LCA COMPARISON OF THE ELKEM SOLAR METALLURGICAL ROUTE AND CONVENTIONAL GAS ROUTES TO SOLAR SILICON

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ABSTRACT: Preliminary Environmental Life Cycle Assessment of solar grade silicon production via gas- and metallurgical route indicates that environmental impacts can be reduced by:

- making efficient use of the metallurgical silicon,
- installing waste heat recovery systems,
- using a clean source of electricity.

The metallurgical route has the advantage of a lower energy consumption compared to the traditional routes with purification via the gas phase resulting in lower environmental impacts.

Keywords: environmental effect, silicon

1 INTRODUCTION

Polycrystalline silicon can be produced with different purities. Electronic grade silicon has the highest purity and is used to grow Czochralski monocrystalline silicon crystals for the semiconductor and solar industry. This high purity silicon requires more energy for purification than the lower purity solar grade silicon which is used to grow multicrystalline ingots or ribbons. The advantage of the monocrystalline silicon is that it results in higher efficiency modules compared to the multicrystalline silicon. The silicon is produced by reducing quartz (silicon dioxide) by difference carbon sources at high temperature. The carbon dioxide produced is emitted to the environment. The purification to make silicon with enough purity to make solar cells can be done at different ways. The traditional route is further purification of the metallurgical grade silicon via the energy intensive distillation of chlorosilanes in the gas phase and deposition of pure silicon. Because the photovoltaic industry is able to use silicon of less purity than the semiconductor industry these steps have been modified to consume less energy. Distillation can be carried out more relaxed and the deposition can be done in a fluidized bed reactor (FBR) instead of a Siemens type reactor. Another possibility is further purification via the metallurgical route producing so-called upgraded metallurgical silicon (UMG-Si).

In this paper the environmental impacts of the production of solar grade silicon via gas phase purification and deposition in Siemens type reactor is compared with purification via the metallurgical route. It is a refinement of the work presented in [1,2]. For the gas routes the recovery of waste heat is included now and the mass flow has been estimated. A general flow diagram for the production of solar grade silicon is given in figure 1.

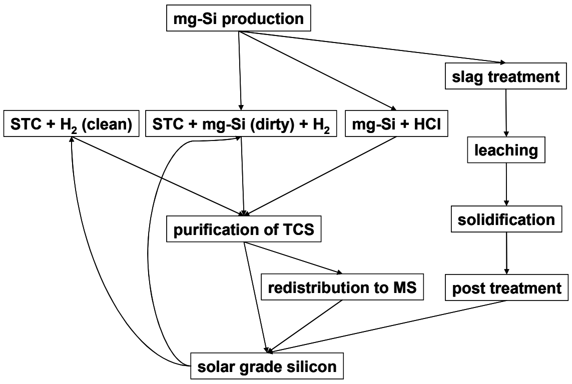

Figure 1 Different production routes for solar grade silicon as analyzed in this study
mg-Si = metallurgical grade silicon,
TCS = Trichlorosilane $SiHCl_3$,
STC = Silicontetrachloride $SiCl_4$,
MS = Monosilane SiH_4.

2 METHODOLOGY

2.1 Data collection

The energy- and materials input and output have been estimated based on process descriptions available in the open literature. These data have been used to calculate the environmental impacts.

2.2 Environmental impact assessment

The environmental impacts are determined using the method of life cycle assessment (ISO 14040 series) using the software Simapro 7.1.8 and ecoinvent 2.0 database.

The energy payback time is calculated by using the Cumulative Energy Demand method version 1.04. The life-cycle greenhouse gas emissions (carbon footprint) are calculated using the IPCC2007 GWP100a values. The following roof-top grid-connected photovoltaic system is assumed to be produced:

- multicrystalline silicon PV modules with 13.2% module efficiency
- 2500 W inverter Ecoinvent 2.0

- Schletter on-roof mounting
- cabling

The system is supposed to be installed in Southern Europe with in-plane solar irradiation of 1700 kWh/m^2.yr and a performance ratio of 0.75.

3 METALLURGICAL SILICON PRODUCTION

The fossil and biogenic carbon dioxide emissions in the ecoinvent 2.0 data for the production of metallurgical silicon have been modified from 3.58 kg and 1.61 kg to 4.65 kg and 3.25 kg using data from [3, table 4.10] for the emissions factors of the different carbon sources used in the production of silicon metal.

4 POLYSILICON PRODUCTION VIA THE GAS ROUTE

Polysilicon is typically produced by the decomposition of trichlorosilane or monosilane. So the first step is to manufacture trichlorosilane by reaction with hydrochloric acid and/or recycled silicon tetrachloride. Then the trichlorosilane is purified after which deposition of polysilicon can take place on rods or on fluidized beads. It is also possible to produce monosilane from trichlorosilane and decompose this to polysilicon.

The following is included in the analysis of the gas routes:

- Products solar grade silicon (and fumed silica)
- Material consumption of all the process steps
- Electricity consumption of all the process steps (see figure 2)
- On-site waste treatment of silane slurry
- Energy recovery (see figure 2).

The following is *not* included in the analysis of the gas routes:

- Emissions from the factory
- Landfill of inert waste solids
- Transport
- Capital goods (production equipment, building hall, etc)
- Packaging of the product

In the case the byproduct fumed silica is generated, the environmental burden of the process is presently almost completely allocated to the solar grade silicon because we assume a very low price of fumed silicon. In future work a better price allocation is needed.

5 POLYSILICON PRODUCTION VIA METALLURGICAL ROUTE

The steps are:

- metallurgical grade silicon production,
- slag treatment,
- leaching,
- directional solidification,
- post-treatment.

Elkem Solar has planned to recover waste heat (15% of the total electricity consumption) and deliver this to the city of Kristiansand.

The following is included in the analysis:

- products: Elkem Solar Silicon plus sidestreams (economic allocation),
- material- and electricity consumption of all the process steps (see figure 2),
- 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 (to inert landfill),
- transport of raw materials and waste to/from the production location in Kristiansand.

The following is *not* included in the analysis:

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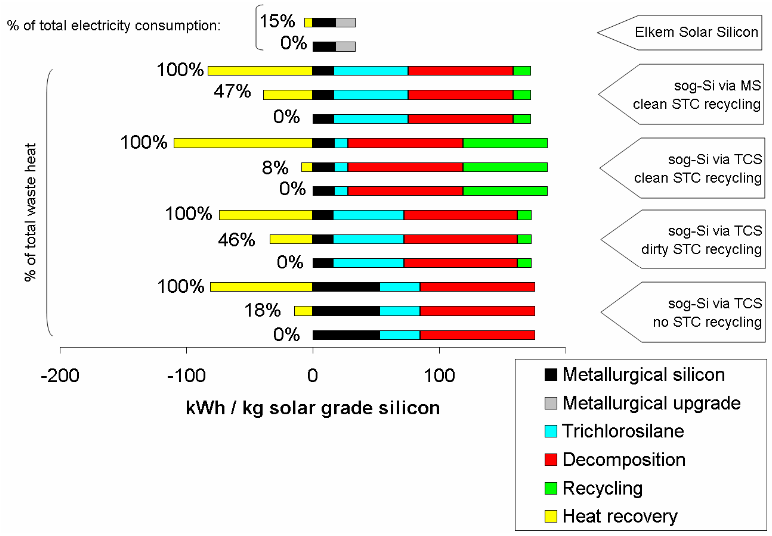

Figure 2 Energy consumption for the production of solar grade silicon via different routes with different percentages of recovered waste heat (no waste heat recovery=0%, with only internal use of waste heat, with internal + external use of waste heat=100%). The 100% waste heat recovery is not achievable in practice.

6 ENERGY PAYBACK TIME

The Cumulative Energy Demand is the total primary energy consumption over the whole life cycle and it is given in figure 3.

Energy payback time for a PV system using Elkem Solar Silicon is given in figure 4.

7 GREENHOUSE GAS EMISSIONS

The life-cycle greenhouse gas emissions are given in figure 5. Elkem Solar Silicon has direct emissions of carbon dioxide meaning that the emissions will be from their factory directly. The emissions of carbon dioxide in the other technologies are included in the mg-Si production and are therefore indirect.

Figure 6 shows the life-cycle greenhouse gas emissions of Elkem Solar Silicon with sensitivity to the electricity mix used. The Norwegian electricity mix is largely based on hydropower with life-cycle greenhouse gas emissions of only 12 grams CO_2-eq emissions / kWh produced. If the plant would be operated using the European UCTE electricity mix the carbon footprint would be much higher because the UCTE mix has a higher greenhouse gas emissions of 530 grams CO_2-eq emissions / kWh produced.

8 PERFORMANCE

Unblended (100%) Elkem Solar Silicon is suitable for application in solar cells [4, 5].

9 CONCLUSIONS

Preliminary Environmental Life Cycle Assessment of solar grade silicon production via gas- and metallurgical route indicates that environmental impacts can be reduced by:

- making efficient use of the metallurgical silicon,
- installing waste heat recovery systems,
- using a clean source of electricity.

The metallurgical route has the advantage of a lower energy consumption compared to the traditional routes with purification via the gas phase resulting in lower environmental impacts.

Future work:

- Update ecoinvent 2.0 metallurgical grade silicon production:
    - include microsilica as by-product
    - refine CO_2 emissions
    - include emissions of Polycyclic Aromatic Hydrocarbons (PAHs) and dioxin
- Fill the data gaps as described in paragraphs 4 and 5
- Add monosilane FBR route
- Refine data Elkem Solar when production is on-line
- Include other environmental impacts in the analysis

10 ACKNOWLEDGEMENTS

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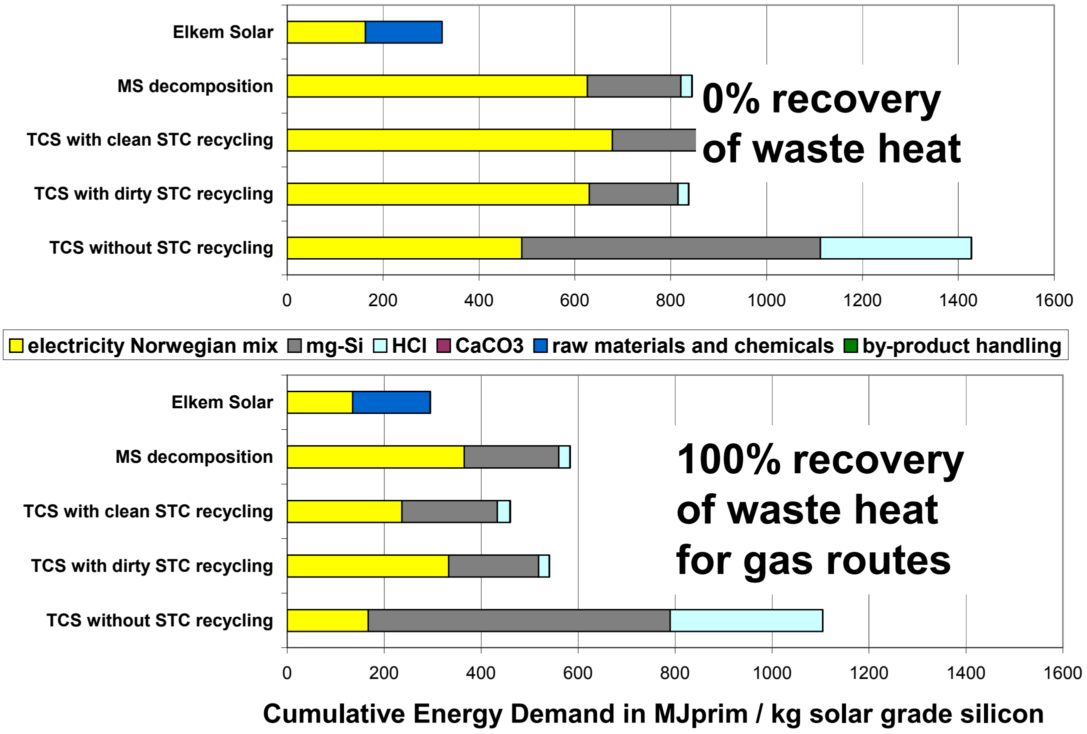

Figure 3 Cumulative Energy Demand for the production of solar grade silicon from different routes.

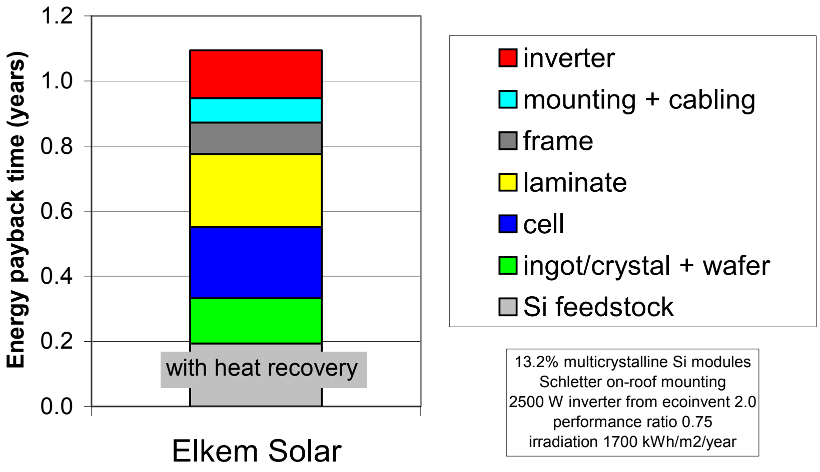

Figure 4 Energy payback time for the production of crystalline silicon PV systems using Elkem Solar Silicon (recovered heat is 15% of the total energy consumption)

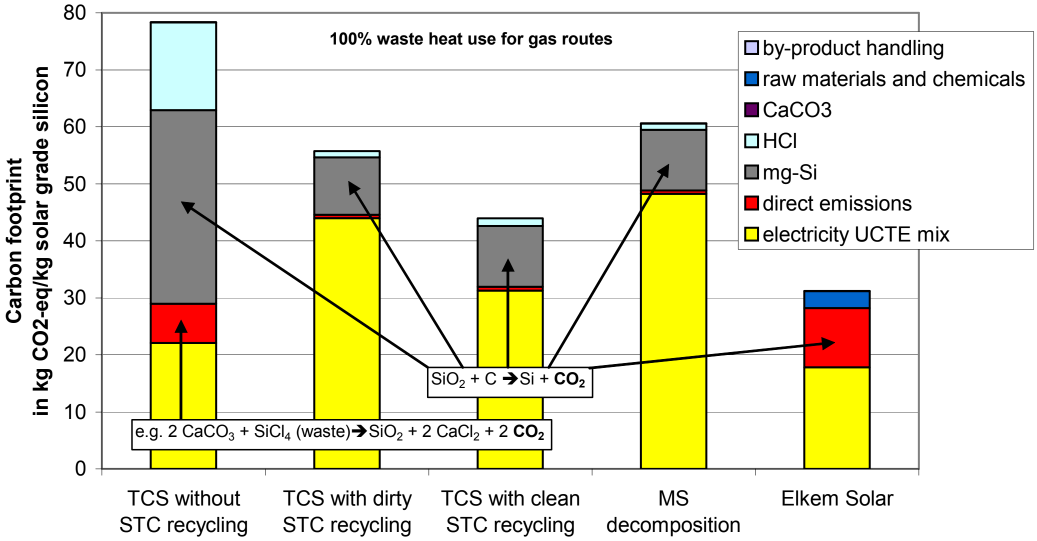

Figure 5 Greenhouse gas emissions for the production of solar grade silicon from different routes with Norwegian electricity mix using the IPCC2007 GWP100a impact assessment method.

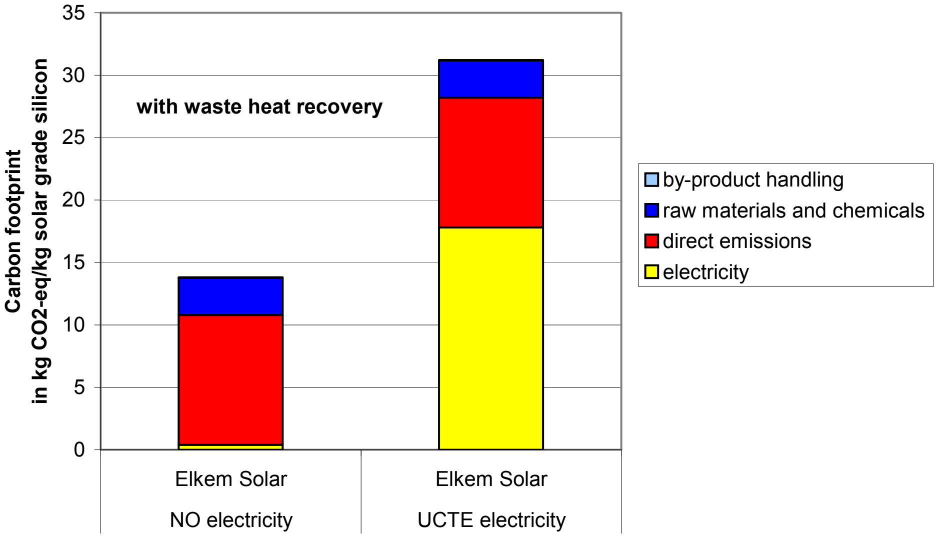

Figure 6 Life-cycle greenhouse gas emissions of Elkem Solar Silicon with sensitivity to the electricity mix used