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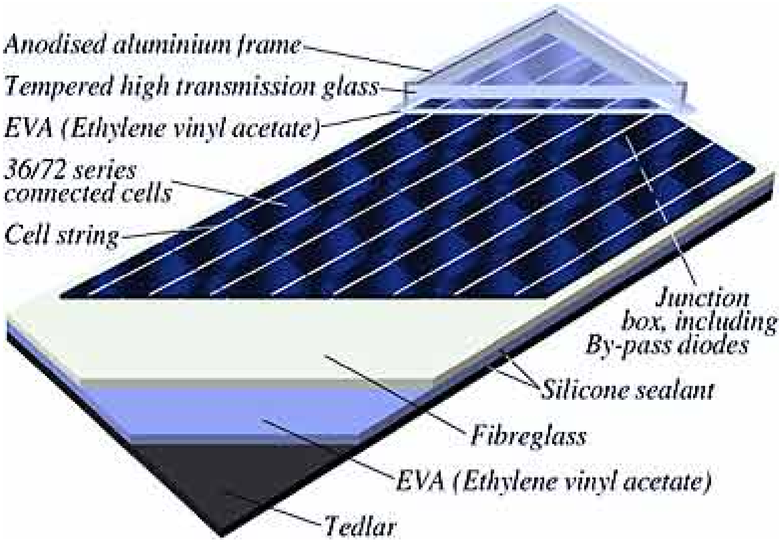
Thematic Research Report on Environmental Issues

WP 3/ Task 2



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PV-NORD - Widespread Exploitation of Building Integrated Photovoltaics in the Northern Dimension of the European Union
5th FW Contract no. NNE5/2001/264
European Commission, DG Energy & Transport

Contents

Abstract

This report provides an overview of lessons learned regarding the environmental sustainability of solar cells used in PV- Nord buildings and the evaluation of the impact of solar cells chemicals on human health and the environment.

The building owner's environmental considerations for adding PV to PV-Nord demonstration buildings were associated to the use of renewable energy sources. Two of the buildings demonstrated different kinds of environmental and sustainable issues e.g. energy and raw materials used in the manufacturing process, used chemicals, maintenance and recycling aspects for used PV components. Nevertheless, only one building owner required a separate environmental declaration for the PV system from the supplier.

In general, there is a lack of environmental knowledge when dealing with PV among the PV-Nord design teams and the building owners. The production of used PV-system involves a chain of suppliers e.g. raw material and chemicals suppliers, solar cells and modules manufacturers in different countries. Multicrystalline/polycrystalline silicon solar cells are commonly used in PV-Nord buildings. Information on chemicals used during the manufacturing processes of PV modules and the content in finished articles were provided by one of suppliers and discussed within the project team. A literature survey was conducted in order to increase the credibility of the information obtained from PV suppliers and study the outcome of environmental assessment of solar cells used in PV-Nord buildings.

As other building materials, PV-system requires energy and involves the use of different chemicals during the manufacturing process. The primary environmental related health concern of silicon cells is associated with the use of toxic gases such as arsine and phosphine; fluorinated compounds (fluorine and fluorides) and organic solvents during the manufacturing process. The energy consumed during the manufacturing process pays back after 4-5 years of the PV modules expected service life of 25-30 years. The maintenance of PV-system rarely requires detergents and no emissions occur except in case of fire or explosion. An important aspect to be taken into account in the maintenance of PV-systems is the fact that in case of a defect solar cell in a PV module, the entire module has to be changed. Extra modules should be stored when using special customer designed modules.

The use of PV-systems is relatively new in Northern Europe and there is no experience of handling used PV modules. However a pilot recycling plant is now available in Germany, which means future recycling opportunities for PV-modules from Northern countries.

List of abbreviations

a-Si	amorphous Silicon
BIPV	Building Integrated PV
CdTe	Cadmium Telluride A polycrystalline thin-film photovoltaic material.
CEC	California Energy Commission
CIS	Copper Indium Selenide
c-Si	crystalline Silicon
EPBT	Energy Pay-Back Time
EPRI	Electric Power Research Institute
HSE	Health, Safety and Environment
IEA	International Energy Agency
LCA	Life Cycle Assessment
mc-Si	multicrystalline Silicon
Novem	Netherlands Organization for Energy and the Environment
NREL	National Renewable Energy Laboratory
PCB	Polychlorinated Biphenyls
PV	photovoltaic
PVPS	Photovoltaic Power Systems

Glossary

Array	Any number of electrically connected photovoltaic (PV) modules providing a single electrical output.
Arsine	A colorless highly toxic gas. Arsine has a garlic-like or fishy odor. CAS-nr 7784-42-1. Synonyms: arsenic hydride, arsenic trihydride, and hydrogen arsenide.
Crystalline Silicon	A type of photovoltaic cell made from a slice of single crystal silicon or polycrystalline/multicrystalline silicon.
Diode	An electronic device that allows current to flow in one direction only.
Dopant	A chemical element (impurity) added in small amounts to an otherwise pure semiconductor material to modify the electrical properties of the material. E.g phosphorous in silicon.
Efficiency	The ratio of output power (or energy) to input power (or energy). Expressed in percent.
Grid	Term used to describe a utility's electricity distribution network.
Inverter	Electric device that converts direct current (DC) electricity into alternating current (AC)
Life-Cycle Cost	The estimated cost of owning and operating a Photovoltaic (PV) System for the period of its useful life.
Multicrystalline/poly crystalline	A semiconductor photovoltaic material composed of variously oriented small individual crystals.
Multicrystalline/poly crystalline Silicon	A material used to make photovoltaic cells, which consist of many crystals unlike of single crystal silicon.
N-Type Silicon	Silicon material that has been doped with a material that has more electrons in its atomic structure than silicon does.

Parallel Connection	A way of joining photovoltaic cells or modules by connecting positive terminals together and negative terminals together. Increases the current at the same voltage
Phosphine	A colorless, flammable, and explosive gas at ambient temperature that has the odor of garlic or decaying fish. CAS-nr 7803-51-2. Synonyms: hydrogen phosphide, phosphorus hydride, phosphorus trihydride, and phosphoretted hydrogen.
Photovoltaic (PV) Array	An interconnected system of PV modules that function as a single electricity-producing unit. The modules are assembled as a discrete structure, with common support or mounting. In smaller systems, an array can consist of a single module.
Photovoltaic (PV) Module	The smallest environmentally protected, essentially planar assembly of solar cells and ancillary parts, such as interconnections, terminals, and protective devices such as diodes intended to generate direct current power under unconcentrated sunlight.
Photovoltaic (PV) System	A complete set of components for converting sunlight into electricity by the photovoltaic process, including the array and balance system components.
Ribbon (Photovoltaic) Cells	A type of photovoltaic device made in a continuous process of pulling material from a molten bath of photovoltaic material, such as silicon, to form a thin sheet of material.
Semiconductor	Any material, that has a limited capacity for conducting an electric current. Silicon, galium arsenide, copper indium diselenide and cadmium telluride are semiconductors.
Series Connection	A way of joining photovoltaic cells by connecting positive terminals to negative terminals. Increases the voltage while the current remains the same.
Silicon (Si)	A semi-metallic chemical element that makes an excellent semiconductor material for photovoltaic devices. It crystallizes in face-centered cubic lattice like a diamond. It is commonly found in sand and quartz as the oxide.

Single-Crystal Silicon	Material with a single crystalline formation.
Thin Film	A layer of semiconductor material, such as copper indium diselenide or galium arsenide, a few microns or less in thickness, used to make photovoltaic cells.
Thin Film Photovoltaic Module	A photovoltaic module constructed with sequential layers of thin film semiconductor materials
Tin Oxide	A wide band-gap semiconductor similar used in heterojunction solar cells or to make a transparent conductive film. Heterojunction is a region of electrical contact between two different materials.

1 Introduction

1.1 Background

Building owners have to comply with several legal requirements addressing the working environment, the living environment as well as the disposal of used building materials. The presence of a particular chemical substance in long life building materials may at the end of the life period represent a problem, particularly when our knowledge about the hazardous properties and risks has increased over time. The most well known example is the uses of PCB in building and electric components, which have caused immense costs to the building owners.

The building owners responsibilities cannot be fulfilled satisfactory in the absence of information about the chemical contents of the building materials they use and the information about the safety measures needed to minimise potential risks. Recycling and/or waste management actors may also face problem costs because of lack of information on the chemical contents of waste from building demolition.

The concept of Building Integrated PV (BIPV) means that solar cells are considered as an energy source and a building component similar to e.g. roof tiles, bricks or concrete. At present, there is no obligation for the supplier of articles (non-chemical products) to provide information to customers about chemical constituents. Many professional users of articles make efforts trying to get information from suppliers on chemical constituents that may be of concern. Northern countries have developed guidelines for building material declarations but the use of PV is limited and relatively new, such environmental declaration does not exist.

1.2 Objectives

Against this background, the particular aim of this task is to identify solar cells types used in the PV-Nord demonstration buildings and investigate chemicals used during the manufacturing of solar cells and in the final products.
The general purpose is to analyse and evaluate the PV-Nord building's qualities in terms of environmental sustainability and evaluate the impact of solar cell chemicals on human health and the environment in the Northern Dimension.
The overall purpose is to contribute to increase the environmental knowledge on solar cells as a building component.

1.3 Approach

A questionnaire was developed and distributed among the owners of the eight PV-Nord demonstration buildings. The aim of the questionnaire was to investigate the environmental considerations taken into account for adding PV in buildings and the knowledge on environmental aspects of solar cells considered as building components.

A visit was made to a PV module manufacturing plant. Information on chemicals used during the manufacturing processes and the chemical constituents of solar cells and modules were required from the PV supplier. The provided data was discussed with other suppliers in the project team to make a general environmental analysis of the PV-Nord demonstration buildings.
A literature survey was conducted in order to increase the credibility of the information from PV suppliers and study the outcome of environmental assessment of solar cells used in PV-Nord buildings.

1.4 Limitations

A product may be either a material or a service focused on the function provided. To evaluate the potential environmental impact of a product over its entire lifetime includes the inventory of material and energy flows from raw materials acquisition through manufacturing, use and final disposal and the assessment of the impacts of such flows. The impact of chemical substance on human health and the environment depend primary on how hazardous the substance is. Secondary on how much is emitted and in what quantities, the concentrations does it reach an environment compartment (air, water and ground) where it can exert its effect and the intensity, frequency and duration of human exposure.

In the PV-Nord project no quantitative data were available on materials, energy flows, chemicals used during the manufacturing process, the released emissions and the chemicals constituents of solar cells or modules. This means difficulties to evaluate the impact of used solar cell chemicals on human health and the environment. Consequently, the assessment carried out in this study is mostly of qualitative nature and mainly based on literature studies. The report is only related to the type of solar cells used in the PV-Nord demonstration building and describes solar cells as building components and an energy source.

2 Photovoltaic Cells and Modules

2.1 General issues

2.1.1 Type of solar cells

Photovoltaic energy is the conversion of sunlight into electricity, through a photovoltaic (PV) cells or solar cell. Solar cells are composed of various semiconducting materials such as silicon, galium arsenide, copper indium diselenide and cadmium telluride. The three main types of solar cells are monocrystalline or single crystalline silicon (α-Si), polycrystalline or multicrystalline silicon (m-Si or p-Si) and thin film. The PV cell market is dominated by silicon based cells. Some of available thin film cells are amorphous silicon (a-Si) silicon commonly, cadmium telluride (CdTe), galium arsenide (GaAs) copper indium diselenide (CIS) and copper indium galium diselenide (CIGS) (EPRI, 2003).
The performance of a solar cell is measured in terms of its efficiency at turning sunlight into electricity. Monocrystalline silicon cells has an efficiency of 13 - 15%. The efficiency of polycrystalline cells is about 12-14% and the amorphous silicon are less efficient (6-8%) than crystalline based cells (Alsema *et al,* 1998; BP solar). The advantage of thin film solar is that they are cheaper to produce and have less material requirements than silicon cells.

Figure 1 Monocrystalline silicon

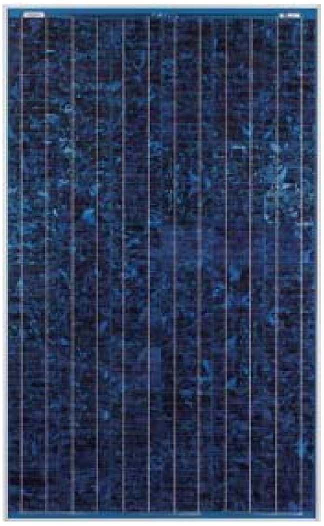

Figure 2 Polycrystalline silicon

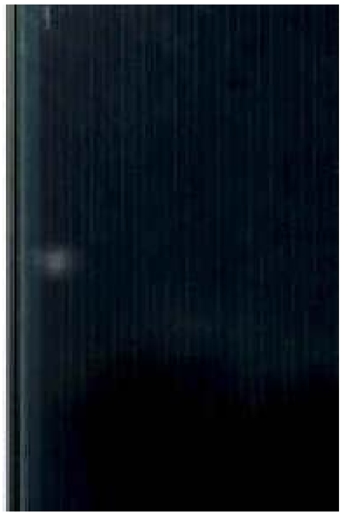

Figure 3 Thin film

2.1.2 PV-module

In order to make the appropriate voltages and outputs available for different applications, single solar cells are interconnected to form larger units, a PV module. Solar cells can be joined by parallel or series connection. Cells connected in series have a higher voltage, while those connected in parallel produce more electric current. The interconnected solar cells are usually embedded in transparent Ethyl-Vinyl-Acetate, fitted in an aluminum or stainless steel frame and covered with transparent glass on the front side.
PV modules are connected to form an array to give required power. Most PV modules deliver direct current (DC) and an inverter is used to convert the low voltage DC to higher voltage alternating current (AC).

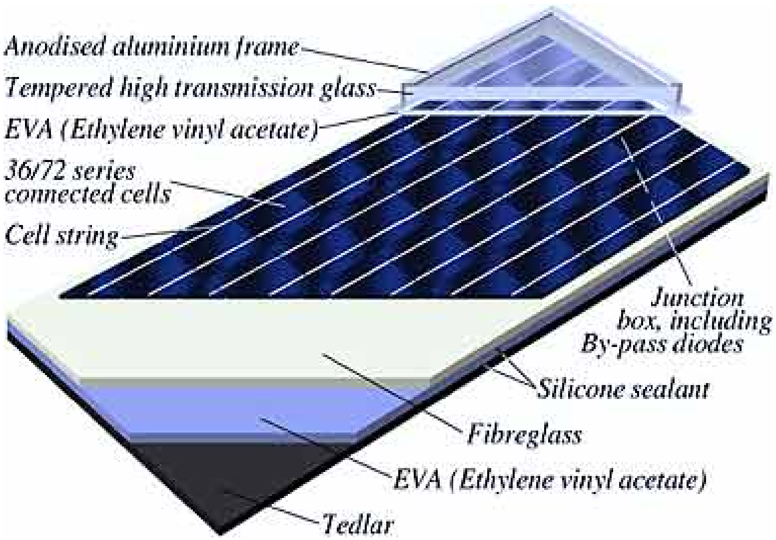

Figure 4 Example of PV module (www.gpv-solar.com)

2.2 Overview of solar cells used in PV-Nord demonstration buildings

Table 1 Solar cells used in PV-Nord demonstration buildings

	Building	**Type of solar cells**	**Supplier**	**Country**
1.	AsOy Helsingin salvia, multi-family building	Polycrystalline silicon	NAPS Systems Oy	Finland
2.	Kollektivhuset – De Vanføres Bolligselskab, multi-family Building, *Københavns Kommune*	Monocrystalline Silicon	Gaia Solar A/S	Danmark
3.	Vest Agder kliniken, clinic center, *Vest-Agder County/TET AS*	Polycrystalline silicone	GPV	Norway
4.	Holmen and Grynnan, multi-family building, *NCC boende*	Mono and polycrystalline silicon	NAPS	Sweden
5.	NCC Head office in helsinki, *NCC Finland Oy.*		NAPS	Finland
6.	Lysande, multi-family building, *Familjebostäder*	Polycrystalline silicon	Gaia Solar A/S	Sweden
7.	PV Parking Zwolle, multi-storey parking), *Parking Luttenbergerstraat B.V.*	Amorphous silicon	Shell Solar	Netherlands
8.	L3/L7 Restaurant, *SIEP B.V.*	Polycrystalline silicon	Shell Solar	Netherlands

2.3 PV-system as a building component

2.3.1 Environmental considerations for adding PV to PV-Nord buildings

In the environmental questionnaire (see appendix 1) sent to building owners, the first question aimed to reveal their environmental consideration for adding PV to their building. Against the background of guidelines for building product declarations in Northern countries, the second question aimed to reveal if building owners have required environmental declaration of used the PV modules.

Table 2 Solar cells used in PV-Nord demonstration building

	Building	**Did you have environmental considerations for adding PV to your building?**			**Did you have environmental declaration for the PV modules or cells that you are planing to use in your building?**		
		Yes	If yes, which	No	Yes	If yes, attach the declaration	No
1.	AsOy Helsingin salvia			X			X
2.	Kollektivhuset			X			X
3.	Vest Agder kliniken	X	To introduce environmental features in building				X
4.	Holmen and Grynnan	X	To demonstrate a sustainable and renewable energy source in the built environment.				X
5.	NCC Head office in helsinki	X	To get the information about the PV technology and follow NCC's environmental friendly strategy.				X
6.	Lysande			X	X	We will force the supplier of PVs to certify that chemical substances listed "not to be used" by Familjebostäder are not utilized.	
7.	PV Parking Zwolle			X			X
8.	L3/L7 Restaurant	X	The sustainability performance of the complex. A so-called greencalc scale measures the performance. The project contributes to the overall environmental goals of Shell EP.				X

The most environmental consideration taken into account by the building owners was the use of renewable energy source. The most drive force was local environmental goals. The fact that solar cells and modules in Building Integrated PV-systems are also a building component was not taken into account by many of the owners. Only one of them, the Swedish Familjebostäder required a separate environmental declaration for the PV system from the supplier. The most important aspect in the requirement was the chemical constituent in the final modules according to Familjebostäder chemical policy and strategy.

2.3.2 PV chemicals

The double function of BIPV as an energy source and building material was discussed within the PV-Nord project team. PV module suppliers involved in the project could not provide data on material and energy flows in the manufacturing of PV cells and modules. The most critical area was the use of chemicals. One of the reasons is the fact that the PV cells and modules have a complex supplier chain. Manufacturing PVs involves different companies who may want to protect business secrets about the use of a substance or the composition of the final products.

However one company in the supplier chain of the product used in one of the PV-Nord building provided the information on the chemical used and constituents of the silicon-based PV-module that had been used in one of the PV-Nord buildings. Other suppliers referred to earlier environmental studies commonly used by the PV suppliers when communicating the environmental issues of PV systems.

The provided information was obtained at the same period as the report “Potential Heath and Environmental Impacts Associated With the Manufacture and Use of Photovoltaic Cells” provided by the Electric Power Research Institute (EPRI) was published (EPRI and CEC, 2003). A comparison of the supplier’s data with the content of EPRI report and an earlier study (Phylipsen *et al,* 1995) showed that the supplier’s data only handled the chemicals used for the module manufacturing but not the production of solar cells. A visit at a PV module plant showed that used solar cells for the module manufacturing came from different part of the world. Consequently several information source has been used to list chemicals and material used in manufacturing PVs (see table 3, 4, 7)
How those chemicals are using during the manufacturing process will be described in chapter 3.

Table 3 Chemicals and materials used in the manufacturing of PV cells

Crystalline Silicon Cells*	Polycrystalline Silicon Cells**	Amorphous Silicon	Cu_2S/CdS Cells**	CdTe/CdS	CIS Cells	CIGS Cells	GaAs Cells
Aluminum	Aluminum	Acetone	Ammonium chloride	Cadmium chloride	Cadmium	Cadmium	Arsenic
Ammonia	Ammonia	Aluminum	Ammonium fluoroborate	Cadmium	Copper	Copper	Arsine
Ammonium fluoride	Arsine	Chloro-silanes	Cadmium sulfide	Molybdenum	Hydride gas	Gallium	Gallium
Hydrochloric acid	Boron trichloride	Diborane	Chromate coating	Nickel	Hydrogen sulfide	Indium	Hydrochloric acid
Hydrofluoric acid	Copper catalyst	Germanium (used in some)	Copper	Sulfur	Hydrogen selenide	Molybdenum	Methane
Hydrogen fluoride	Diborane	Germanium tetrafluoride (used in some)	Cuprous chloride	Tellurium	Indium	Selenium	Phosphine
Isopropyl alcohol	Ethyl acetate	Hydrochloric acid	Gold	Thiourea	Molybdenum	Zinc	Trichloroethylene
Nitric acid	Ethyl vinyl acetate	Hydrofluoric acid	Hydrochloric acid	Tin	Selenium		Triethyl gallium
Nitrogen	Hydrochloric acid	Hydrogen	Hydrogen sulfide		Zinc		Trimethyl gallium
Oxygen	Hydrogen	Isopropanol	Methanol				
Phosphorus	Hydrogen fluoride	Nitrogen	Nickel				
Phosphorus oxychloride	Hydrogen peroxide	Phosphine	Nitrogen				
Silane	Ion amine catalyst	Phosphoric acid	Polyvinyl butyrol				
Silicon	Isopropyl alcohol	Silane	Silicon monoxide				
Silver	Nitric acid	Silicon tetrafluoride	Sodium chloride				
Sodium hydroxide	Nitrogen	Silicon	Tantalum pentoxide				
Sulfuric acid	Phosphine	Sodium hydroxide	Zinc				
Tin	Phosphorus trichloride	Tin	Zinc fluoroborate				
	Silicon						
	Silicon dioxide						
	Silane						
	Silicon trioxide						
	Silicon tetrachloride						
	Silver						
	Sodium hydroxide						
	Stannic chloride						
	Sulfuric acid						
	Tantalum pentoxide						
	Titanium						
	Titanium dioxide						
	Trichlorosilane						

* Compiled list of chemicals and materials based on the publishers' personal contact with solar industry.
** Complete list of chemicals and materials used in the manufacturing process
Reference: *Potential Health and Environmental Impacts Associated with the Manufacture and Use of Photovoltaic Cells,* EPRI, Palo Alto, CA, and California Energy Commission, Sacramento, CA: 2003. 1000095.

Table 4 Example of chemicals and materials used in the manufacturing of PV-Nord PV module

Silicone
4,4,7,7-Tetraethoxy-3,8-dioxa-4,7-disiladecan
3-(2-Aminoethylamino)-propytrimetoxysilan
3-Aminopropylyltrieethoxysilan
Methanol
n-hexan
Butan-2-on O, O´, O´´-(methylsidyn)trioxim
Oxim silan
3-(diethoxymethylsily)propylamine
Polysiliconureaethylester
Propan-2-ol
Toluene
Butanol
Isoalcane C7-C10
Aluminum
Hotmelt adhesive
Sand
Soda
Dolomite
$CaCO_3$
Acrylonitrile-butadiene-styrene copolymer
Tetrabrombisfenol A, 6-15
Antimonoxid, 2-6
Brominated epoxioligomer, 4-8
Vinyl acetate
Copper tin plated
Modified Epoxy
EVA
Ethylene vinyl acetate copolymer
Stabiliser and addditives
2-propanol
Carboxylic acids
Modified resin
Polyvinylfluorid
Titanium dioxide
Modified acrylic dispersion
Silver
Tin

Note: this list provides only a general information on PV modules (not solar cells) and is not applicable to a specific product.

3 Environmental issues

3.1 Environmental aspects of used silicon-based PV module

Comparing to other products a building has a relatively long lifetime. When applying environmental analysis on building materials/ products particular aspects has to be taken into account:

– The impacts of the production phase of the building
– The impacts during the use phase
– Possible future impacts
– How to convey information from the design team to the builders, tenants and users and finally to the waste operators.

As illustrated by the figure 5, to analyse such impact requires a lot of information from e.g the manufacturing chain. Many actors in the northern make substantial efforts trying to get information from their suppliers of building products. Guidelines for environmental declaration have been developed in collaboration between building owners, material suppliers and consultants aiming to examine a building product over its complete life cycle, from ”cradle to grave”

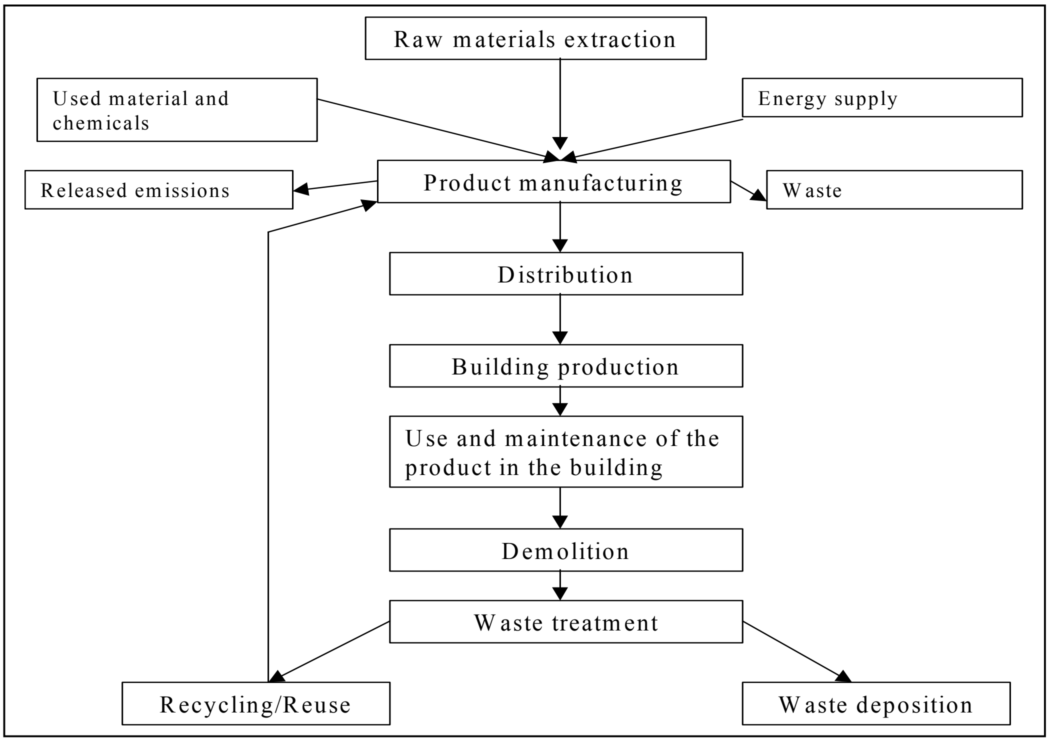

Figure 5 Example of life cycle phases of building products

3.1.1 Raw materials and product manufacturing

Raw materials for the production of silica (SiO_2) are quartz and sand. According to the PV-supplier from the project team, PV industry uses a supply of low cost silicon material from the semiconductor industry. Multicrystalline silicon contains more impurities than monocrystalline silicon, that is with the solar cell efficiency is lower than in monocrystalline solar cells. The manufacturing process of multicrystalline silicon involves several steps in order to minimize the decrease in cell efficiency (Phylipsen *et al,* 1995; EPRI, 2003). The manufacturing process has been described by Phylipsen and Alsema and can be resumed as followed:

The 1st step consists of the mining of raw materials and reducing silica to silicon using the carbon use from charcoal, cokes, low ash coal or wood scrap.

$$SiO_2 + 2\ C \rightarrow Si + 2\ CO$$

The released emissions from this step are CO, SiO, methane (CH_4), CO_2 , and ethane (C_2H_6) etc react oxygen from the air to oxygen from the air CO_2 ,H_2O, SiO_2, etc. The silicon obtained contains aluminum and calcium impurities, slag and respirable silica particles metaloxides are emitted and by a filter and disposed of as solid waste. The impure silicon is purified to so-called metallurgical grade silicon (mg-Si) that has with a purity of 99,6%. But the mg-Si still has impurities and can be used in semiconductor or solar cell manufacturing.

The 2nd step is the production of high purity silicon. The mg-Si is hydrochlorinated to trichlorosilane (TCS, $SiHCl_3$) and converted with hydrogen to so-called semiconductor grade silicon or electronical grade (eg-Si) that has a purity of > 99.99999% and is expensive. For this reason solar cell industries often use so-called scrap material, which does not fully meet the exigencies of the semiconductor industry. But this cheap source of raw material can face the increasing production of silicon of solar cells. So-called solar grade silicon (sog-Si) is cheaper than eg-Si. sog-Si can be produced by hydrogenated mg-Si in a fluidized bed reactor (FBR) at 500°C and 3.5 MPa in the presence of a copper catalyst and by adding $SiCl_4$ and H_2. The reaction produces chlorosilanes.

$$3SiCl_4 + Si + 2H_2 \leftrightarrow 4SiHCl_3$$
$$4SiHCl_3 \leftrightarrow 2SiH_2Cl_2 + 2SiCl_4$$
$$6SiH_2Cl_2 \leftrightarrow 4SiHCl_3 + 2SiH_4$$

The releases from this step are directly led through a $Ca(OH)_2$ –scrubber in the presence of SiCl4 and H_2 and converted into $CaCl_2$ and SiO_2. The product obtained is said to have near 100% purity.

The 3rd step consists on casting and sawing the silicon. The high purity Si is converted into blocks of multicrystalline Si called ingots. The silicon blocks are then cut into very thin slices, sawing process. Silicon carbide (SiC) is used in the process. After sawing the wafers they are cleaned, rinsed and dried.

In the 4th step wafers are etching with sodium hydroxide (NaOH, 33%) in water and rinsed in water and concentrated sulphuric acid. Releases are H_2, H_2O, Na_2SO_4 and Na_2SO_3 (sodium silicate).

$2NaOH + Si + H_2O \rightarrow Na_2\, SiO_3 + 2H_2$
$H_2SO_4 + 2\, NaOH \rightarrow Na_2SO_4 + 2H_2O$

The 5th step called emitter formation consists on doping wafer with usually phosphorus atoms to create so-called n-type emitter layer. The P_2O_5 and Cl_2 are released and treated to form NaH_2PO_4 and NaOCl.

$4POCl_3 + 3O_2 \rightarrow 2P_2O_5 + 6Cl_2$

The phosphoric pentoxide (P_2O_5) obtained forms a layer of phosphorus-silica glass (SiO_2 .P) on the wafers and the phosphorus atom diffuses then to the upper part of the wafer. The phosphorus-silica-glass layer is removed by etching with fluoric acid:

$SiO_2 + 6HF \rightarrow H_2SiF_6 + 2H_2O$

The phosphorus-containing layers are then etched off by CF_4

$Si + 4F \rightarrow SiF_4$

HF, H_2SiF_6 and SiF_4 and F_2 are formed respectively and treated to form SiO_2, NaF and CaF_2. CO_2 and some fluoridized oil are released.

The 6th step is the metallization. A layer of an aluminum and silver containing paste is first screenprinted on the backside of the cell. Screenprinting pastes contain also solvents, resins, fillers, etc. The next step is the passivation and antireflective coating. Hydrogen atoms are used to inactivate impurities that can reduce solar cell efficiencies. Antireflective coatings can also be formed by e.g TiO_2 ,Ta_2O_5.

The last step is the module assembly. Solar cells are encapsulated into a module.

The tested cells are laid out in a module matrix and interconnected with tin-coated copper strips. The next step is embedding the cell matrix in EVA. The encapsulation of materials consists of a thick sheet of chemically hardened glass, EVA foil, the cell matrix, again the EVA foil, and Tedlar/Al/Tedlar foil. The lamination occurs at 120-150°C. The edges of the module are sealed with a polysulphide elastomer and the modules are washed and dried. Finally a polyester junction box is attached, and if necessary the module is framed commonly with an aluminum frame).

3.1.2 Potential impact of crystalline cell chemicals on the human health

The chemical list and information on released emission provided by the supplier of the polycrystalline PV module differs from that published in the EPRI report and earlier LCA studies (EPRI, 2003; Phylipsen *et al*, 1995; Alsema, 1996). The mentioned report was published at the end of 2003 and provides an overview of chemicals used in manufacturing solar cells and modules under 2002. The information from the PV supplier was obtained at the end of 2003. A hypothesis is that some of data in the EPRI report was outdate. The other hypothesis is that the PV module supplier did not have any information on the chemicals used by the solar cell producers. However a qualitative description of potential hazard of chemicals listed by the supplier and those published in the EPRI report is provided in table 5. The description is based on the European Union Directive 67/548/EEC (substances) and 1999/45/EC (preparations). The PV module supplier's own general qualitative hazard estimation of released emission is presented in table 6.

Table 5 Potential hazard of crystalline cell chemicals

Polycrystalline Silicon Cells**	**CAS-nr**	**Hazard classification**
4,4,7,7-Tetraethoxy-3,8-dioxa-4,7-disiladecan	16068-37-43	
3-(2-Aminoethylamino)-propytrimetoxysilan	1760-24-3	
3-(diethoxymethylsily) propylamine/ 1-Propanamine, 3-(diethoxymethylsilyl)-	3179-76-8	
3,5,3',5'-Tetrabromobisphenol A	79-94-7	
Acrylonitrile-butadiene-styrene copolymer	9003-56-9	
Alkanes, C7-10-iso-	90622-56-3	
Aluminum	7429-90-5	
Ammonia	7664-41-7	
Antimony oxide	1309-64-4	– Limited evidence of a carcinogenic effect
Arsine	7784-42-1	– Extremely flammable – Very toxic by inhalation – Danger of serious damage by prolonged exposure – Very toxic to aquatic organisms and may cause long-term adverse effects in the aquatic environment
Boron trichloride	10294-34-5	– Reacts violently with water – Causes burns – Very toxic by inhalation and if swallowed
Brominated epoxioligomer, 4-8	158725-44-1	
Butan-2-on O, O´, O´´-(methylsidyn)trioxim /Methyltri(methylethylketoxime)silane	22984-54-9	
Butyl alcohol	71-36-3	– Flammable and irritating to skin and respiratory system – Risk for serious damage to eyes and vapors may cause drowsiness and dizziness.
Copper catalyst		
Copper tin plated		
Diborane	19287-45-7	

Dolomite		–
Ethyl acetate	141-78-6	– Highly flammable – Irritating to eyes – Repeated exposure may cause skin dryness or cracking – Vapors may cause drowsiness and dizziness.
Ethylene-vinyl acetate copolymer	24937-78-8	
Glass (sand, soda, dolomite, $CaCO_3$)		
Hydrochloric acid	7647-01-0	– Causes severe burns – Toxic by inhalation
Hydrogen	1333-74-0	– Highly flammable
Hydrogen fluoride	7664-39-3	– Very toxic by inhalation – Very toxic in contact with skin and if swallowed. – Causes severe burns
Hydrogen peroxide	7722-84-1	– Contact with combustible material may cause fire – Causes burns – Irritating to eyes and skin
Ion amine catalyst		
Isopropyl alcohol	67-63-0	– Highly flammable – Irritating to eyes – Vapors may cause drowsiness and dizziness.
Methanol	67-56-1	– Highly flammable – Danger of very serious irreversible effects by inhalation, when swallowed and in contact with skin.
Modified Epoxy		
n-Hexane	110-54-3	– Highly flammable – Irritating to the skin – Possible risk for impaired fertility. – May cause lung damage if swallowed – Vapors may drowsiness and dizziness. – Toxic to aquatic organisms and may cause long-term adverse effects in the aquatic environment
Nitric acid	7697-37-2	– Causes severe burns – Contact with combustible material may cause fire
Nitrogen	7727-37-9	
Oxim silan		–
Phosphine	7803-51-2	– Poisonous
Phosphorus trichloride	7719-12-2	– Reacts violently with water – Very toxic if inhaled or swallowed Contact with water liberates toxic gas – Causes severe burns – Danger of serious damage by prolonged exposure

Polysiliconureaethylester		
Polyvinylfluorid		
Silicon		
Silicon dioxide	14464-46-1	
Silane		
Silicon trioxide		
Silicon tetrachloride	10026-04-7	– Reacts violently with water – Irritating to eyes, skin and the respiratory system
Silver	7440-22-4	
Sodium hydroxide/ Caustic soda	1310-73-2	– Causes severe burns and irritating to eyes and skin
Stannic chloride (Tin(IV) chloride)	7646-78-8	– Irritating to eyes, skin and the respiratory system – Harmful to aquatic organisms and may cause long-term adverse effects in the aquatic environment
Sulfuric acid	7664-93-9	– Irritating to eyes and skin and causes severe burns
Tantalum pentoxide	1314-61-0	
Tin	7440-31-5	
Titanium	7440-32-6	
Titanium dioxide	13463-67-7	
Toluene		– Highly flammable and harmful by inhalation
Trichlorosilane		
Vinyl acetate	108-05-4	– Highly flammable

Table 6 PV supplier's estimation of environmental impact of released emissions from PV module manufacturing

Material and substances	CAS-nr	Emission to environmental compartment	Effect in the compartment
Silicone			
4,4,7,7-Tetraethoxy-3,8-dioxa-4,7-disiladecan	16068-37-43	water	Slightly hazardous
3-(2-Aminoethylamino)-propytrimetoxysilan	1760-24-3	"	"
3-Aminopropylyltrieethoxysilan	919-30-2	"	"
Methanol	67-56-1	"	"
n-hexan	110-54-3	"	"
Butan-2-on O, O´, O´´-(methylsidyn)trioxim	22984-54-9	"	"
Oxim silan		"	"
3-(diethoxymethylsily)propylamine	3179-76-8	"	"
Polysiliconureaethylester		"	"
Propan-2-ol	67-63-0	"	Hazardous
Toluene	108-88-3	"	"
Butanol	71-36-3	"	"
Isoalcane C7-C10	90622-56-3	"	"
Aluminum			
Hotmelt adhesive			
Sand			
Soda			
Dolomite			
$CaCO_3$			
Acrylonitrile-butadiene-styrene copolymer	9003-56-9	Air	Can release hazardous gases
Tetrabrombisfenol A, 6-15	79-94-7	"	"
Antimonoxid, 2-6	1309-64-4	"	"
Brominated epoxioligomer, 4-8	158725-44-1	"	"
Vinyl acetate			
Copper tin plated			
Modified Epoxy			
EVA			
Ethylene vinyl acetate copolymer			
Stabiliser and addditives			
2-propanol	67-63-0		Slightly hazardous
Carboxylic acids	68603-84-9		"
Modified resin	68458-54-8		
Polyvinylfluorid			
Titanium dioxide			
Modified acrylic dispersion			
Silver			
Tin			

3.1.3 Environmental sustainability

3.1.3.1 Raw materials and the manufacturing phase

Because of the abundance of sand, raw material supply for silicon solar cells is not expected to become a problem if the PV production increase in the future.

As shown in 2.3.2, 3.1.1 and 3.1.2 and table 5 and 7 the manufacturing process of PV cells and modules involves the use of and emit different materials and a large number of chemical substances that can affect the human health and the environment.

Table 7 Summary of materials and chemicals used during the manufacturing processes and releases

Process	**Materials and chemicals requirements**	**Emission to Air**	**Emission to water**	**Solid waste**
Mining and refining of silica (silica production)	– Quartz	– Respirable dust		– SiO_2
Reduction of silica to silicon (silica reduction)	– Charcoal – Low Ash Coal – Cokes – Wood scrap	– CO_2 – SO_2		– SiO_2
Production of high purity silicon	– Silane Tetra Chloride – High purity carbon – HCl (20%) – $Na_2\ CO_3$ – $Ca\ CO_3$ – Al_2O_3	– CO_2 – Si-powder – F containing dust – Cl containing dust	– $CaCl_2$ – NaCl	
Casting of silicon	– Argon gas	– Argon gas		
Sawing of silicon	– Mineral oil – SiC			
Wafering				– Si (in mineral oil) – SiC – mineral oil
Etching and texturing	– NaOH – H_2SO_4 – KOH – HNO_3		– $Na_2\ SO_4$ – KCl – $NaNO_3$	
Emitter formation	– $POCl_3$ – HF – CF_4	– CO_2 – "solvents"	– NaH_2PO_4 – NaOCl – NF	– CaF_2

Metallization	– Al/ – Ag-paste – Ag-Paste – Al-paste	– "solvents" – CO_2 + HO_2		
Passivation/ antireflective coating (ARC)	– SH_4 – NH_3 – N_2	– N_2		
ARC	– $Ti[(CH_3)_2CHO]_4$	– Isopropanol – HO_2	– TiOx	– TiOx
Contouring				– Contaminated Si
Cell testing				– Rejected cells
Module assembly	– Sn-coated Cu-strips – EVA foil – chem. hardened glass – Tedlar/Al/Tedlar – Al (in Tedlar) – Polyester – Silicon adhesive	– Cross linking products		– EVA foil – Silicon adhesive
Framing	– Aluminum – Polysulphide elastomer			– Polysulphide elastomer
Module testing	–			– Rejected modules

The environmental impacts associated with the emissions occurring during the manufacturing of PV cells and modules are:

- CO_2, global warming
- SO_2, acidification and human toxicity and
- Solvents, photochemical ozone formation. Solvents contribute to the formation of the ground level Ozone.
- Isopropanol, photochemical ozone formation and human toxicity, see table 5
- Fluoride, human toxicity, see table 5
- Fluorine (F) and chlorine (Cl), human toxicity
- Nitrate, human toxicity.
- Silica particles, human toxicity

The silica reduction process uses different carbon sources (wood scrap, Low Ash Coal) and is the biggest contributor to CO_2 emissions during a PV module lifetime (Phylipsen et al, 1995). The impact associated with the CO_2 emissions from solar energy production is higher compared to the energy produced by wind and nuclear power (see figure 6). But unlike the wind power the PV modules do not produce noise during the period they are used to produce electricity and solar power do not regenerate radioactive waste as the nuclear power.

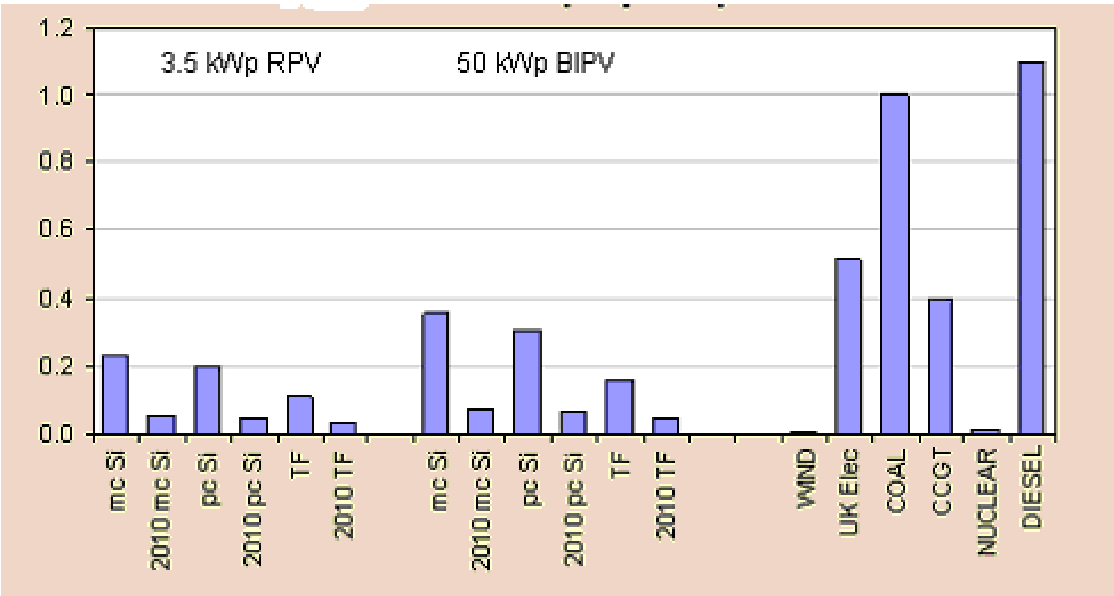

Figure 6 Estimation of CO2 emission from the manufacturing of PV modules for 35 KWp roof system resp. 50 KWp BIVP.

Reference University of Strathclyde, Scotland, UK
http://www.esru.strath.ac.uk/EandE/Web_sites/98-9/grid_connected_pv/lca.htm

3.1.3.2 The use phase

No emissions occur during the usage of PV modules for electricity production except when modules are exposed to high temperatures such as in case of fire or explosion (EPRI, 2003, Phylipsen et al, 1995). Burning products of Ethylene Vinyl Acetate (EVA) and acids such as HF and HCl can be emitted from Tedlar foils.

Dirt and dust can accumulate on the solar module surface, obscuring sunlight and reducing the output. Rain normally cleanses off dirt and dust (California Energy Commission, 2001). Occasional or more regular washing of the top glass sheet is needed and depending on the complexity of the PV-system design and the site location. The environmental impact then depends on the cleaning agents used and the frequency of washing of the modules.

An important aspect that has to be taken into account in the maintenance of PV-systems is the fact that if a solar cell is defect in a PV module, the entire module has to be changed. Extra modules should be stored when using special customer designed modules.

3.1.3.3 Energy PayBack Time (EPBT)

The EPBT is the time the PV module has to function to produce as much electricity as was needed for producing the module. The EPBT has been estimated in several studies (Phylipsen et al, 1995; University of Strathclyde; Alsema et al, 1998, 2000).

The manufacturing of solar cells and modules requires energy and according to PV suppliers from the project team different energy sources are used in different manufacturing plants. Processing silica to solar cell and the encapsulation materials is the main contributor to the energy input. The production of the energy required for solar cell manufacturing causes different kind of emissions that can influence the environmental profile of the PV-system.

From Phylipsen et al it can be derived that the amount of energy required for PV manufacturing is relatively low if the aluminum frame is excluded.
PV modules have an expected service life 25-30 years according to PV-Nord supplier group and the literature review (Phylipsen et al, 1995; University of Strathclyde; Alsema et al, 1998, 2000). The EPBT is estimated to be 4-5 years depending to the PV system efficiency and the site insolation. The EPBT can be lower if a frameless module or recycled aluminum frame is used.

3.1.3.4 Waste management

Because of the long service life of PV modules and the fact that the use of PV-systems is relatively new in Northern Europe, there is no experience of handling used PV modules.

In different studies standard leaching test have been used to calculate the potential release of metals from PV, mostly CdTe and CIS modules (Fthenakis, 2004; EPRI, 2003). However, recycling should be considered as the best waste management measure for used PV modules rather than final deposition in landfills. A pilot recycling plant is now available in Germany, which means future recycling opportunities for PV-modules used in PV-Nord demonstration buildings.

4 Conclusion

Generally, producing electricity by PV systems offers several environmental advantages. The sun's energy is free and infinite and the main raw material for the PV production is one the most frequent element in all countries. PV modules can replace traditional building materials and supply electricity at the same time. The PV-system presented good opportunities to local self-sufficiency by generating electricity locally without the main network infrastructure. However the production of PVs and other PV-system components requires a lot of energy; toxic chemicals of concern for the work environment are used and occurred emissions have some health and environmental impacts.

Because of the long lifetime of the building, the present PV technology may show other environmental impacts in the future. Building owners will comply with these according to legal requirements or other exigencies. Better opportunities should be developed e.g. a harmonized environmental declaration to convey the environmental information of the product from the solar cell and module production chain to the users. The double function of the BIVP may require an other approach to environmental declaration of PV cells and module than the type of environmental declaration of building material used in different countries to day. The declaration can then be adapted to local requirements depending on e.g. national waste legislation and environmental goals.

Integrating a PV-system into the structure of a building can reduce the cost of the system because the PV performs two functions. It replaces traditional building materials such as concrete, brick, glass and tile and generates electricity at the same time. Comparative studies should be carried out to evaluate the benefits of the double function performing by BIVP including maintenance aspects during an assumed building lifetime.

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Appendix

Questionnaire on Environmental information on the PV Nord buildings (Task 3.2)

1. **Did you have environmental considerations for adding PV to your building?**
   - ❑ Yes

   If yes, which
   - ❑ No

2. **The concept of Building Integrated PV means that the solar cells are considered as an energy source and a building component similar to e g concrete. Northern countries have developed guidelines for building product declarations. Did you have environmental declaration for the PV modules or cells that you are planing to use in your building?**

   - ❑ Yes

   If yes, please attach the declaration

   - ❑ No

   If no, please require the environmental declaration from the PV suppliers. The declaration should contain:

2.1. Product name/supplier (name and address)

2.2. Energy and raw materials used in manufacturing

Non-renewable energy (e.g nuclear power, in KWh/kg):

Renewable energy (e.g nuclear power, in KWh /kg):
Source of renewable energy:

Non-renewable raw materials (KWh /kg):

Renewable raw materials (KWh/kg):

2.3. Emissions occurring in manufacturing

Emissions to air

Emissions to water

Emissions to soil

Please state significant effects on soil in manufacturing and whether hazardous emissions occur:

2.4. Contents in the finished product

State substances contained in finished product and the proportion of the substance in percent by weight. Please specify the CAS-nr of the substance if possible and the Classification according to EG directive 67/548/EEG

Substances	Proportion (weight % or g/kg)	CAS-nr	Hazardous classification

2.5. Estimated service life in normal use of the product in the building

Service life: …years

2.6. Maintenance

2.6.1 State the products (cleaning agents, surface protection) necessary to preserve the product's function and properties during the user phase of the building.

2.6.1 Can the product be replaced in case of deficiency?

Yes, just defected solar cells
Yes, complete modules have to be changed even if just some cells are affected
No

2.6.2 Can the product you use/supply today be replaced letter if more efficiently PV products are developed?

- ❑ Yes
- ❑ Yes, but:

(State in the free-text field the replacement require other modalities)

- ❑ No

2.7. Waste recycling and/or deposition
Can the product be reuse or recycled?

- ❑ Yes, by product recycling
- ❑ Yes, by energy released from combustion of product

Do hazardous waste or emissions arises during the combustion of the product?

- ❑ Yes

If yes, which? Please specify

- ❑ No