Life cycle analysis of modules: A multicrystalline silicon case study

Trond Westgaard, Renewable Energy Corporation, Sandvika, Norway, & **Carol Olson** & **Ton Veltkamp**, Energy Research Centre of the Netherlands, Petten, The Netherlands

ABSTRACT

The improved performance and reduced manufacturing costs of photovoltaic (PV) modules that have been achieved in recent years have positioned this technology as an economically attractive renewable electric energy source. In order to verify that this also has a positive impact on energy payback time (EPBT) and carbon footprint, the Energy Research Centre of the Netherlands (ECN) has conducted a life cycle analysis (LCA) for REC Peak Energy-series PV modules produced by Renewable Energy Corporation (REC). The LCA study was based on a full set of actual production data obtained for the first quarter of 2011 from REC's manufacturing sites. Because REC is an integrated manufacturer, the LCA study includes internal data for the production steps from polysilicon production to module assembly, as well as for all materials and transportation associated with production. ECN used generic figures for installation, operations and recycling together with the REC data to assess the environmental impact indicators. For polysilicon produced in the USA, and for wafers, cells and modules produced in Singapore, an EPBT of 1.2 years was achieved, with a corresponding carbon footprint of 21g CO_2-eq/kWh for PV systems located in southern Europe (1700kWh/m² · year irradiation). For modules with wafers and cells produced in Norway, the corresponding values were 1.1 years and 18g CO_2-eq/kWh. A key contributor in achieving these values is REC's highly efficient fluidized bed reactor (FBR) process for the production of polysilicon.

Background

Photovoltaic modules convert absorbed energy from sunlight directly into electricity. In this sense, PV technology represents an effective way of producing clean electric energy from a renewable source. PV power plants can produce electricity for decades with minimal energy consumption and without carbon dioxide emissions. However, there is direct energy consumption associated with the production and installation of PV systems, and there is indirect energy consumption associated with the materials that are used. This energy consumption leads to associated carbon dioxide emissions. A complete life cycle analysis (LCA), or life cycle assessment, also considers these factors during the operations period and in the dismantling and recycling phases of PV power plants.

The total energy consumption associated with PV system manufacturing is used to calculate the energy payback time (EPBT). This refers to the time a PV system has to operate after installation before it has produced the amount of electricity corresponding to the energy used to produce, install and finally recycle its components. The calculation is done for a typical installation at a specific location. The energy mix used for the supply of electricity to the grid has to be considered at production locations and at the location where the PV system is installed. The carbon footprint is calculated for the assumed lifetime of the installation.

In a recent article by van der Meulen [1], PV module customer awareness of PV's carbon footprint is discussed. Although the general impression is that module manufacturers are not yet active in documenting the carbon footprint, this is actually important for PV manufacturers. Documentation of low energy consumption and low carbon footprint is crucial for maintaining support from the public and regulators for PV as a technology that provides clean electricity. Some markets already have a strong awareness of environmental issues: an example of this is France, where there are regulations in place that provide incentives for commercial systems using PV modules from suppliers that document the modules' environmental impact.

An integrated manufacturer such as REC monitors consumption and emissions starting from polysilicon production, through wafer, cell and module manufacturing, and ending with the final recycling of the modules. The value chain is based on primary materials, which makes it possible to establish a reliable value for the environmental impact of the technology. A primary material is a material that is not a by-product of the production of other materials. (LCAs for other PV manufacturers that use, for example, discarded PV cells or secondary metals need to correctly represent the impacts of the primary activities, such as cell production or mining and refining of the associated primary metals.)

LCA methodology

An LCA evaluates the environmental impact of a product (or service) from the first associated production phase to the recycling phase. The international standard ISO14040 describes the general principles and framework for LCAs. A set of more specific methodology guidelines on life cycle assessment of photovoltaic electricity has been published by the International Energy Agency [2]. These guidelines were used for the present LCA study. A complete data set for consumption factors and emissions has to be collected from the value chain under consideration. These data are then processed to obtain the LCA metrics. ECN uses the software SimaPro 7.2.4 [3] combined with the ecoinvent 2.2 database [4]. This database contains data associated with energy supply and data for externally supplied materials.

Since ECN uses the ecoinvent database, the ecoinvent methodology is used in order to maintain internal consistency. For example, when a PV module is recycled and aluminium from the module frame is going to recycling, no credits are obtained for the avoidance of the production of primary aluminium. The credits are obtained at the moment the aluminium is consumed in the manufacturing of the module (20% primary Al, 47% secondary Al from new scrap, 33% secondary Al from old scrap).

Energy payback time

The *energy payback time* is the time needed for the PV system to generate the amount of electric energy that replaces the amount of primary energy required to produce it (Equation 1).

The energy input is calculated using the 'cumulative energy demand' (CED) method, which is the total life cycle primary energy consumption. In this study the CED 1.07 method is used as implemented in SimaPro. The efficiency of the electricity supply used in the calculation is 11.4$MJ_{primary}$/kWh (UCTE electricity mix).

Energy payback time is a metric that is easy to relate to, but it is important to note that it does not consider the system lifetime. Reliable PV systems with long lifetimes represent an important aspect of PV as a viable source of renewable energy.

Carbon footprint

The *carbon footprint* is obtained from the LCA by considering all emissions that have an effect on climate change. It is quantified using the global warming potential (GWP) index. The Intergovernmental Panel on Climate Change (IPCC) has defined the GWP100a index as the relative effect of a greenhouse gas in terms of climate change over a fixed time period of 100 years and is expressed as carbon dioxide equivalents (CO_2-equivalents). ECN uses the IPCC2007 GWP100a method version 1.02 as it is implemented in SimaPro. Standardization of carbon footprinting is described by the SETAC Europe LCA Steering Committee [5]. The most relevant metric for renewable electricity sources is the total GWP of the PV system divided by the total electricity production of the system during its lifetime (Equation 2).

"An LCA has to consider both the consumption of energy and materials involved in its production and the actual electricity production during its lifetime."

This metric allows the low carbon footprints of renewable electric energy sources to be compared to the carbon footprints of electricity produced in coal- or gas-fired power plants. A particularly favourable situation occurs when renewable energy, such as hydroelectricity, is used in the manufacture of PV products.

System considered and collection of production data

Since a PV module is intended to produce electricity, an LCA has to consider both the consumption of energy and materials involved in its production and the actual electricity production during its lifetime. The PV system analyzed is a multicrystalline silicon photovoltaic system using REC Peak Energy-series modules of dimensions 1665mm × 991mm (area 1.65m^2). One module is made up of 6 × 10 solar cells of size 156mm × 156mm. The considered PV system is an on-roof installation in southern Europe (or a location with equivalent conditions), having an in-plane irradiation of 1700kWh/m^2 · year and a system performance ratio of 0.84. This performance ratio was demonstrated in tests performed in 2010 in San Luis Obispo, California, which is a location with conditions very close to the considered case. Tests performed by *Photon* magazine show a higher performance ratio for this module type, but these results do not include energy loss in the inverters [6]. A generic data set obtained by ECN is used for installation materials, inverters and end-of-life recycling of the PV modules. The lifetime of the system is assumed to be 30 years. During operation of the PV system, it is taken into account that the inverters will be replaced after 15 years of operation, which is considered realistic for present inverter technology.

The LCA is performed with actual production data for the first quarter of 2011 from REC manufacturing sites in the USA, Norway and Singapore. This ensures that real values for production output, yield factors and waste streams are considered. For each production site the energy mix associated with electricity consumption is the actual mix for the production site. REC's manufacturing sites use predominantly hydroelectricity and electricity generated from the combustion of natural gas. The transportation distances between the USA, Norway and Singapore were calculated using on-line logistics calculators for freight transport by sea and land, as it actually took place. Average transport distances were used for shipping of materials from European countries to Norway. Transport of module materials

$$\text{Energy payback time} = \frac{\text{Primary energy input}}{\text{Replaced primary energy relating to the electric energy output per year}}$$

Equation 1.

$$\text{Carbon footprint} = \frac{\text{Emissions (g } CO_2\text{-equivalents)}}{\text{Total electric energy production over lifetime (in kWh)}}$$

Equation 2.

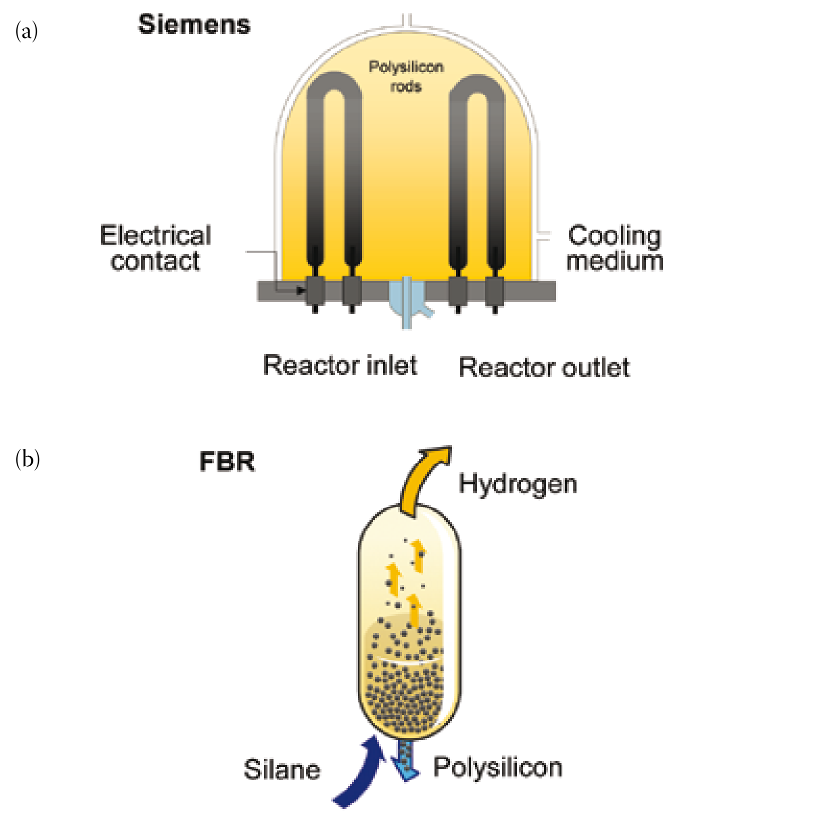

Figure 1. Schematic of the principles of (a) a Siemens polysilicon reactor, and (b) a fluidized bed reactor (FBR) for polysilicon production.

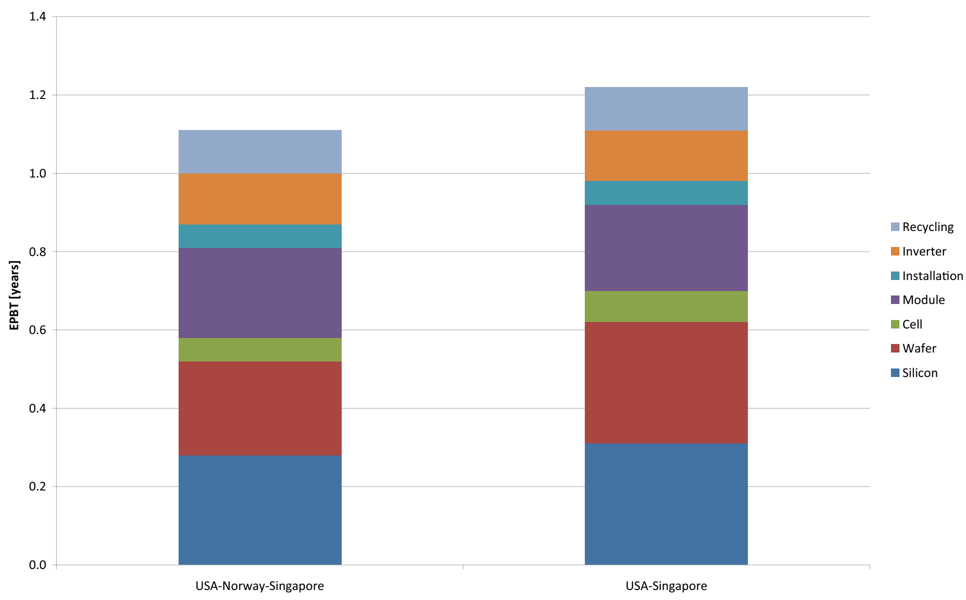

Figure 2. Energy payback time (EPBT) of on-roof PV systems with REC modules installed at a location in southern Europe (1700kWh/m^2 · year irradiation).

from Tokyo to Singapore was used as an average estimate of the transport of components from suppliers located in Southeast Asia to Singapore.

Data for polysilicon production were obtained from the manufacturing units in Moses Lake, Washington, USA. These units produce semiconductor-grade silane gas from metallurgical-grade silicon. The silane gas is converted into polysilicon in conventional Siemens-type reactors and in fluidized bed reactors (FBRs). The principles of these two processes are illustrated in Fig. 1. The direct energy consumption for the FBR process is approximately 80% lower than the classical Siemens process via the silane route. The electricity consumption reduction associated with the FBR process is even more distinct.

Multicrystalline silicon wafer production data are collected from the REC production sites in Herøya, Norway, and in Singapore. There are only minor differences in consumption data between these sites. However, the energy mix for electricity in Norway is mainly hydroelectricity, while electricity in Singapore is produced from natural gas. The granular form factor of FBR polysilicon enables up to 29% higher silicon charges in the ingot-casting process when blended with polysilicon from the Siemens process than when conventionally charged with polysilicon chunks. The LCA is based on the actual blend of FBR and Siemens polysilicon that was used by REC.

In the period considered in the LCA, REC produced solar cells in Narvik, Norway, and in Singapore. These sites also had equivalent consumption data, but with the same difference in electricity supply as for wafer production. PV modules were manufactured in REC's automated module assembly unit in Singapore.

LCA results

The analysis is based on data from two production flows within REC. One is based on wafer and cell production at Norwegian locations, with module assembly in Singapore: a PV module from this value chain has a cumulative energy demand of 13.0MJ/W_p and a carbon footprint of 570g CO_2-eq/W_p. The other production flow is for the integrated wafer, cell and module production at the Singapore site, with corresponding values for cumulative energy demand of 15.2MJ/W_p and a carbon footprint of 726g CO_2-eq/W_p. Both production flows include polysilicon from the Moses Lake production facility. The major difference between these two production flows is that the first is based on electricity from a renewable source (hydroelectricity), while the second is based on electricity produced by the combustion of natural gas.

These LCA results are easier to relate to when the complete system is considered. Fig. 2 shows energy consumption related to energy production, reported as energy payback time. It is seen that the energy payback time including recycling is just above one year, and it can in fact be brought down below one year by using 100% FBR polysilicon. (In order to have optimal silicon charging of crucibles it is practical to run with a blend of polysilicon feedstock.) Polysilicon feedstock is an important (but not dominating) part of the energy consumption. Ingot casting and wafer production contribute to roughly the same extent. The results show a distinct advantage in using renewable electric energy for production of wafers (including ingot production) and cells over using electricity from natural gas. This advantage would be even larger if a comparison were made with potential production based on electricity from coal-fired power plants. Although the impact of cell production appears minor, high cell efficiencies reduce the impact of all other factors.

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The same issues are reflected among the factors contributing to the carbon footprint shown in Fig. 3. The polysilicon feedstock contribution to the carbon footprint is relatively small compared to the total carbon footprint, which ranges from 18 to 21g CO_2-eq/kWh. The difference in relative impact between wafer production (including ingot production) in the two value chains is even more pronounced for carbon footprint than it is for energy consumption. It is also evident that the contributions from installation and recycling are important. Continued improvements in module efficiency are an effective way of further reducing these contributions.

Conclusions and outlook

ECN and REC's LCA study of PV modules with multicrystalline silicon cells shows that both module production value chains – one based on hydroelectricity and the other on electricity generated from natural gas – result in systems with environmental impacts at the lowest end of the range

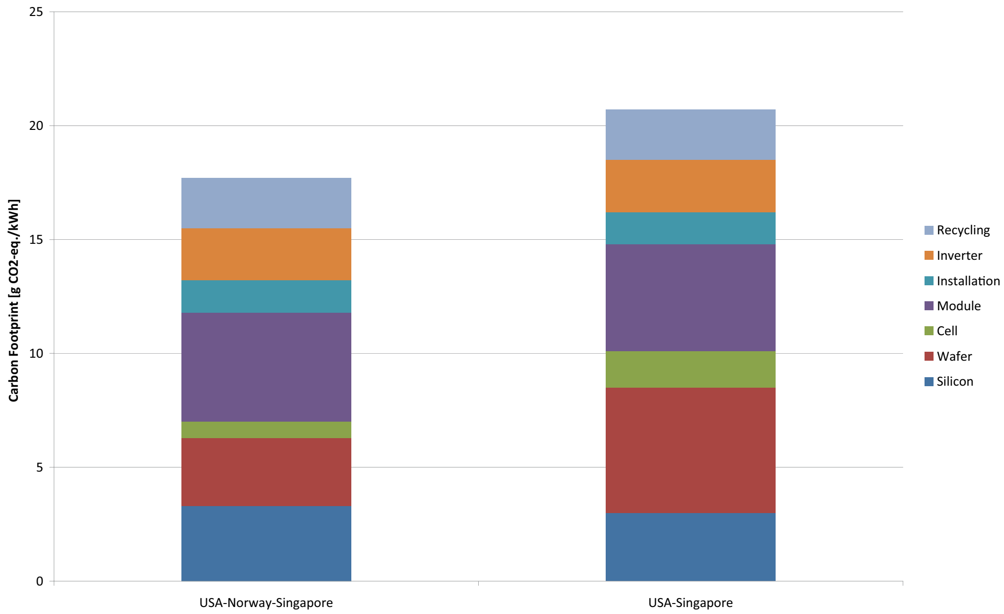

Figure 3. Life cycle greenhouse gas emissions (carbon footprint) per kWh of electricity produced for REC PV systems installed at a location in southern Europe (1700kWh/m^2 · year irradiation, with system lifetime of 30 years).

indicated in van der Meulen [1], with energy payback times just above one year and carbon footprints of approximately 20g CO_2-eq/kWh. There is a distinct advantage in using a renewable electricity source, but both value chains have enormous advantages over electricity from fossil fuel-based power plants. For reference, the carbon footprint of electricity from natural gas is 330–440g CO_2-eq/kWh, and electricity from coal-fired power plants has a considerably higher value of 670–1000g CO_2-eq/kWh [7,8].

Further reductions of the environmental impact are imminent: PV modules with higher conversion efficiency due to increases in cell efficiency will reduce the impacts of all factors along the value chain. The PV industry is also continuously striving to reduce energy consumption and therefore costs by using more efficient production methods.

References

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About the Authors

Trond Westgaard holds a Dr. ing. degree in semiconductor physics from the Norwegian University of Science and Technology, Trondheim. He is currently Vice President of Technology at Renewable Energy Corporation ASA, based in Sandvika, Norway, where his primary tasks are development strategies and benchmarking of PV products. Before joining REC in 2008, Dr. Westgaard worked on development of silicon-based detectors and MEMS sensors.

Carol Olson received a Ph.D. in physics from Imperial College, London, in 2003. After joining ECN in 2006, she carried out research in the areas of thin-film photovoltaics and characterization of silicon solar cells. Currently, Dr. Olson is a project manager of projects relating to life cycle assessment of photovoltaic products and processing lines, as well as those relating to cost and sustainability of photovoltaics.

Ton Veltkamp obtained his Ph.D. in chemistry at the Free University of Amsterdam in 1989. He worked as a research scientist in environmental chemistry at ECN from 1989 to 1990, after which he managed various research laboratories at NRG and ECN, then later joined ECN Solar Energy as manager of the thin-film photovoltaics group. Since 2008, Dr Veltkamp has been the manager of the crystalline silicon photovoltaics manufacturing technology group at ECN, where he is responsible for the environmental assessment studies of photovoltaic technologies. He is a member of the EPIA sustainability working group and a member of the IEA-PVPS Task 12 working group that deals with PV environmental health and safety activities.

Enquiries

Renewable Energy Corporation ASA
Kjørboveien 29
PO Box 594
NO-1302 Sandvika
Norway
Email: post@RECGroup.com

Energy Research Centre of the Netherlands
P.O. Box 1
1755 ZG Petten
The Netherlands