Single issue assessment versus full life cycle assessment: the case of a monocrystalline PV panel.

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Abstract The consequences of climate change and lack of sustainability of current energy models are debated at international level. The use of renewable energies is central to international strategies to battle climate changes. In literature there are several studies on environmental impacts of renewable energy technologies based on the life cycle approach. However, research published to date on these technologies, are limited to submit only two indicators of environmental impact: Carbon Footprint and the Energy Payback Time. This study, conducted in 2010, presents the results of a life cycle assessment of a mono-crystalline silicon solar panel of 1 kWp. The results demonstrate that, to support the choices and decisions in the field of renewable energy, is not sufficient to limit the impact assessment to individual indicators but it is necessary to extend the evaluation to other impact categories and to conduct a full environmental assessment.

1 Introduction

Climate Change is central to international debates. Many worldwide initiatives have been undertaken, such as the United Nations Framework Convention on Climate Change [1] and recently the Copenhagen Accord [2]. The consumption of fossil fuels to produce energy and heat is recognized to have the greatest contribution to the emission of green house gases that causes climate change [3]. When dealing with energy issue, several aspects must be considered: the energy dependency, the environmental impacts of energy production and use and the cost of energy for the citizens. In this context the research of alternative sources of energy lead to the diffusion of renewable energy technologies such as solar-power, wind-power and hydro-power [4]. The scientific community, to support the development of this technologies, has for years invested in the development of so-called renewable energy sources and in assessing the environmental impacts that these technologies generate along their life cycle [5, 6].

In literature there are several studies on the application of these technologies based on the life cycle approach. However, research published to date are limited to submit only two indicators of environmental impact of these technologies: Carbon Footprint (using IPCC 2007 method) and the Energy Payback Time (using Cumulative Energy Demand method) [5-7]. Therefore a complete environmental assessment of these technologies is missing.

In this study, conducted in 2010, a full life cycle assessment of 1 kWp mono-crystalline silicon solar panel is presented.

The objective of this research was to conduct a complete environmental impacts assessment in order to verify the existence of any other significant impact categories beyond those already considered in literature.

2 Materials and methods

To achieve the objective of the research a full environmental assessment was conducted according to the Life Cycle Assessment (LCA) methodology presented in ISO 14040 and ISO 14044 standards [8,9]. An LCA study supplies a comprehensive vision of the environmental aspects of a product or service considering many categories, evaluating the potential impacts and trying to create a holistic view, avoiding the shifting of the problems from an environmental category to another [10].

In this study the environmental impacts of 1 kWp mono-crystalline silicon solar were investigated. According to ISO 14040 this study is structured in four stages: goal and scope definition, inventory analysis, impact assessment and interpretation. To achieve the objective of the research three different impact assessment methodologies were used.

2.1 Goal and scope definition

The objective of the study is to conduct a life cycle assessment of 1 kWp mono-crystalline silicon solar panel (PV) in order to identify which impacts are most relevant and to identify which processes should be improved in order to reduce environmental impacts. The product system consists of the processes necessary to produce a solar panel. The function is the production of a PV panel. The functional unit is the kilo Watt peak (kWp), or rather the maximum power that a solar plant can bestow in ideal conditions. Table 1 reports on the main characteristics of the PV panel under study.

Tab.1: Characteristics of the PV panel under study

Main carachteristics of the PV module		Unit
Technology	Monocrystalline silicon	
N° of Modules	5,56	p
Nominal power	180	W
Module surface	1,292	m2
Module weight	15	kg
N° of cells per module	72	p
Total number of cell	400	p
Cell dimension	0,125 x 0,125	m2
Cell thickness	250	µm

The following processes were considered in the system boundaries:

1) Production of metallurgical grade silicon (MG-Si)
2) Production of electric grade silicon (EG-Si poly) – Siemens
3) Formation of mono crystalline silicon ingot – Czochralsky
4) Waste washing;
5) Second crystallization –Czochralsky
6) Ingot squaring
7) Ingot cutting into wafer
8) Cell production
9) Assembling and testing of the PV panel.

The Balance of System (BOS), or the electronic devices needed for grid connection (such as inverter and cables) were excluded. Other processes that were excluded are: the supporting plate frame, the transport to the place were the panel is supposed to be used and the end of life. This processes were excluded because of lack of information and relevant data. Most of the data were primary and supplied by a big PV panel production enterprise from the north-east of Italy. Secondary data from scientific accredited databases were also used.

2.2 Life cycle inventory

The second phase of the LCA study consists of data collection for the realization of a model representing the life cycle of the PV panel.

To ease the data collection and to clearly identify the processes involved, a scheme has been elaborated highlighting the input flows in terms of electric energy, fuels, coolants, water, raw and auxiliary materials and the output flows in terms of emission to air and water and waste production.

Consequently, the whole system has been subdivided into sub-processes which have been analyzed separately to identify the related input–output flows.

2.3 Life cycle impacts assessment

To achieve the objective of the research three impact assessment methods were used:

10) IPCC 2007: this method assess the impact that a product or process has on climate change impact category; it is widely used in literature to assess the Carbon Footprint of renewable energies [7,11].
11) Cumulative Energy Demand: this method helps in the identification of energy demanded by the different life cycle stages of the product; it is widely used in literature to assess the energy payback time of renewable energies [7,11,12].
12) Eco-Indicator 99: that leads to environmental end-point evaluation; in fact it considers several impact categories and aggregates results in three different area of protection: Human health, Natural Resources and Natural Environment; the application of this method lead a complete environmental impacts assessment [13].

3 Results of Life Cycle Assessment

3.1.1 Life cycle impacts assessment using IPCC 2007

IPCC 2007 method is used to assess impacts of green house gases emissions on climate change in kgCO2-eq. Results of the application of this methodology are presented in Table 2.

Tab.2: IPCC 2007 results

Processes	**Kg CO2eq/kWh**
MG-Si production	125,55
EG-Si poly production	706,90
Silicon Ingot formation	367,99
Waste Washing	1,12
Second crystal.	917,44

Ingot squaring	9,32
Ingot cutting	899,31
Cell production	59,29
Assembling and testing	222,36

3.1.2 Life cycle impacts assessment using Cumulative Energy Demand

Cumulative Energy Demand (CED) method is focused on renewable and fossil energy sources consumption. It was used to determine the quantity and quality of the primary energy relevant to the PV panel product system. This methodology classify energy sources in 5 categories: non renewable, fossil; non renewable, nuclear; renewable, biomass; renewable, wind, solar, geothermic; renewable, water. The results of the impact assessment are presented in Tables 3 and 4.

Tab.3: CED results (Part 1)

Impact category	**Unit**	**MG-Si production**	**EG-Si poly production**	**Silicon Ingot formation**	**Waste Washing**
Non renewable, fossil	MJ eq	1298,04	14260,708	5040,02	13,80
Non renewable, nuclear		21,17	3005,486	98,91	6,21
Renewable, biomass		3,26	172,318	17,46	0,03
Renewable, wind, solar, geothermic		2,82	69,603	15,60	0,02
Renewable, water		67,05	670,582	365,57	1,26

Tab.4: CED results (Part 2)

Impact category	**Unit**	**Second crystal.**	**Ingot squaring**	**Ingot cutting**	**Cell production**	**Assembling and testing**
Non renewable, fossil	MJ eq	1256,039	127,579	9684,49	811,384	2898,275
Non renewable, nuclear		226,638	1,834	353,31	11,661	375,878
Renewable, biomass		43,660	0,446	32,73	2,838	52,694
Renewable, wind, solar, geothermic		39,026	0,399	29,26	2,538	5,398
Renewable, water		911,731	9,271	705,31	58,960	281,688

3.1.3 Life cycle impacts assessment using Eco-indicator 99

The Eco-indicator 99 method was applied adopting the Individualist perspective. This approach considers a 100 year time horizon. For weighting the average of the following perspectives has been adopted: egalitarian, hierarchical and individualistic. Eco-indicator 99 method allocates the results of inventory analysis into the following impacts categories: Carcinogens, Respiratory organics, Respiratory Inorganics, Climate change, Radiation, Ozone layer, Ecotoxicity, Acidification/Eutrophication, Land use e Minerals. The results show that the PV panel under study impacts on all these categories (Tables 5 and 6).

Tab.5: Eco-indicator 99 impact assessment results (Part 1)

Impact category	Unit	MG-Si production	EG-Si poly production	Silicon Ingot formation	Waste Washing
Carcinogens	DALY	2,45E-06	1,91E-06	7,79E-07	1,68E-08
Resp. Oragnics		3,02E-08	2,96E-07	1,51E-07	6,18E-10
Resp. Inoragnics		2,32E-05	1,37E-04	7,04E-05	2,71E-07
Climate change		2,50E-05	1,41E-04	7,34E-05	2,24E-07
Radiation		2,79E-09	5,51E-08	1,15E-08	1,23E-09
Ozone Layers		4,79E-09	7,02E-08	2,57E-08	6,66E-10
Ecotoxicity	PAF*m2yr	1,42E+00	8,47E+00	4,25E+00	1,98E-02
Acidication/ Eutrophication	PDF*m2yr	1,92E+00	1,05E+01	5,49E+00	1,72E-02
Land use	PDF*m2yr	4,87E-01	4,92E+00	2,29E+00	2,56E-02
Minerals	MJ surplus	3,39E-01	3,56E+00	1,82E+00	7,61E-03

Tab.6: Eco-indicator 99 impact assessment results (Part 2)

Impact category	Unit	Second crystal.	Ingot squaring	Ingot cutting	Cell production	Assembling and testing
Carcinogens	DALY	1,89E-06	1,82E-08	1,45E-05	1,16E-07	7,06E-06
Resp. Oragnics		3,74E-07	3,76E-09	3,82E-07	2,39E-08	1,04E-07
Resp. Inoragnics		1,75E-04	1,77E-06	2,07E-04	1,13E-05	7,07E-05
Climate change		1,83E-04	1,86E-06	1,80E-04	1,18E-05	4,55E-05
Radiation		2,42E-08	1,58E-10	2,45E-07	1,00E-09	2,77E-08
Ozone Layers		6,33E-08	6,30E-10	7,49E-08	4,00E-09	1,27E-08
Ecotoxicity	PAF*m2yr	1,06E+01	1,07E-01	9,36E+00	6,81E-01	1,02E+01
Acidication/ Eutrophication	PDF*m2yr	1,37E+01	1,39E-01	1,27E+01	8,82E-01	4,23E+00
Land use	PDF*m2yr	5,63E+00	5,59E-02	8,12E+00	3,56E-01	2,20E+00
Minerals	MJ surplus	4,54E+00	4,61E-02	4,97E+00	2,93E-01	1,85E+01

The next step is damage assessment that sums the results of impact assessment into three area of protection: Human Health, Ecosystem Quality e Resources (Table 7).

Tab.7: Area of protection results

Area of protection	Unit	Total
Human Health	DALY	0,001
Ecosystem Quality	PDF*m2yr	78,143
Resources	MJ surplus	34,124

3.2 Life cycle interpretation

3.2.1 Life cycle interpretation of the eco-indicator 99 results

The categories that most affects Human Health (total value of 0,001 DALY) are: Respiratory inorganics (6,97E-04 DALY), Climate change (6,61E-04 DALY), Carcinogens (2,87E-05 DALY) and Respiratory organics (1,36E-06 DALY).
The imapct is manly due to energy production and consumption.
Ecosystem Quality has a total value of 78,143 PDF*m2*year. The most impacting categories are Ecotoxicity (45,1 PAF*m2*anno), Acidification/Eutrophication (49,5 PDF*m2*anno) and finally Land use (24,1 PDF*m2*anno). The processes that most affect these results are: second crystallization and production and use of energy.
Resources have a total value of 34,124 MJ. This area of protection is mainly affected by aluminium production of the supporting structure of the PV panel (14,2 MJ surplus) and electricity production (12,2 MJ surplus).

3.2.2 Life cycle interpretation of cumulative energy demand results

The 86% of the energy used to produce the PV panel comes from the use of fossil fuels that has great impacts on environment. Nuclear energy contribution to PV panel production is 7,5%. Renewables have a limited contribution.
The processes that have greatest contribution to energy use are: the silicon production (58% of the total energy use) and the ingot cutting (33% of the total energy use).

3.2.3 Life cycle interpretation of IPCC 2007 results

The most impacting process resulted to be the Czochralsky used for the second crystallization with 917,44 kgCO2-eq other relevant processes are the cutting of ingots into wafer and Siemens process used in the production of electronic solar grade silicon.

These results are the same obtained through the application of Eco-indicator 99 methodology relevant to Climate Change category.

4 Discussion

Eco-indicator 99 was used to do a complete environmental assessment of the PV Panel, in fact CED and IPCC 2007 focus on specific environmental issues such as energy use and climate change.

The results of the three methods seem to identify as most impacting the same processes: production of EG-Si, second crystallization and ingots cutting into wafer, assembling and testing. However going deeper into the analysis of the results the three methodologies suggest to intervene in this processes with a different priority.

Eco-indicator 99 suggests to work first on the efficiency of the process of assembling and testing, CED on EG silicon production and IPCC 2007 on second crystallization process.

Moreover through the application of Eco-indicator 99 emerges that PV panel has a greater impacts on Respiratory Inorganics then on Climate Change, which is the most investigated category in literature.

The production and use of energy (4,71E-04 DALY), the production of silicon carbide (1,43E-04 DALY), the production of the aluminium for the supporting structure of the PV panel (3,01E-05 DALY), the production of glass (2,45E-05 DALY) and Tedlar (5,65E-06 DALY) are the most impacting processes when looking at Respiratory Inorganics category.

From these results clearly emerges the necessity to conduct a complete environmental evaluation in order not to exclude shifting of impacts. Basing only on IPCC 2007 results processes such as production of silicon carbide should not be considered as priority when setting environmental impacts reduction actions.

5 Conclusions

Climate change is central to international debates as it affects the economy, the environment and the society worldwide. The use of fossil fuels as source of energy is recognized to give the greatest contribution to this issue.

The scientific community has invested a lot in the identification of new resources of energy and in the assessment of their environmental impacts. However from literature emerges that only partial environmental evaluation of this sources of energy are conducted and are focused on two single indicators: Carbon Footprint and Energy Pay Back Time.

This study conducted in 2010 investigated the environmental impacts of a mono-crystalline silicon solar panel of 1 kWp using a life cycle approach following ISO 14040 and ISO 14044 standards. The assessment was conducted using three different methodologies: IPCC 2007, Cumulative Energy Demand, Eco-indicator 99.

The analysis and interpretation of the results of the three methods lead to some interesting conclusions. Infact each method suggest to intervene in a different process in order to lower environmental impacts:

13) IPCC 2007 identified the second crystallization as the most impacting process.
14) CED identified the production of solar grade silicon as the most impacting process.
15) Eco-indicator 99, which consists of a comprehensive method and lead to a complete environmental evaluation, however identified the assembling an testing as the most impacting process.

As the objectives of the assessment is to understand the major environmental impacts in order to reduce them, if only a single indicator were used to do this assessment we would have invested in the wrong process.

The results demonstrate that, to support the choices and decisions in the field of renewable energy, is not sufficient to limit the impact assessment to individual indicators but it is necessary to extend the evaluation to other impact categories and to conduct a full life environmental assessment.

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