Life cycle assessment of electricity generated by photovoltaic systems manufactured in Europe and installed in buildings in the city of Rome

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Abstract

The aim of this paper is to evaluate the impact on human health and on the ecosystem caused by electricity produced by photovoltaic systems. The analysis was carried out with the life cycle assessment methodology (LCA) and the eco indicators method.

It includes a study of raw materials and energy consumption and their polluting emissions in air, water and soil during the production phase in Europe and transport, use and disposal in the city of Rome of the crystalline silicon and all other materials and components used to produce 1 kWh of electricity. The kWh is the functional unit of the LCA analysis.

The study considers the relationship between the energy consumption needed to build a PV system and the energy produced by the same system over 25 years. The study also considers the relationship between global and local environmental impact caused by the manufacturing and disposal of the PV system and the avoided environmental impact due to the energy produced by renewable sources. Finally, the analysis compares global and local emissions of CO_2 caused by the PV system's manufacturing and disposal and the avoided emissions of CO_2 using electricity from renewable sources. The study describes the possible solutions to reduce environmental impact through innovation.

Keywords: PV system, LCA, Mayor's Pact, saving CO_2.

1 Introduction

The IV Report on Climate Change, referenced by the European Union in its climate policies points out that within the first half of the century global emissions should be reduced by at least one half compared to 1990. Facts

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indicate that in order to reduce the presence of carbon in energetic systems, an efficient policy should aim at developing technologies and new kinds of combustibles. It is in such a context that the reduction on CO_2 emissions becomes one of the goals targeted by the European Union's new energy politics. With the directives proposed on January 23, 2008, the EU aims at reducing total CO_2 emissions by 20% before 2020. In January 2008 the EU also sponsored the Mayor's Pact, an initiative that involves European cities in a common path towards energetic and environmental sustainability. This recent initiative, based on voluntary participation, urges European cities to develop an Action Plan committed to reducing CO_2 emissions by 20% due to local policies that would make use of renewable sources, increasing energy efficiency and enacting programs to save and rationalize energy use.

Since energy used in buildings is responsible for 30%–40% of CO_2 emissions, in 2002 the EU published the directive n.91 on energy efficiency in an attempt to increase energy performance of buildings, develop and value the use of sustainable sources and energy diversification and contribute to national objectives on global emissions imposed by the Kyoto Protocol.

In this scenario, in order to evaluate the sustainability of a building's energy system, it is legitimate to ask how much energy and raw materials the system took to be built, installed and dismissed and how much energy it produced in its entire life. One would also have to consider emissions released and if and how these emissions have been taken into account by the cities' Action Plans.

This kind of evaluation can be calculated with a life cycle assessment (LCA).

Talking about a photovoltaic system we will consider impacts caused from the production, installation and dismissal of the system and confront them with the lesser environmental impacts resulting from the use of renewable sources.

Values of global CO_2 emissions will be attributed to the city in which the system was built, whereas the city in which the system is installed only the emissions deriving from installation, maintenance and dismissal will be taken into account.

The goal is to provide values that indicate clearly the energy and environmental benefits of using photovoltaic systems in buildings.

2 LCA of PV system: methodology

The environmental impact's evaluation, with the LCA methodology considers data regarding the consumption of raw material and energy and the pollutant emissions of a photovoltaic system produced in Europe and installed in roofs of buildings in Rome and connected to the electricity grid of the city. This PV system can produce 1 kWh peak. The functional unit of this analysis is the kWh peak.

The PV system is equipped with silicon polycrystalline cells with an efficiency of 10–15%. The PV system's life cycle is considered to be 25 years. (The LCA analysis of the inverter and all electrical accessories necessary to work the system are not included in this study.)

The environmental evaluation considers the impacts on human health and the ecosystem coming from the production of the system and during the installation and finally at the end of its lifespan. The evaluation also considers environmental benefits coming from a PV system which produces energy from renewable sources.

The study considers the relationship between energy consumption to produce, install and disassemble the PV system and the energy produced by the same in its 25 year span life; the relationship between local and global environmental damage caused by the manufacture, installation and decommissioning and the damage avoided by using renewable sources.

Finally, the analysis compares global and local emissions of CO_2 produced by the manufacture, installation and disposal of the PV system and the emissions avoided by using renewable sources.

2.1 Inventory data

The data for energy and raw material consumption come from two companies specialized in PV modules assembly, a company that produces silicon and from specific topic literature [1]. (The energy necessary to eliminate the impurities of metallurgical grade silicone in order to obtain electronic grade varies from 430kWh/kg to 600kWh/kg [2]. So to produce a 1 kg of crystalline silicone you need about 600kWh of electricity, which corresponds to 19kWh for every silicone wafer. If 1kg consumes 100kWh just to crystallize, for 7.54 it will use 755kWh and each wafer will consume 23kWh (which will become 46 given a 50% process yield). For the production, installation and maintenance in 20 years of a 1kWp system you need 6MWh of energy [3]).

The data has been normalized by the kWh peak and calculations were carried out assuming the following values:

wafer thickness = 0.35 mm
wafer area = 12.5x12.5 cm = 156.25 cm^2
wafer volume 54.68 E^{-7} m^3
wafer weight = 12.57 E^{-3} kg
silicon density = 2300 kg/m^3
number of wafers necessary to produce 1kWh = 600
efficiency of wafer cutting process = 50%.

2.2 Life cycle phases analyzed

The life cycle phases analyzed are the following: (table 1)

2.2.1 Production phase

The environmental analysis evaluates the impact caused by the following activities:

- Production of metallurgical grade silicon (Si-MG) having a purity of 95%;
- Production of Trichlorosilane ($SiHC1_3 + H_2$) having a purity of 98.9%;
- $SiHC1_3$ purification (distillation) with a purity grade of 2 parts per billion (triple stadium distillation);

- Deposition of the pure silicon micro crystal (reaction with H_2 at 1000°C, Siemens process) $SiHC1_3 + H_2 = Si + 3HC1$ with a purity of 2 parts per billion;
- Crystallization in order to obtain the bars (if mono crystalline with Czochralsky where a seed of pure silicon is grown slowly, if polycrystalline with deposit in a quartz crucible and radio frequency mixer even using leftovers from silicon grains or the head and bottoms of pure bars produced by the Czochralsky method);
- Cutting and work of bars needed to produce the wafers;
- Work needed on wafers to obtain the cells (washing, spinning, texturizing, pickling, serigraphy, efficiency tests);
- Module assembly.

Table 1: Energy consumption data relating to each of the materials and components needed to produce 1kWhp of electricity with a photovoltaic system in polycrystalline silicone.

Process	**Energy consumption: European mix UCPTE kWh/ kWhp**
Production of metallurgical grade silicon (Si-MG)	450
Production of Trichlorosilane ($SiHCl_3 + H_2$)	75
Purification $SiHCl_3$ (distillation) (triple stadium distillation)	225
Deposition of Si pure micro crystal (reaction with H_2 at 1000°C, Siemens process)	6750
Crystallization	1500
Cutting and work of the bars to produce wafers Work on the wafers to obtain cells	733
	Energy consumption: Italy mix kWh/ kWhp
Module assembly	301
	Total 10034

During the production phase, the following assumptions were made:

Energy:

- The electricity needed during manufacture was produced using the continental Europe energy mix: UCPTE region medium voltage level, [4] since two European countries are the main producers: Germany and Spain. (Average data of medium voltage (1–24kV) electricity energy production in Europe. It includes initial investments, exploration of energy sources and transport. Power distribution system is included up to delivery of medium voltage electricity. Grid loss of 1.8%. Data on waste disposal is not included. The emissions caused by burning and recycling are however included. All of the "radio nuclides" are combined in one category as radioactive substances.) The European energy mix was used in the production of metallurgical grade silicon, in the purification to obtain electronic grade micro crystalline silicon (Czochralsky process) and poly crystalline silicon (radio frequency mixer oven process), for wafer and cell production.

- For the module assembly and module disassembly phases, the Italian energy mix was used [5].
- The energy produced by the PV system and thus the energy saved is assumed to be the same as the Italian energy mix.

Raw materials:

- The data regarding the argon, ammonia, hydrochloric acid, nitrogen, hydrofluoric acid and mineral oil production processes was taken from the ETH-ESU Zurich data base;
- The EVA production process was assimilated to that of high-density polyethylene.

2.2.2 Installation phase and transport

- This phase should include all the processes from the finished product to its use: the assembly, the transport, the construction site activities and the installation modes. The methodology proposed, quantifies the environmental impacts derived from transporting the PV cells from Germany (1200 km by railroad). The incidence of transport related air pollution, due to the reduced weight, is irrelevant compared with the impacts caused during the production phase. If we consider air transport for 1200 km and an average weight of 12 gr. per cell for 585–600 cells the impact is equal to 0.6Pt.
- The impacts derived from transporting the various components from the production plant to the building site for a distance of up to 50 km with a 40-ton diesel truck are also considered and similarly inconsequential.

2.2.3 Use phase

- The use phase quantifies the environmental benefits deriving from the production of 1kWhp of electricity from a renewable source during the 25 year life cycle of a PV system installed in building's roof in the city of Rome.
- The average sun radiation is equal to 1737.4lWh/m^2.
- The average amount of direct current electricity produced in one year is equal to 1737.4kWhel/kWp (=8m^2 of PV panels).
- We assume that panels' inclination angle is 30° and that they are pointing south. A conservative value of 12.5% has been considered for efficiency (modules can be up to 16–17% efficient) and 85% for BOS (this includes inverter efficiency and cable loss) [6].

- The average amount of alternating current electricity produced in a year is equal to 1477 kWhel/kWp.

2.2.4 End of life phase and waste treatment scenarios

- The end of life phase provides an hypothesis, based on the referenced legislation, about environmental damage evaluation of different waste disposal operations deriving from the panel assembly and disassembly activities.
- At present there is not enough data to conduct a study on PV panel recycling. The only data available refers to recycling glass and aluminum recovered from a panel disassembly at the end of its life cycle [7].
- Disposed cells will be treated according to the 2002/96/CE Directive, effective since August 2005, regarding electrical and electronic equipment (RAEE). In Italy the Directive was transformed into law by the DL 151/2005 and the DM 18/2007. All these new obligations started on January 1st, 2008 and force producers to deal with product's end of life.
- The hypothesis on waste treatment considered in this study assumes: 100% recycle of aluminum and glass, and waste treatment according to Directive 2002/96/CE, keeping in mind that "Printed circuits contain heavy metals like ammonium, silver, chrome zinc, lead, copper and tin" (according to some estimates there is no other product for which the sum total of the environmental impact on unrefined materials, extraction, processing, finishing, production, use and sales is so noteworthy as it is for printed circuits [8]).

3 Results

The LCA includes all the phases previously described:
LCA = Production phase + Transport and installation phase, Use phase; maintenance/management, End of life phase and waste treatment scenarios.

The results regard energy consumption, environmental damage and CO_2 emissions associated with the PV system's manufacture in Europe and during 25 years of use in the city of Rome.

Table 2: Environmental damage caused by the production of a PV system in Europe.

Damage category	Unit (Pt)	Total	Si-MG production 1kg	Purification in Si-EG 1kg	Crystallization Si-EG 1kg+ water	Work on wafer and cells	Panel assembly
Human health		115	4.79	75.1	16	11.6	7.53
Ecosystem Quality		27.2	1.17	18.3	3.89	2.42	1.44
Resources		325	13.3	209	44.4	35	23.2
Total		467	19.3	302	64.2	49	32.2

Table 3: Environmental damage caused during the life span estimated in 25 years of the PV system installed in the city of Rome.

Damage category	Unit (Pt)	Total	Production phase	Use phase	Disposal phase
Human health		-618	115	-732	-1.25
Ecosystem Quality		-125	27.2	-152	-0.341
Resources		-1.88E3	325	-2.2E3	-0.484
Total		-2.62E3	467	-3.09E3	-2.08

Table 4: Results of energy consumption, environmental damage and CO_2 emissions in Europe and in the city of Rome.

	Energy consumption (kWh/kWp)	Damage points (Pt)	CO_2 emissions in Europe (ton)	CO_2 emissions in Rome (ton)
Manufacture	9733	435	4.93	-
Assembly and installation	301	32.2	-	-
during 25 years	- 36925	- 2620	-	-32
during 1 year	- 1477	- 124	-	-1.26
Payback time (years)	8	5	5	0

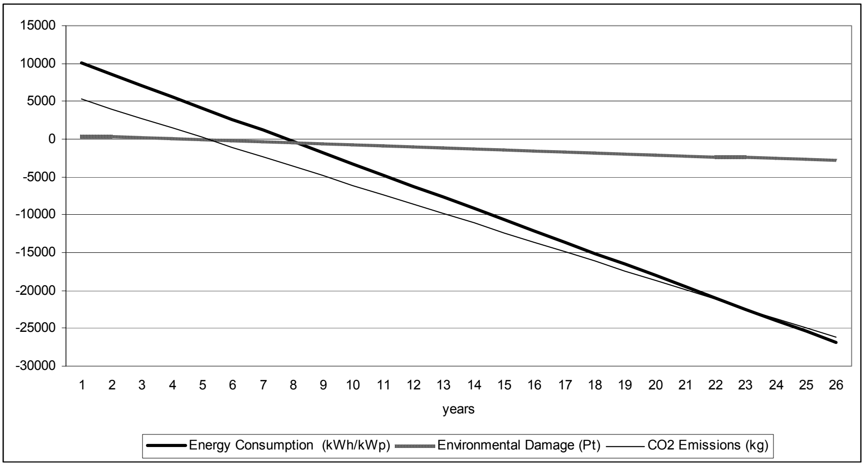

Figure 1: Trend of energy consumption, environmental damage and CO_2 emissions during the entire life cycle of the PV system.

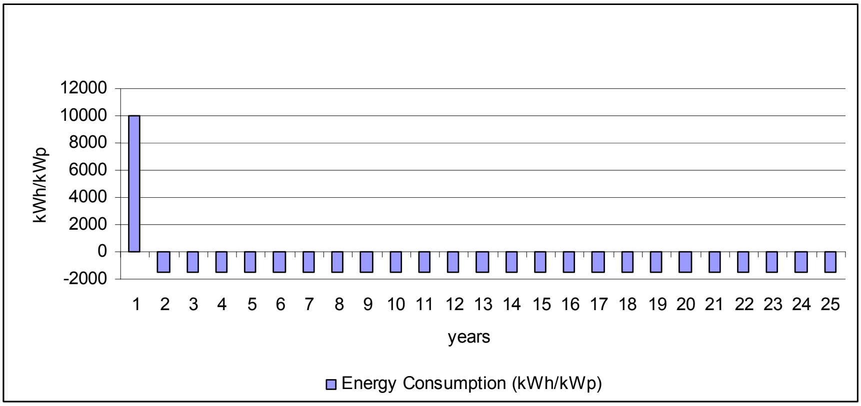

Figure 2: Energy consumption during the period (1 year) of system manufacture and energy saving during the PV system time operation.

4 Exploring improvements

- Reduction of wafer's thickness.
- More efficient wafer cutting.
- Other sources of silicone procurement: currently the two sources of silicone for the photovoltaic industry are waste products from the electronics industry and direct extraction and refinement. Both are related however to the production process of electronic grade silicone. The proposed solution, which already exists but is not yet economically competitive, is the development of technology for "true" solar grade silicone.
- In this study we have not included materials resulting from recycling. However innovations in this sector, regarding both the silicone and the recycling of the wastewater from the cutting of the wafer, exist and should be noted and perhaps included in subsequent studies.
- Silicone resulting from wafer recycling, developed by IBM. With this patent IBM ensures the reuse of wafers that would otherwise be thrown away. The Semiconductor Industry Association estimates that 250,000 silicon wafers are produced daily and 3.3% of these are defective, so rejected and thrown out. IBM using a delicate abrasion technique with water counts on being able to recycle, for cell production, about 3,000,000 wafers yearly (equal to 13MW).
- The Japanese company, Sharp, produces about 710MW of solar modules per year. Recycling however is energy intensive even though it reduces the current 21 phases of processing to 5–12 phases.
- The process of recycling the water used during the cutting of wafers with a diamond saw would result in a 15% reduction in environmental impact.

5 Conclusions

Photovoltaic systems that use renewable sources to produce energy cause an environmental impact close to zero during the usage phase even though one should evaluate the impacts caused by maintenance that have not been considered in this study. For this reason photovoltaic systems seem, at first sight, to be environmentally friendly solution.

If we evaluate the PV system using LCA we must include the environmental impacts caused by the production of modules. During this phase the consumption of raw materials and energy necessary to transform these raw materials in a finished product are relevant. The activities necessary to produce modules are the reduction, purification and crystallization of the silicon, the production of cells and wafers, the assembly of the modules and finally the installation of the panels. The LCA of a PV system produced in Europe and installed in Rome points out how, even for latitudes that guarantee a high level of sun radiation, the energy payback time is about 8 years, mainly due to the processes necessary to obtain electronic grade silicon. The payback damage time in terms of environmental impacts and CO_2 emissions are less than the energy pay back due to various reasons: the environmental damage is evaluated considering not only the energy consumption but also the associated emissions. At equal consumption, the European energy mix is more efficient than the Italian one. Therefore it is more convenient to manufacture the PV system in Europe rather than in Italy. Moreover, the energy produced by a renewable source in 25 years in Rome avoids having to use the Italian energy mix. Considering the sun radiation in the city of Rome, the convenience in terms of environmental damage amounts to 4 or 5 years of payback damage time compared to the 8 years needed for the consumption energy. The same can be applied to CO_2 emissions.

The energy consumption to manufacture the PV system is 10034kWh/kWp and the energy produced in 25 years from a renewable source is 36925kWh/kWp.

The environmental damage associated with the manufacture of a PV system is 467 eco points and the avoided damage in 25 years is – 2620 eco points.

The CO_2 emissions during the manufacture of a PV system in Europe are 5 tons and the avoided emissions in Rome during 25 years are – 32 tons.

In order to evaluate the CO_2 emissions and use the data in the elaboration of a city Environmental Action Plan to improve measures for its reduction, a PV system built in Europe and installed in Rome guarantees for the city a level of zero emissions in 25 years (except for the emissions caused by maintenance and decommissioning), compared to the 17 years of zero emissions of the same PV installed in one of the countries that produce silicon. Also, the change in latitude will influence the results.

Energy consumption during manufacture can further be reduced by using new technologies to produce crystalline silicon and by using thin films and other silicon alternative materials, such as cadmium, natural substances or plastic. In the future, the LCA analysis will have to include the environmental impacts associated with the decommissioning of panels about which we still do not know anything.

The quantification of energy consumption associated with each of these activities point out how, aside from the economic considerations, there is an energy pay back time of from 8 to 14 years. Moreover, since energy use is associated with polluting emissions, the environmental compatibility of the system must also take into account the damage caused by these emissions. Only after having carried out an LCA will we have the true “measure” of environmental compatibility.

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