# HIGH PERFORMANCE SOLAR CELLS BASED ON LOW COST SOLAR SILICON WITH LOW CARBON FOOTPRINT

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Elkem Solar has updated its environmental life cycle assessment (LCA). Elkem Solar Silicon® now demonstrates an industrial scale energy payback time (EPBT) of 1.3 months vs. 4 months for the best Siemens-based production process for solar grade silicon. The green house gas (GHG) emission rate for Elkem Solar Silicon® is calculated to 25% of the best Siemens-based production processes. The high quality of Elkem Solar Silicon® can be exploited to achieve high cell efficiencies of 17% with an industrial applicable cell process. Comparing the solar cell parameters of Elkem based solar cells to polysilicon based solar cells shows advantages in Voc and FF and comparable Jsc of the Elkem Solar Silicon®, leading to similar or even higher efficiencies and indicating the potential for high-efficiency processes.

## Background

Elkem Solar has developed a metallurgical process route for production of solar grade silicon (Elkem Solar Silicon®) and implemented the production in industrial scale with a current capacity of 6.000 MT. Elkem Solar Silicon® is proven to be suitable for PV applications and has demonstrated cell efficiencies up to more than 18% in multi- and mono- crystalline silicon cells. Elkem Solar Silicon® complies with Category IV in SEMI standard PV17-0611 - Specification for Virgin Silicon Feedstock Materials for Photovoltaic Applications.

In 2008, before the plant was complete, Elkem Solar presented a life cycle assessment (LCA) related to energy usage and green house gas (GHG) emissions for a plant with capacity of 4800 MT SoG - Si per year (1,2). In addition, Elkem Solar published a thermodynamical comparison on direct process energy usage and $CO_2$ emission between ESS™ and SoG – Si from gas route processes (3). The 2008 LCA - data was based on experience from a pilot plant with main equipment for all process stages in industrial scale. In this study Elkem Solar has updated the LCA with numbers from real industrial operation and the observed and measured energy and material usage, waste streams and emissions. The results are based on a full LCA, but should be regarded as preliminary as the plant is presently being ramped up to a capacity beyond 6000 MT per year. Life cycle assessment was done according to ISO14040/ISO14044. Simapro 7.3.2 software and ecoinvent 2.2 database are used to calculate the environmental impacts.

**Life cycle assessment (LCA)**

Preliminary results, based on operation at 6000 MT per year show that the energy payback time (EPBT) and carbon footprint of ESS™ are significantly lower than traditional solar grade silicon produced via purification in the gas phase and deposition in a Siemens-type reactor. Figure 1 shows the EPBT for 100% Elkem Solar Silicon® with the plant located in Norway and using a Norwegian energy mix and Siemens gas route process with a renewable ("best case") and fossil based electricity mix ("worst case"), respectively. In the LCA calculations a total area module efficiency of 14.3% is used.

Green house gas (GHG) emissions are shown in Figure 2. Lower intrinsic energy demand for the process itself contribute largely to a GHG emission of approximately 25% of that of best case Siemens process.

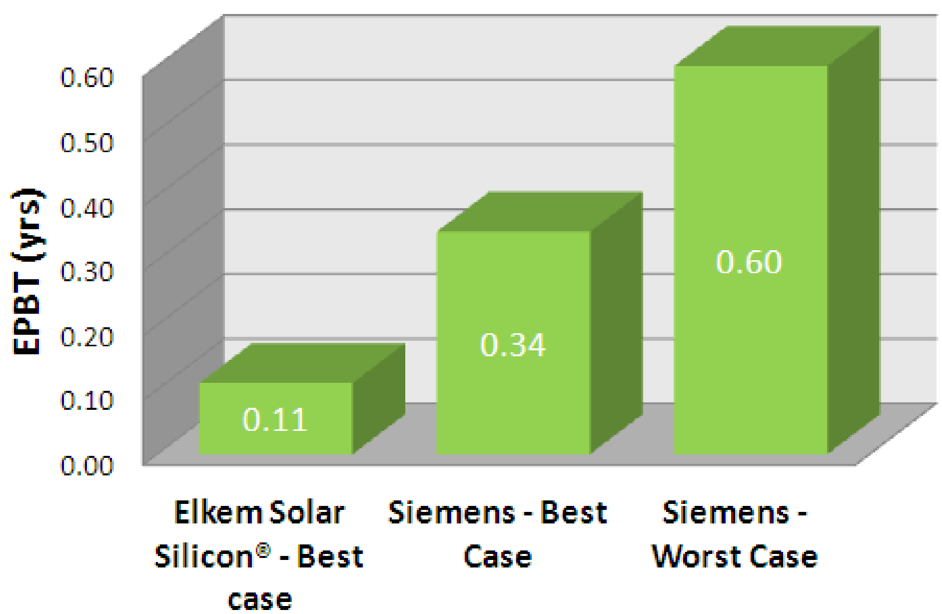



Figure 1: Preliminary results of the energy payback time (EPBT) of 100% Elkem Solar Silicon® in a typical multicrystalline silicon PV module installed at an in-plane irradiation of 1700 $kWh/m^{2}\cdot$year. Comparison with Siemens production, best case with data from ecoinvent 2.2 database (with electricity and heat modified from hydropower and cogeneration) and the worst case with data from ecoinvent 2.2 database with Chinese electricity mix and heat from natural gas. A module efficiency of 14.3% is used in the calculations.

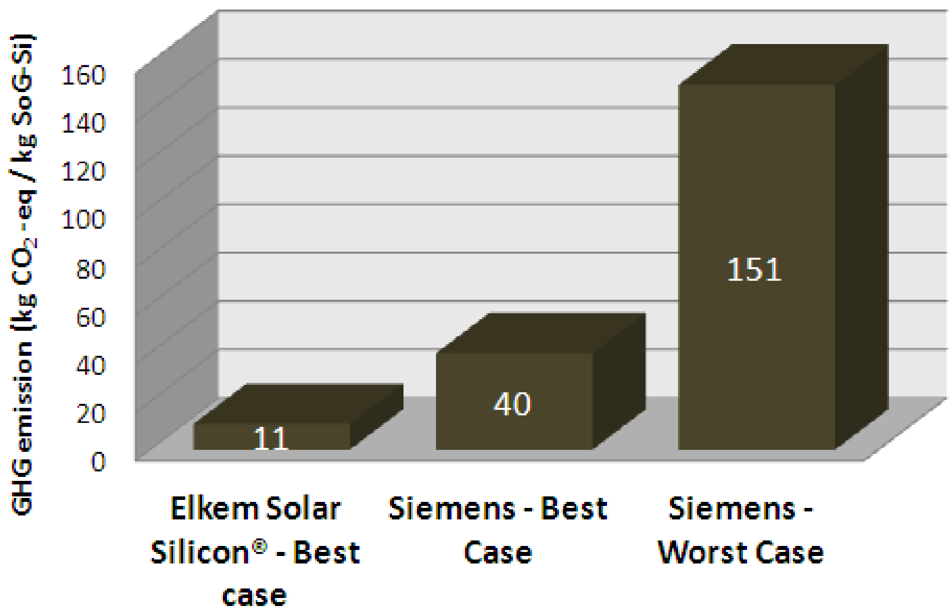



Figure 2: Preliminary results of the carbon footprint of Elkem Solar Silicon®. Comparison with Siemens production, best case with data from ecoinvent 2.2 database (with electricity and heat modified from hydropower and cogeneration) and the worst case with data from ecoinvent 2.2 database with Chinese electricity mix and heat from natural gas.

## Results on multicrystalline solar cells made from Elkem Solar Silicon®

Multicrystalline silicon wafers from three different bricks number 1 (corner), 13 (center) and 20 (edge) each out of two different ingots containing 70% ESS and a poly based reference ingot, respectively, were processed to solar cells at ISC Konstanz in their standard baseline cell process. Approximately 16 wafers from each position were taken out for solar cell process, on the other wafers resistivity measurements were carried out.

The applied cell process included laser numbering, iso-texturisation, wet chemical cleaning, phosphorous diffusion, PECVD SiNx deposition, Ag-screen printing on the front side, full Al BSF screen printing on the rear side, co-firing and edge isolation. IV-, RBV- and LID measurements were carried out on the finished solar cells. Table 1 gives an overview on the processed wafers.

**Table 1**: Overview on processed wafers

| Ingot | Brick number | Wafers in process |
|---|---|---|
| 70% ESS | 1 (corner) | Every 3rd (16 out of 50) |
| 70% ESS | 13 (center) | Every 3rd (16 out of 50) |
| 70% ESS | 20 (edge) | Every 3rd (16 out of 50) |
| Poly ref ingot | 1 (corner) | Every 3rd (16 out of 50) |
| Poly ref ingot | 13 (center) | Every 3rd (16 out of 50) |
| Poly ref ingot | 20 (edge) | Every 3rd (16 out of 50) |

Resistivity measurements were carried out on all wafers, which had not been processed. Figure 3a shows the measured distribution of resistivity. Additionally, ESS wafers show a slightly increase of resistivity towards the top position, while poly reference wafers show a decrease towards the top. Generally, ESS based wafers show a lower resistivity and a narrower distribution than poly-references. The resistivity values of ESS wafers are mainly between 1.2 - 1.4 Ω·cm.

The average solar cell parameters of all investigated groups are shown in Table 2. Additionally are shown the highest achieved values. Table 2 shows that the 70% ESS wafers show better results than the poly-reference. The better performance of ESS is mainly caused by higher Voc and FF. The current is nearly the same for both materials. Average efficiencies of 70% ESS ingot are reaching from 16.5% to 16.7%. Best solar cell made out of ESS achieves 17.0 % efficiency. Average efficiencies of poly-reference are between 16.3% and 16.4%, with highest reached efficiency of 16.7%.

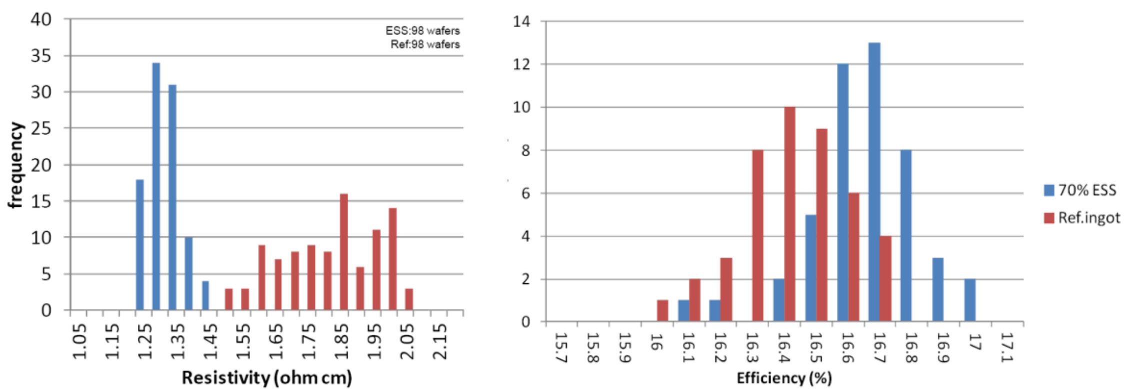
ESS based wafers show generally higher Voc than the reference-material, due to the higher doping concentration and Fermi level shift. ESS wafers from brick 1 and 13 show quite constant values over the whole ingot height, during brick 20 shows increasing values at the bottom positions. The Voc values of ESS wafers are between 618mV and 628mV. The Voc values of reference wafers are between 612mV and 625mV. The Jsc values of ESS wafers are between 33.4 mA/cm² and 34.2 mA/cm². Jsc of reference bricks 13 and 20 are also decreasing towards higher wafer positions. This correlates with the decreasing resistivity. The average values of all ESS and reference cells are nearly the same. ESS shows an average Jsc of 33.8 mA/cm², while Poly-wafers show an average of 33.8 mA/cm². Generally, FF is higher on ESS wafers, due to lower resistivity leading to a lower series resistance. Most of the ESS wafers show FF between 78.5% and 79.1%, this indicates a very good contact formation during contact firing process. Because of the higher resistivity the reference wafers show lower fill factors; wafers from all reference bricks show a very slight increase of FF towards the higher wafer positions, due to the decreasing resistivity. Most of the reference wafers show FF between 78.0% and 78.7%.

**Table 2**: IV data for ESS and poly ref solar cells

| Ingot | Brick | Wafer no. | Voc [mV] | Isc [mA/cm²] | FF [%] | Eta [%] |
|---|---|---|---|---|---|---|
| 70% ESS | 1 | Average | 623 | 33.7 | 78.7 | 16.5 |
| 70% ESS | 13 | Average | 625 | 33.8 | 78.8 | 16.7 |
| 70% ESS | 20 | Average | 624 | 33.9 | 78.7 | 16.7 |
| **70% ESS** | **All** | **Average** | **624** | **33.8** | **78.7** | **16.6** |
| **70% ESS** | **All** | **Maximum** | **628** | **34.2** | **79.1** | **17.0** |
| | | | | | | |
| Poly ref. | 1 | Average | 618 | 33.8 | 78.4 | 16.4 |
| Poly ref. | 13 | Average | 618 | 33.7 | 77.7 | 16.3 |
| Poly ref. | 20 | Average | 618 | 33.8 | 78.4 | 16.4 |
| **Poly ref.** | **All** | **Average** | **618** | **33.8** | **78.1** | **16.3** |
| **Poly ref.** | **All** | **Maximum** | **625** | **34.2** | **78.7** | **16.7** |

Light induced degradation of the solar cell efficiency was measured to be below 0.8% relative for ESS and poly reference. Reverse voltage characteristics at -10 and -12 V were taken from all processed wafers, the results can be seen in the following figure 4. Reverse current should be below 3 Ampere, this fulfilled by far for the most cells.

The investigation also focuses on further enhancing the reverse current-voltage characteristics at -14.5 V by different texturization methods, which still enable high efficiencies. For these purpose five different textures including isotexture, soft isotexture, alkaline texture, a mix of isotexture and alkaline texture and flat etching by NaOH were applied to both ESS™ wafers and poly-Si wafers. Applying an alkaline texturization lowered the reverse current at -14.5V from above 9.2A to 3.3A, while enabling the same efficiencies compared to isotextured solar cells. A further reduction of the reverse current was obtained on NaOH flat etched solar cells, which also show remarkable cell efficiencies even though the higher light reflectivity and thus a lower Jsc. On the poly-Si solar cells the reverse current is below 2A for all texturization methods. The mixed texturization and the NaOH flat etching lead to a improvement of the reverse voltage-current characteristics, but it has to be mentioned that NaOH flat etched solar cells show in average a 0.2% absolute lower efficiency than all other processed solar cells.




(a) (b)

Figure 3: (a) Measured resistivity distribution on ESS wafers and poly ref wafers, (b) efficiency distribution.

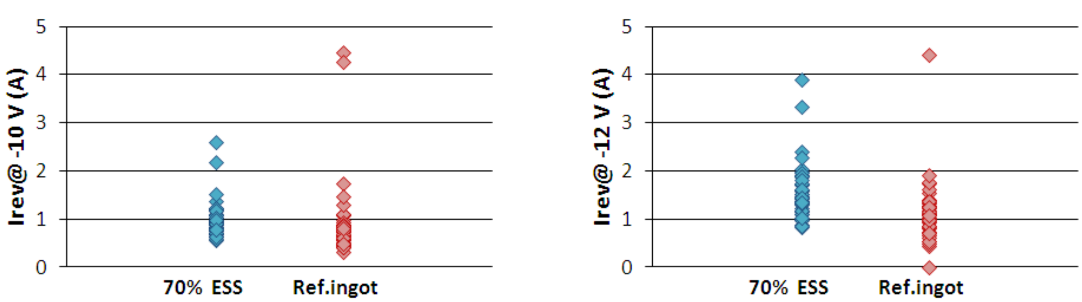



Figure 4: Reverse current measured at two different voltages.

**Table 3**: IV parameters obtained by different texturization methods and a standard solar cell process. The reverse current was determined at -14.5V.

| Ingot | Brick | Texture | Voc [mV] | Isc [mA/cm²] | FF [%] | Eta [%] | Irev [A] |
|---|---|---|---|---|---|---|---|
| 70% ESS | 10 | iso | 618 | 33.0 | 79.2 | 16.2 | 10.6 |
| 70% ESS | 10 | soft | 616 | 33.2 | 79.4 | 16.2 | 10.4 |
| 70% ESS | 10 | mix | 617 | 33.3 | 78.8 | 16.2 | 3.6 |
| 70% ESS | 22 | iso | 619 | 33.2 | 79.2 | 16.3 | 9.2 |
| 70% ESS | 22 | alka | 618 | 33.4 | 79.1 | 16.3 | 3.3 |
| 70% ESS | 22 | NaOH | 620 | 32.6 | 79.4 | 16.1 | 1.9 |
| Ref ingot | 3 | iso | 615 | 34.1 | 78.8 | 16.5 | 1.7 |
| Ref ingot | 3 | soft | 613 | 34.3 | 78.8 | 16.5 | 1.9 |
| Ref ingot | 3 | mix | 614 | 34.2 | 78.7 | 16.5 | 0.9 |
| Ref ingot | 24 | iso | 615 | 34.2 | 78.9 | 16.6 | 1.3 |
| Ref ingot | 24 | alka | 614 | 34.2 | 78.8 | 16.5 | 1.2 |
| Ref ingot | 24 | NaOH | 616 | 33.5 | 78.8 | 16.3 | 0.8 |

## Conclusion

A full life cycle assessment of Elkem Solars metallurgical process route to SoG – Si has shown that Elkem Solar Silicon® has a significantly lower energy payback time and carbon footprint than the traditional Siemens-type solar grade silicon. The picture will further improve as the Elkem Solars plant reaches it maximum capacity.

Wafers from a 70% ESS ingot and a poly-reference ingot were processed to solar cells at ISC Konstanz. Generally, the wafers from the 70% ESS ingot show higher efficiencies than the reference material. The average efficiencies of the ESS-based wafers are between 16.5% and 16.7%, with best cell achieving 17.0%. The average efficiencies of the reference material are between 16.3% and 16.4%. ESS wafers show higher Voc, due to the higher doping concentration and higher FF, because of the lower series resistance according to the lower resistivity. Jsc is at the same level for both ingots. Reverse voltage behaviour of the wafers show reverse currents below 3 Ampere for most of the cells, and further improving the reverse current by texturization was demonstrated. Light induced degradation are below 0.8% relative for both ESS and poly ref solar cells.

## References


1. M.J. de Wild-Scholten, R. Gløckner, J. O. Odden, G. Halvorsen, R. Tronstad (2008) "Life cycle assessment on GHG emissions and energy consumption for the Elkem Solar Metallurgical process route to solar grade silicon ", *Silicon for the Chemical and Solar Industry X*, Oslo, Norway, June 2008
2. M.J de Wild-Scholten, R. Gløckner, J. O. Odden, G. Halvorsen, R. Tronstad (2008) "LCA comparison of the ELKEM SOLAR metallurgical route and conventional gas", *23rd European Photovoltaic Solar Energy Conference*, Valencia, Spain, 1-5 September 2008,
3. J. O. Odden, G. Halvorsen, H. Rong, R. Gløckner, "Comparison of the energy consumption in different production processes for solar grade silicon", *Silicon for the Chemical and Solar Industry X*, Oslo, Norway, June 2008