above allows us to calculate the GWP impact. To do so, we use the collected data related to all process steps described in Table 1. We are considering the impacts generated from the raw materials until the end of life (landfill) of these solar modules and excluding transportation, labour and recycling. In this section, we present the results for GWP (Figure 1) of Al-BSF, PERC, PERC + LaserH and PERC + FurnH processes and discuss their differences.

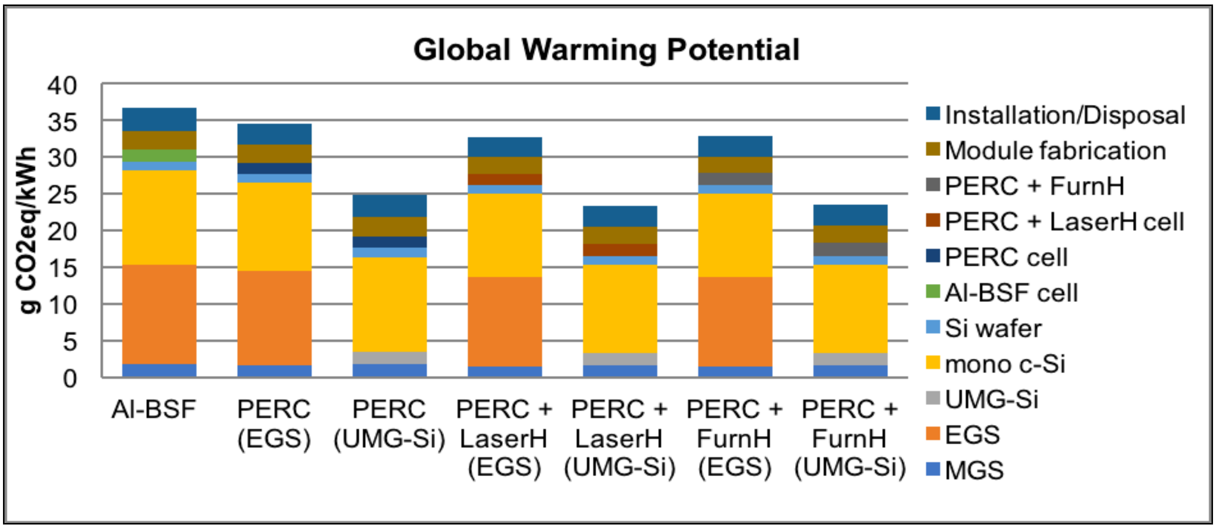

Figure 1: Global warming potential results (g CO^2 eq / kWh).

The GWP is the environmental impact related to the use of energy and the emission of greenhouse gases during each process[23]. It can be seen in Figure 1 that the silicon treatment processes have the most significant GWP impacts. The CZ process (mono c-Si) is the most important step in this impact category. In this process, the solid silicon is placed in a crucible where electrical heaters are used to melt the silicon and to maintain an appropriate temperature trajectory throughout the crystallization process[24]. This intense use of energy in this step is the main cause for this impact[25].

The improvement in the efficiency and the benefits over the lifetime, due to the reduction of the light-induced degradation effects from the hydrogenation processes also influence in the environmental outputs. Figure 1 shows that the higher efficiency and the impacts on the degradation mechanisms present better GWP results, due to the lower energy usage to produce the same amount of energy (1 kWh, is the functional unit of this LCA) during the module's lifetime.

These results demonstrate that a better performance of the cells and modules can produce better environmental impacts when considering the GWP category. The use of lower quality silicon (UMG-Si) combined with hydrogenation processes show the best outcomes compared with the other technologies studied in this LCA, which encourages even more the studies on cell and module performance improvements.

3.2. Energy Payback Time (EPBT)

It is very common in LCA studies to have the Energy Payback Time (EPBT) calculation in addition to the GWP results. In this case, EPBT is defined as the period required for a PV system (considering solar modules and other components - i.e., module supports, cabling and power conditioning) to generate the same amount of primary energy that was used to produce the system itself[26].

In this LCA we are considering for this calculation: the primary energy from China (coal), the annual insolation as 1700 kWh/m^2/year, the performance ratio[27] as 0.75 and the respective efficiencies shown in Table 2. We are not considering in these calculations the losses due to distribution. The results for the EPBT are shown in Table 4.

As it can be seen in Table 4 the structures that use EGS present higher EPBT than the structures that use UMG-Si. This is because the use of energy is more intensive in the EGS process when compared with UMG-Si. The higher efficiencies present better EPBT results and well as the use of less energy during the process.

Table 3: EPBT results for Al-BSF, PERC (EGS) PERC (UMG-Si), PERC + LaserH (EGS), PERC + LaserH (UMG-Si), PERC + FurnH (EGS) and PERC + FurnH (UMG-Si).

Structure	EPBT (years)
Al-BSF	1.51
PERC (EGS)	1.20
PERC (UMG-Si)	1.15
PERC + LaserH (EGS)	1.11
PERC + LaserH (UMG-Si)	0.95
PERC + FurnH (EGS)	1.12
PERC + FurnH (UMG-Si)	0.95

Considering the structures that use hydrogenation processes, the EPBT is even better. The better performance of this module results in an even better EPBT, which shows the importance of this process not only for the best environmental results but also for the effective use of input energy.

With these analysis, we can see that the best results are shown by the PERC structures that use UMG-Si (low energy required during the silicon treatment) and the hydrogenation process (both laser and furnace), because of the increase in the efficiency of the devices.

4. Conclusion

A LCA of advanced silicon solar modules, considering GWP and EPBT of Al-BSF, PERC (with EGS and UMG-Si feedstocks), PERC + LaserH and PERC + FurnH processes was conducted.

The silicon purification and treatment processes have the most significant impacts. Alternative technologies for the improved CZ process (mono c-Si) should be implemented to reduce this impact. Comparing the EGS and the UMG-Si processes we can observe that there is a decrease on the GWP results, due to the lower use of electricity in the UMG-Si process.

The hydrogenation processes improves the cell's efficiency and reduces its light-induced degradation effects, which influences positively in the environmental outputs, due to the lower energy usage to produce the same amount of energy during the module's lifetime.

The key finding of this LCA, related to the GWP impacts, is that the UMG-Si combined with the hydrogenation methods result in better environmental outcomes for this category. In other words, the processes with higher efficiency have the lower impacts, which mean that the hydrogenation helps to produce better environmental outcomes for the technologies studied in this LCA.

The advanced technologies studied in this LCA show better EPBT, which demonstrates the importance of the hydrogenation processes not only for the best environmental results but also for the effective use of energy input. However, we are not considering losses due to distribution and/or poor weather conditions.

Not many LCAs include the end of life of solar modules, mainly because of the lack of data for this process. However, it is important to consider this step of the process, since the European waste electrical and electronic equipment directive confirms the potential environmental risks associated with the management and treatment of this waste.

For this LCA we didn't consider recycling, so all materials are assumed to go to landfill. For future works the recycling processes and its impacts should be considered in this analysis.

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