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Environmental life cycle assessment of the Elkem Solar metallurgical process route to solar grade silicon with focus on energy consumption and greenhouse gas emissions

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Abstract

Today more than 95% of solar grade silicon feedstock is produced by decomposition of (chloro)silanes using Siemens, Komatsu or FBR (Fluidised Bed Reactor) – technology. Metallurgical refined silicon of solar grade quality will in the coming years become increasingly available to the solar market and may reach a market share of 20-30% within 2011. Energy consumption and life cycle CO_2 - emission are important competitive factors. The industry will be faced with complete life cycle assessment (LCA) studies to compare solar energy with other sustainable energy sources. The present paper reports on an environmental LCA study performed on Elkem Solar Silicon (ESS™) as the single source of solar grade silicon (SoG-Si) used in the production of a rooftop multicrystalline photovoltaic system. Life cycle green house gas (GHG) emissions and cumulative energy demand (CED) are estimated for feedstock plants located in Norway. A sensitivity analysis is done using Norwegian and European electricity mixes. Energy pay-back times (EPBT) are calculated for PV-systems mounted in Southern and North Western Europe. The results show that the EPBT applying ESS produced in Norway is 1.1 and 1.9 years for a system installed in Southern and North Western Europe, respectively. Life cycle emissions of GHG are estimated to be ~14 g CO_2-eq / kg ESS produced. The total life cycle GHG emissions for a rooftop PV system installed in Southern Europe is estimated to be approximately 23 g CO_2-eq / kWh. For both EPBT and GHG emissions, the contribution from production of ESS is comparable in size to contributions from production of wafer, cell, laminate and inverter and more than 3 times lower than for conventional gas route processes.

Introduction

In the present paper the method of LCA is used to estimate results of the intrinsic advantages that lie in the use of the Elkem Solar metallurgical route to SoG – Si. In addition to the production cost factor, important to make solar power available to new and larger markets in the future, there is a clear advantage with regards to the climatic challenges that we face. The LCA method is well adapted to give the full picture with regards to GHG emission, EPBT, resource depletion and other environmental factors important as input for reaching sustainability in the energy sector.

Methodology

To determine the environmental impact the method of environmental life cycle assessment is used. The effect to the environment is determined over the whole life cycle including mining, production of materials, energy consumption and treatment of waste and emissions. For this purpose the software tool Simapro 7.1 is applied. The impact assessment methods used are Cumulative Energy Demand for energy payback time calculation and IPCC2007 GWP 100 years for global warming potential calculation. The database ecoinvent 2.0 is used for background data. We analyzed a multicrystalline silicon PV system as described in [[1]]. A sensitivity analysis is done for the Norwegian and UCTE electricity supply mixes, which have life cycle greenhouse gas emissions of 12 grams CO_2-eq / kWh and 530 grams CO_2-eq / kWh produced, respectively [[2]].

Elkem solar silicon production

At present Elkem Solar is completing a solar silicon plant with an annual capacity of 5000 MT. This is a first-of-its-kind plant where metallurgical grade silicon (MG-Si) is produced and refined to solar grade silicon (SoG-Si) through five process stages, three of which are purification stages. The five process stages are:

1. Carbo-thermal reduction of quartz to produce MG-Si in electric arc furnace
2. High temperature slag treatment
3. Low temperature wet-chemical leaching
4. Directional solidification
5. Post treatment

A schematic view of the Elkem Solar process route is given in Figure 1.

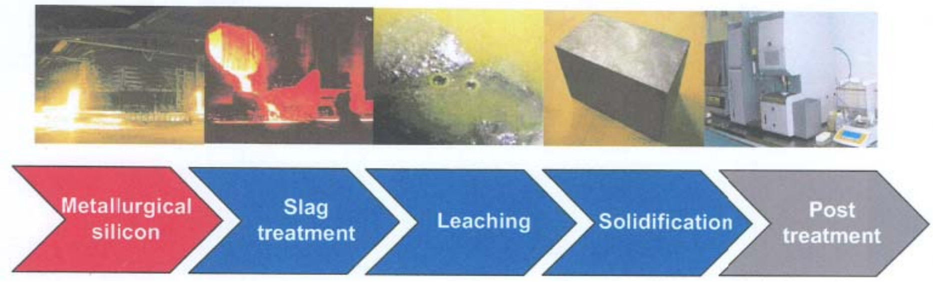

Figure 1. Diagram of the production route of Elkem Solar Silicon. Purification stages are coloured blue.

The Elkem Solar process is based on well known processes operated by the metallurgical industry today and avoids the transition of MG-Si into any form of silicon containing gas (silanes). Key numbers for the Elkem Solar process (unit process raw data), such as energy consumption and CO_2 emissions are given in [[3]]. The multicrystalline silicon module efficiency using ESS is the same as standard solar grade silicon [[4]]. No blending is needed with other sources of solar grade silicon.

The data used in the present LCA are based on design parameters for the plant being built and on extensive experience from pilot scale operation in the period from 2005 – 2008. The plant will start producing solar grade silicon autumn 2008 and go through a ramp up to its nominal capacity of 5000 MT / year during 2009. Expected operational status as nominal capacity is reached in the beginning of 2010 founds the basis for the LCA modeling results.

In 2010 Elkem Solar estimate that approximately 15% of the electricity consumption will be recovered and sent to the local heat distribution system for the town of Kristiansand.

The following parameters are included in the analysis:

- products: Elkem Solar Silicon plus sidestreams (economic allocation)
- material- and electricity consumption of all the process steps,
- direct emissions from the plant, based on estimated emissions as provided to SFT (Norwegian Pollution Control Authority) for obtaining permits,
- on-site waste treatment
- external waste storage (inert to landfill)
- transport of raw materials and waste to/from the production location in Kristiansand

The following parameters are excluded from the analysis:

- capital goods (production equipment, building hall)
- packaging of the product

Energy pay-back time (EPBT)

Cumulative energy demand (CED), on which EPBT is based, is the energy used throughout the life cycle of a product (see ref. [5] for more details). Figure 2 shows the CED for the production of ESS using Norwegian and UCTE grid energy mixes.

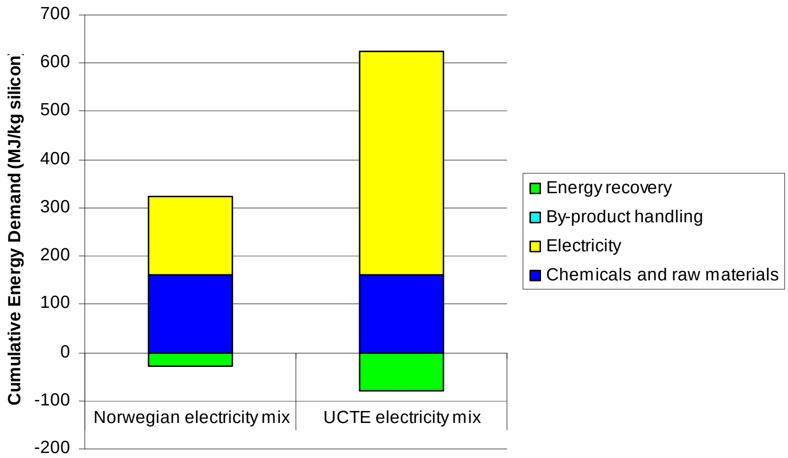

Figure 2. Cumulative Energy Demand for the production of Elkem Solar Silicon using Norwegian or UCTE electricity mix.

The CED for production of ESS using European electricity mix is almost double that of a Norwegian location. This may be explained by the large difference in fossil based power generation and hence the primary energy content compared to actual amount of energy produced (energy efficiency).

Energy payback time (EPBT) is defined as the number of years a PV system has to operate to produce the energy which was needed to manufacture it. EPBT and assumptions based on two irradiation regimes representing North Western and Southern Europe are shown in Table 1.

Table 1. Energy payback time calculation of multicrystalline silicon PV system using Elkem Solar Silicon (Norwegian electricity mix) for two irradiation regimes.

	Irradiation NW Europe	**Irradiation S Europe**
Energy input	16171 MJ_p / kW_p	16171 MJ_p / kW_p
Irradiation	1000 kWh / m^2 / yr	1700 kWh /m^2 /yr
Performance ratio	0.75	0.75
Annual yield	750 kWh / kW_p / yr	1275 kWh / kW_p/yr
Energy output (1 kWh_e = 11.6 MJ_p)	8694 MJ_p / kW_p/yr	14780 MJ_p / kW_p/yr
Energy payback time = energy input / output	1.9 years	1.1 years

Figure 3 shows EPBT for an irradiation regime representing Southern Europe split into contributions from all processes - from production of ESS feedstock to the PV system inverters.

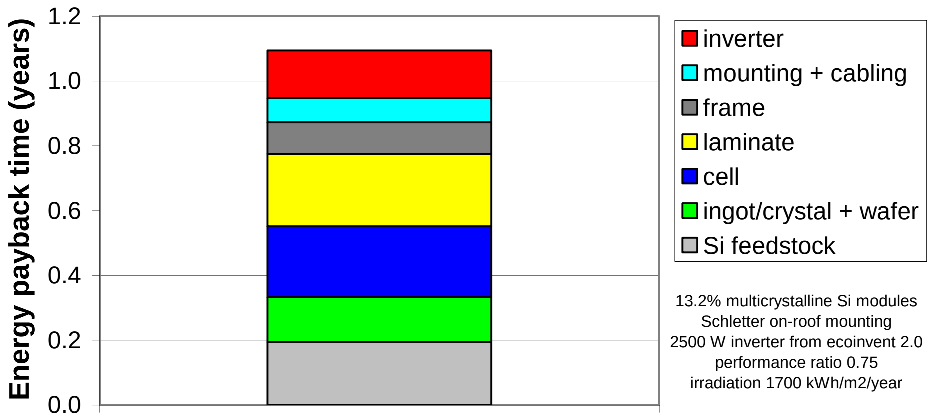

Figure 3. Energy payback time of a multicrystalline silicon PV system using Elkem Solar Silicon (Norwegian electricity mix) installed on a rooftop in Southern Europe.

Global warming potential

Global warming potential (GWP) is estimated for a Norwegian and European electricity mix and is shown in Figure 4. The low CO_2 intensity of the Norwegian electricity mix limits the contribution from grid electricity to only 3.4% of the total GHG emissions, while the contribution from grid electricity for a plant using European electricity mix adds 62% to the total GHG emissions. Energy recovery will have a greater impact in the more fossil - intensive European electricity mix, contributing to a negative impact of around 4 g CO_2-eq / kg silicon.

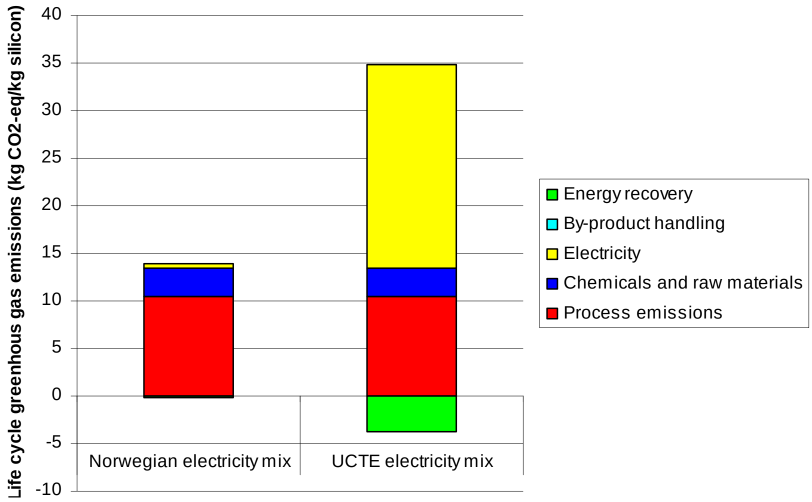

Figure 4. Life cycle greenhouse gas emissions for the production of Elkem Solar Silicon.

Life cycle greenhouse gas emissions split into contributions from all major production processes from Si – feedstock to inverters are presented in Figure 5.

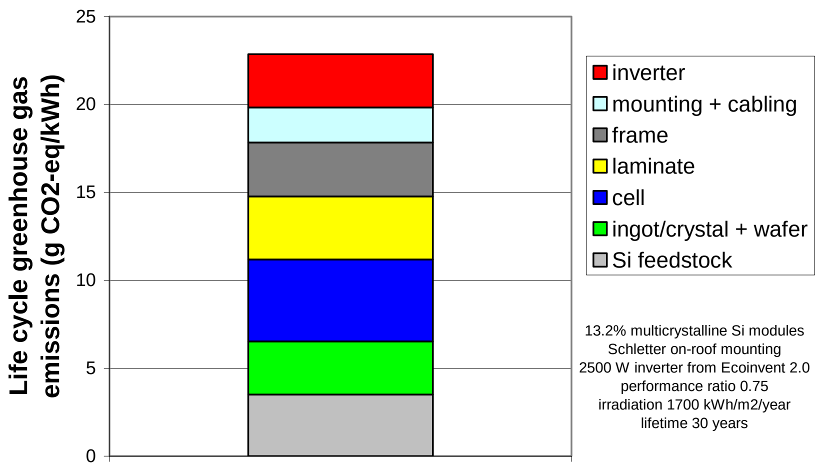

Figure 5. Life cycle greenhouse gas emissions for the production of a rooftop multicrystalline silicon PV system using Elkem Solar Silicon.

Conclusions

The Elkem Solar metallurgical route to SoG-Si does not involve any energy intensive gas route process step. This gives a clear advantage when comparing EPBT and life cycle greenhouse gas emissions with conventional gas route processes to SoG-Si. Figure 6 and Figure 7 shows EPBT and life cycle greenhouse gas emissions for ESS and Siemens type gas route processes, respectively.

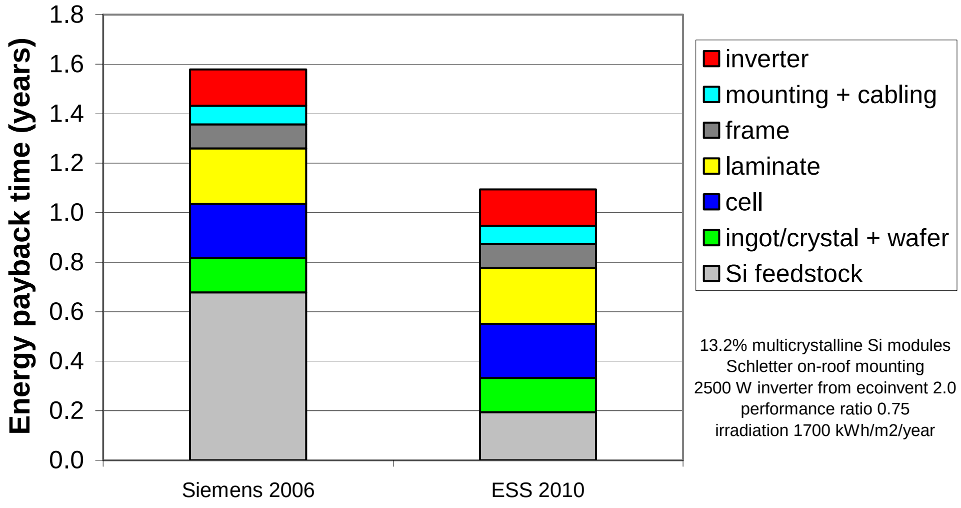

Figure 6. Energy payback time comparison between conventional gas route to SoG-Si (Siemens 2006 [1]) and ESS (ESS 2010).

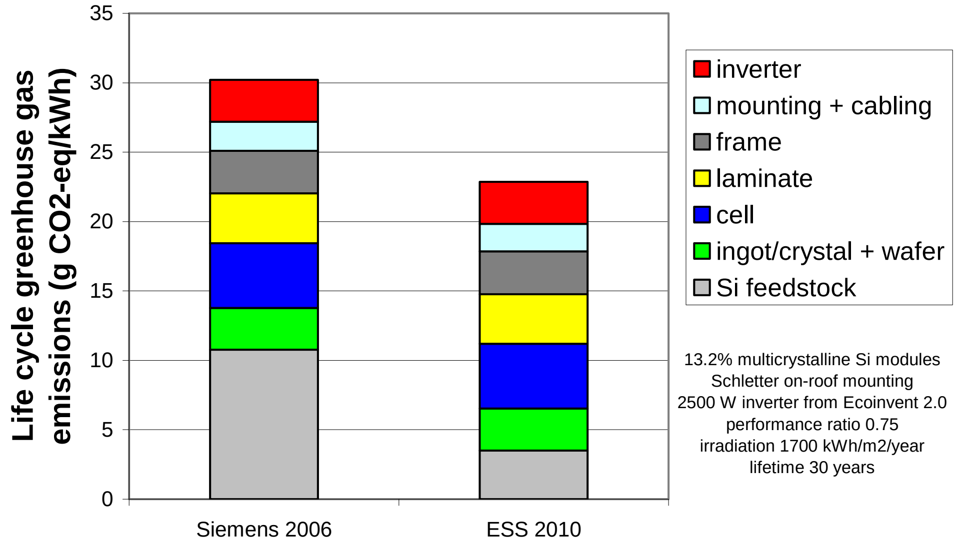

Figure 7. Life cycle greenhouse gas emissions comparison between conventional gas route to SoG-Si (Siemens 2006 [1]) and ESS (ESS 2010).

EPBT for multicrystalline silicon PV systems installed in Southern Europe are 1.6 and 1.1 years for Siemens type processes and ESS, respectively. The contribution from feedstock production is through the Elkem Solar metallurgical route reduced to a fraction comparable in size to the other process stages. Feedstock contribution to the EPBT is more than 3 times lower for ESS than for conventional technology.

Life cycle greenhouse gas emissions (GWP100) of multicrystalline silicon PV systems installed in Southern Europe are 30 and 23 g CO_2-eq / kWh based on Siemens type processes and ESS, respectively. As for the EPBT, contribution from feedstock production is comparable to contributions stemming from the other process stages and more than 3 times lower than for conventional gas route processes.

Future outlook

The results from the present paper should be regarded as preliminary and will be continuously updated as operational experience is gained from the industrial plant. There is improvement potential for the Elkem Solar production with regards to readily available energy recovery options, side – stream product definitions and energy efficiency and yield improvements as beyond 2010.

A more detailed LCA comparison of EPBT and environmental impacts of ESS with SoG – Si produced from conventional and improved gas route processes will be published at the 23rd European PV Solar Energy Conference in Sevilla - Spain [[6]].

Acknowledgements

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