Silicon for the Chemical and Solar Industry XI
Bergen -Ulvik, Norway, June 25 - 29, 2012

Environmental footprint of Elkem Solar Silicon®

Mariska de Wild - Scholten[1)] and Ronny Gløckner[2)]
1) SmartGreenScans, Wagenmakersweg 22, 1873 GH Groet - The Netherlands, Mariska@smartgreenscans.nl
2) Elkem Solar AS, Fiskaavn. 100, PO Box 8040 Vaagsbygd, 4675 Kristiansand - Norway

Abstract

Elkem Solar has completed a life cycle assessment (LCA) study on the environmental footprint of Elkem Solar Silicon® (ESS™) based on full scale commercial operation of plant #1 in Norway. The results from this study verify the earlier results from the 2008 pilot plant study and show even lower energy usage and GHG footprint due to a higher realised plant capacity.

In this study energy payback time (EPBT) and green-house gas (GHG) emissions for 6000 MT per year capacity (rated capacity in 2011) and short-term future optimisation to 7500 MT per year is calculated using standard LCA methodology. For comparison EPBT and GHG emissions for poly-silicon from a state-of-the-art Siemens process based on hydro power for electricity and co-generation power plant for electricity and heat is calculated.

The results show that the EPBT and GHG emissions from production of ESS™ is a factor 3 to 4 lower than for Siemens based poly-silicon. In fact, the energy pay-back time for the energy invested in the production of ESS™ is only 1 month. The GHG emissions for ESS™ are estimated to approximately10 kg CO_2-eq/ kg ESS™ or ~1.4 g CO_2-eq / kWh at 1700 kWh/m^2·year in-plane irradiation. For the calculations an average module efficiency of 14.3% and a module expected lifetime of 30 years is used.

Background

In 2008 two studies were published on LCA related to energy usage and greenhouse gas (GHG) emissions for the production of ESS™ [1,2]. In addition, Elkem Solar published a comparison of energy usage and CO_2 emissions for ESS™ and poly-silicon from Siemens type production based on thermodynamical data for the two processes [3].

The 2008 LCA results were based on pilot plant operation and on the assumption that a total capacity of close to 5000 MT / yr would be reached. The Elkem Solar pilot operated industrial scale equipment on all process stages. The 2008 results showed ESS™ as a more environmentally benign product than poly-silicon from gas route (Siemens based processes) with lower energy usage and GHG emissions. Compared to poly-silicon from gas route processes, ESS™ was produced with only 25% of the energy and GHG emissions.

Elkem Solar started to produce ESS™ from the industrial plant in Kristiansand in 2009. In 2011, the plant showed a production capacity of 6000 MT ESS™ per year. ESS™ is a solar grade silicon with wafer, cell and module performance equal to poly-silicon - Siemens process). ESS™ is today used in mix-in ratios from 40 to 80%, but shows the same performance results as poly-Si even as a100% product [4].

For the Elkem Solar plant a potential of 7500 MT per year has been identified with a combination of capacity and yield optimisations. Furthermore, the potential for heat recovery is estimated at approximately 20% of the total electricity consumption.

Methodology

For industrial scale production of ESS™ in Kristiansand (Norway) the environmental footprint was determined using Life Cycle Assessment methodology according to ISO14040 and ISO14044 international standards and with the ecoinvent 2.2 database. The product carbon footprint was determined using the ISO/DIS 14067 draft international standard.

For the impact categories selected, methodology of impact assessment and subsequent interpretation this study used:

- Cumulative Energy Demand with CED version 1.08 in Simapro 7.3.3
- Energy payback time, methodology from IEA PVPS task 12 guidelines [5]
- Carbon footprint with IPCC2007 GPW100a version 1.02 in Simapro 7.3.3

The system boundary determines which processes are included in the assessment. These are listed in Table 1.

Elkem Solar is selling part of their “waste” as co-products. Price allocation is used to divide the inputs and outputs between the product ESS™ and the co-products.

For the production of ESS™ the Norwegian electricity mix, which is largely based on hydropower, is used. ESS™ is compared with standard Siemens-type poly-Si production which is produced with electricity and heat from a mix of hydropower and combined heat & power (ecoinvent 2.2 data). For the production of crystals/ingots, wafers, cells and modules an electricity mix was based on production locations in the world [6]. For the production of ingots, wafers, cells and modules, a new data set was applied [7]. Details on the ecoinvent 2.2 inventory for production of poly-Si based on the Siemens process is given in the Appendix – table 2.

For the use phase a roof-top installation is assumed with an irradiation on optimized angle of 1700 $kWh/m^2 \cdot yr$. The following is assumed according to IEA PVPS task 12 guidelines (2011):

- Life expectancy: 30 years for PV modules, 15 years for inverters, 30 years for mounting structure, 30 years for cabling.
- Performance ratio of 0.75.
- PV module degradation of 0.7% per year.

For the end-of-life phase it is assumed that all the PV modules are entering the take-back and recycling scheme of PV CYCLE.

Table 1: System boundary description for the life cycle assessment of ESS™

ESS™ production	*PV system*	*End-of-life phase*
Included	**Included**	**Included**
Raw material extraction	PV module production	Packaging of PV modules
Transport of raw materials to the factory	Mounting system production	Transport to PV module collection point and recycling facility according to PV CYCLE scheme
Manufacturing	Cabling production	
Facilities like climate control, ventilation and lighting for production halls	Inverter production	
On-site emission- and waste treatment,	Maintenance of inverter: replacement after 15 years.	
Off-site waste treatment		
Storage		
Factory building		
Not yet included	**Not yet included**	**Not yet included**
Manufacturing equipment to produce ESS™	Transport of modules and Balance-of-System (BOS), components to installation site	Transport of BOS to municipal waste collection points,
Commuting (transportation to and from work), administration, sales, research and development		Recycling of BOS.
Packaging of ESS		

Results and discussion

In the following results on EPBT and GHG emissions of ESS™ will be presented. In order to compare with poly-Si from, we have also estimated EPBT and GHG emission for a standard commercial Siemens gas route process as these data are available through the Ecoinvent 2.2 data base. We are aware of other energy saving modifications to process equipment and new processes for poly-Si production such as the REC FBR technology, developments of more efficient CVD reactors and process design and the possibilities for increased heat recovery in the Siemens process. It is expected that this will further improve energy and GHG footprint of Siemens type processes.

The poly-Si Siemens case presented here is a state-of-the-art plant and all electric power supplied by hydro power and co-generation. The heat needed in the process is assumed taken from a co-generation power plant using natural gas and would represent a present day “best-case” scenario. Poly-silicon production capacity set up in other more coal based energy mix parts of the world would result in a much higher EPBT and GHG footprint.

In LCA methodology Cumulative Energy Demand (CED) is the basis for estimating EPBT. It states the amount of primary energy put into the production of 1 kg ESS™. Primary energy will include the energy content of for example natural gas where a certain efficiency of converting to electricity is used to transform natural gas to usable energy. The underlying assumptions on CED are given in the appendix – table 3. The Cumulative Energy Demand for production of ESS™ is shown in figure 1.

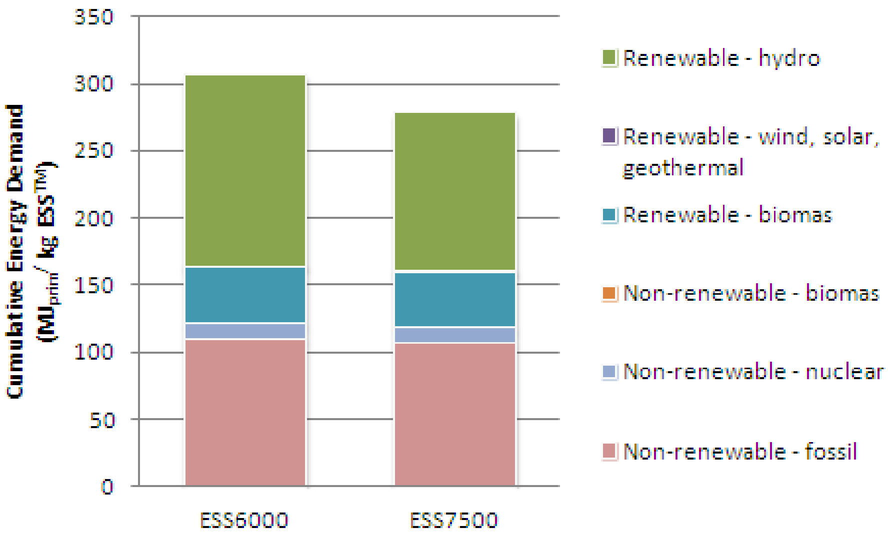

Figure 1: Cumulative Energy Demand (CED) in MJ_{PRIM} (primary energy) for production of ESS™

Figure 2 shows the EPBT for the present 6000 MT and 7500 MT ESS™ plant #1 production case compared to poly-Si production from a Siemens type process. The time needed for a PV system installed at an in-plane irradiation of 1700 $kWh/m^2\cdot year$ and based on ESS™ to produce the amount of energy that was originally put into producing the feedstock (EPBT) is estimated to one month only. The same number for poly-Si from Siemens, as estimated in this study, is 3.5 months.

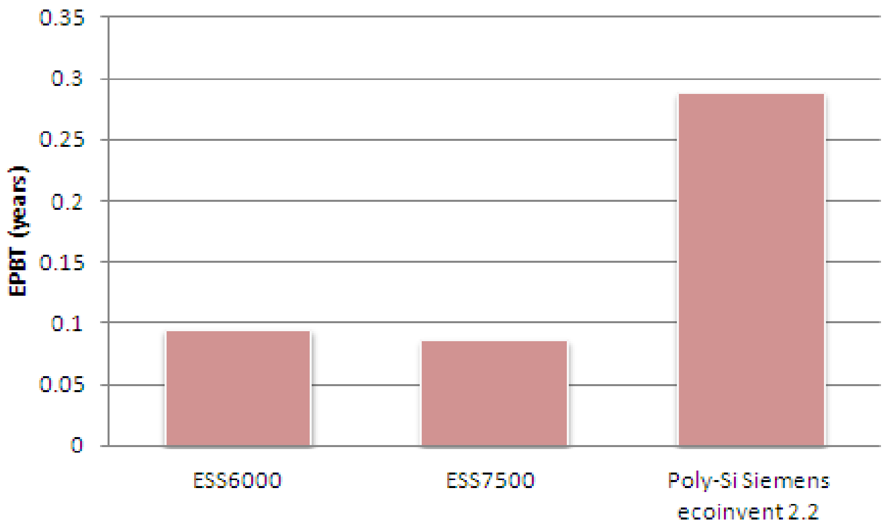

Figure 2: EPBT for production of solar grade silicon for plant #1 ESS™ production compared to Poly-Si from a Siemens type process at an in-plane irradiation of 1700 kWh/m^2.year

In figure 3 the EPBT for the entire PV energy system value chain is shown. We typically see that for production of ESS™ from plant #1 the EPBT contribution from feedstock production is reduced well below that of inverter, laminate and wafer production.

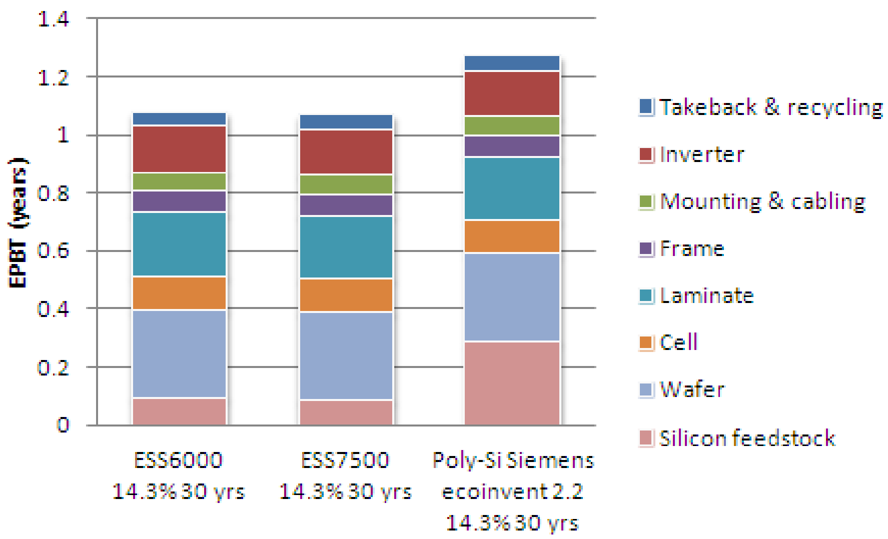

Figure 3: EPBT for entire PV energy system value chain for ESS™ production from plant #1 compared to Poly-Si from Siemens type process at an in-plane irradiation of 1700 kWh/m^2.year

Carbon footprint (GHG) for plant #1 production of ESS™ is shown in figure 4. Here the carbon footprint is calculated to be ~75% lower than that of poly-silicon Siemens production. GHG emissions contribution from production of ESS™ is hence lower than each of the single down-stream contributions. This is shown graphically in Figure 5.

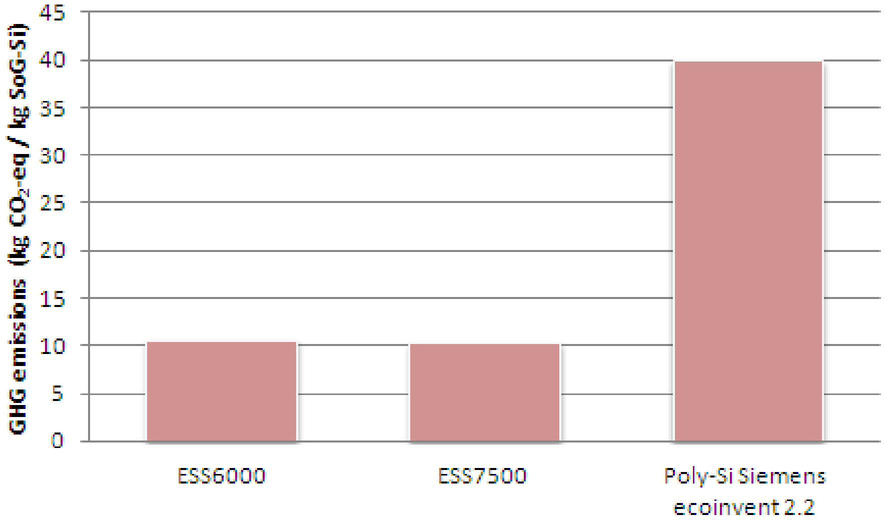

Figure 4: GHG emissions in kg CO_2 per kg SoG-Si for production of solar grade silicon for plant #1 ESS™ production compared Poly-Si from a Siemens type process

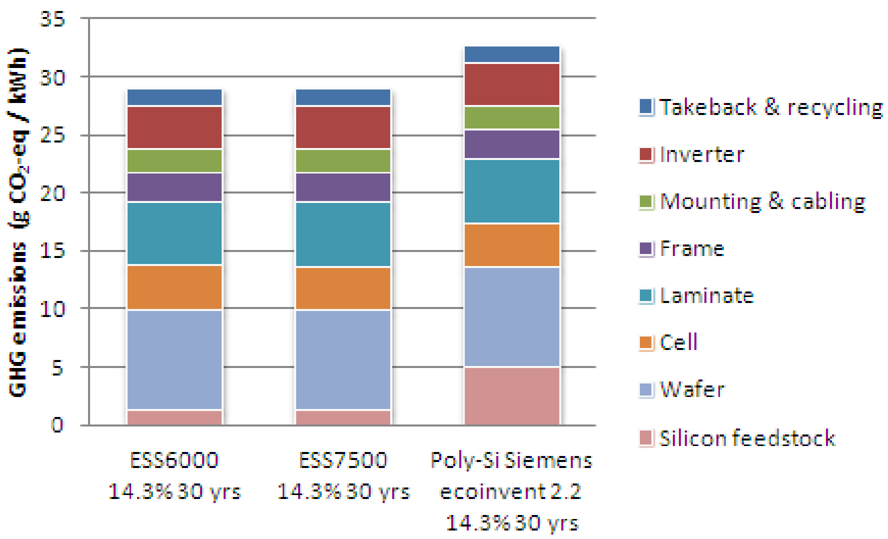

Figure 5: GHG emissions in grams of CO_2-eq per kWh for the entire PV energy system value chain for ESS™ production from plant #1 compared to Poly-Si from Siemens type process at an in-plane irradiation of 1700 kWh/m^{2}·year

In terms of other step-changing technologies REC recently estimated their EPBT and GHG emissions from their commercialised FBR (Fluidised Bed Reactor) technology. For a 100% FBR product, which is not realised yet, they estimate an EPBT of ~0.18 years. The EPBT estimate for a FBR to poly-Si mix (mix-in ratio is not stated) is said to be ~0.26 years [8]. A direct comparison between Elkem Solars ESS™ is however not straightforward as essential underlying assumptions such as for instance module efficiency, electricity mix, etc are not stated and may differ.

Conclusion

Elkem Solar has recently optimized and identified a large optimization potential on its solar grade silicon production plant in Kristiansand. In 2011 the capacity was rated at 6000 MT ESS™ per year, but a capacity of 7500 MT ESS™ will be reached in the short-term.

Pay-back time for the energy invested in production of Elkem Solar Silicon® (ESS™) is now below 1 month. At these capacities ESS™ is produced with ~70% less energy than state-of-the-art poly-silicon from the dominating Siemens gas route process. This is also reflected in the green house gas (GHG) emissions which are 10 kg CO_2-equivalents per kg ESS™ produced a factor of 4 lower than for poly-Si from the Siemens route. The results are significantly lower than for any other solar grade silicon production route and come from a life cycle assessment (LCA) study based on a total overview of mass and energy balance from the plant in Kristiansand.

Acknowledgements

The authors wish to acknowledge Magne Berg, Ragnar Tronstad, Gunnar Halvorsen, Jan Ove Odden, Rolf Birkeland, Bjørn Sandberg and Hallgeir Grinde for their contribution to the work.

Appendix

Table 2: Ecoinvent 2.2 data for the production of “Silicon, solar grade, modified Siemens process, at plant/RER U”

Products		
Silicon, solar grade, modified Siemens process, at plant/RER U	1	kg
Resources		
Materials/fuels		
MG-silicon, at plant/NO U	1.13	kg
Hydrochloric acid, 30% in H2O, at plant/RER U	1.6017	kg
Hydrogen, liquid, at plant/RER U	0.050139	kg
Sodium hydroxide, 50% in H2O, production mix, at plant/RER U	0.34819	kg
Transport, lorry >16t, fleet average/RER U	2.66	tkm
Transport, freight, rail/RER U	2.4	tkm
Electricity, at cogen 1MWe lean burn, allocation exergy/RER U	45	kWh
Electricity, hydropower, at run-of-river power plant/RER U	65	kWh
Heat, at cogen 1MWe lean burn, allocation exergy/RER U	185	MJ
Silicone plant/RER/I U	1E-11	p
Emissions to air		
Heat, waste	396	MJ
Emissions to water		
AOX, Adsorbable Organic Halogen as Cl	1.262E-05	kg
BOD5, Biological Oxygen Demand	0.0002047	kg
COD, Chemical Oxygen Demand	0.00202	kg
Chloride	0.035991	kg
Copper, ion	1.024E-07	kg
Nitrogen	0.0002075	kg
Phosphate	2.804E-06	kg
Sodium, ion	0.03379	kg
Zinc, ion	1.963E-06	kg
Iron, ion	5.609E-06	kg
DOC, Dissolved Organic Carbon	0.00091	kg
TOC, Total Organic Carbon	0.00091	kg

Appendix

Table 3: Cumulative Energy Demand, Energy payback time and carbon footprint of ESS™, poly-silicon, PV modules and systems

	Reference	Manufacturers, Date	multi or mono	Details	Module efficiency	Irradiation on optimized-angle (kWh/m^2.yr)	Performance ratio	Life expectancy (years)
1	Westgaard 2012	REC 2011-Q1	multi	US poly-Si blend with FBR, wafers/cells Norway, modules Singapore, Peak Energy series multicrystalline Si modules, module efficiency …	?	1700	0.84	30
2	Westgaard 2012	REC 2011-Q1	multi	US poly-Si blend with FBR, wafers/cells/modules Singapore, Peak Energy series multicrystalline Si modules, multi module efficiency …	?	1700	0.84	30
3	Wetzel 2011	Wacker, Bosch, Solar World 2010	mono	poly-Si Wacker DE (CHP, hydro, German electricity), wafers/cells/modules Germany	15.0%	1700	0.75	30
4	Wetzel 2011	Wacker, Bosch, Solar World 2010	multi	poly-Si Wacker DE (CHP, hydro, German electricity), wafers/cells/modules Germany	13.9%	1700	0.75	30
5	This study	Elkem Solar Silicon 6000 MT	multi	ESS Norwegian electricity, wafers/cells/module PV world electricity	14.3%	1700	0.75	30
6	This study	Siemens-type poly-Si (ecoinvent 2.2)	multi	poly-Si hydro&CHP, wafers/cells/module PV world electricity	14.3%	1700	0.75	30

	CED of solar grade Si (MJ/kg Si)	CED of module (MJ/Wp)	EPBT of module (years)	EPBT of PV system (years)	CF of solar grade Si (kg CO_2-eq/kg Si)	CF of module (g CO_2-eq/Wp)	CF of module (g CO_2-eq/kWh)	CF of PV system (g CO_2-eq/kWh)
1	?	13.0	0.8	1.1	?	570	12	18
2	?	15.2	0.9	1.2	?	726	15	21
3	?	?	1.3	1.5	?	?	?	?
4	?	?	1.1	1.3	?	?	?	?
5	306	11.7	0.8	1.1	10.6	660	22	29
6	961	14.5	1.0	1.3	39.8	874	25	33

References

1. M.J. de Wild-Scholten, R. Gløckner, J.O. Odden, G. Halvorsen, R. Tronstad, *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, *LCA comparison of the ELKEM SOLAR metallurgical route and conventional gas routes to solar silicon*", 23rd European Photovoltaic Solar Energy Conference, Valencia, Spain, 1-5 September 2008
3. J.O. Odden, G. Halvorsen, H. Rong, R. Gløckner, *Comparison of energy consumption in different production processes for solar grade silicon*, Silicon for the Chemical and Solar Industry X, Oslo, Norway, June 2008
4. T. Ulset, *Solar Cell Silicon for High Performing PV Systems*, Photon 1st PV Material Conference, Shanghai, China, May 16th 2012
5. V. Fthenakis, R. Frischknecht, M. Raugei, H.C. Kim, E. Alsema, M. Held and M. de Wild-Scholten, *Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity*, 2nd edition, IEA PVPS Task 12, International Energy Agency Photovoltaic Power systems Programme, 2011
6. M.J. de Wild-Scholten, *Environmental profile of PV mass production: globalization*, 26th European Photovoltaic Solar Energy Conference, Hamburg, Germany, 5-9 September 2011
7. M.J. de Wild-Scholten, R. van der Meulen, *Carbon- and environmental footprinting of photovoltaic modules*, to be published at 27th European Photovoltaic Solar Energy Conference, Frankfurt, Germany, 24-28 September 2012
8. T. Westgaard, C. Olson, T. Veltkamp, *Life cycle analysis of modules: A multicrystalline silicon case study*, Photovoltaics International, 15th edition, February 2012, p. 136-140
9. T. Wetzel, F. Feuerstein, *Update of energy payback time data for crystalline silicon PV modules*, 26th European Photovoltaic Solar Energy Conference, Hamburg, Germany, 5-9 September 2011