Environmental impact of PV systems

A Review of the environmental impact of different solar PV based systems by using Life Cycle Assessment

AR0531 Innovation & Sustainability
AR1B025-D3 BT Research Methodology

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30-10-2016

Number of words: 2108

Focus and restrictions – The focus lies on the environmental impact of three different PV systems and is restricted to the EPBT (energy payback time) and the GHG emission.

Abstract – Over the last years the use of renewable energy sources is strongly encouraged. PV systems are one of these sources but they use a lot of energy during its total life cycle. This paper represents a review of the environmental impact of different solar PV based systems by using life cycle assessment (LCA). The main question of this literature review paper is: What is the environmental impact of different solar PV based systems by using life cycle assessment (LCA)? Based on a review of research reports and journals, this paper reviews the environmental impact of three different Solar PV systems. It appears that pc PV systems have a shorter EPBT and lower GHG emissions than mc PV systems. The performance of EPBT and GHG emission are better of Amorphous PV systems than of the crystalline PV modules. The differences in the results of the systems were caused by different factors: manufactures, production methods, research methods, efficiency of the modules, installation methods, use of frames and different climates, countries, irradiation and grids.

Key words – PV systems, Environmental impact, Life cycle assessment, EPBT, GHG emission, AR0531

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1 Introduction

Over the last years the use of renewable energy sources is strongly encouraged. Large numbers of fossil fuels are still being used, which among other leads to climate change and global warming. For this reason the use of renewable energy sources and the development of these sources is becoming increasingly important. One of these sources are solar based PV systems.

Generally speaking, PV systems generate electricity from solar energy. Thus it would be free from fossil energy consumption and would be free from environmental impacts. However, it uses a lot of energy during its total life cycle, for example: the manufacturing process, transportation, installation of the modules and recycling.

Life cycle assessment (LCA) is a technique to investigate the environmental impact of a specific product. The life cycle phases of a product can be subdivided into production, usage and end of life phase (Hildebrand, L. ,2014). ISO 14040 and 14044 regulate the procedure in four phases: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA) and interpretation (Hildebrand, L. ,2014:54). In goal and scope the starting point of the LCA is defined. In the inventory analysis the flows of pollutants, materials and resources will be analysed. In the impact assessment phase the energy consumption will be analysed, focussing on different environmental problems. The conclusions of the LCA will then be determined in the interpretation phase (Peng, J. et al., 2014).

These days the LCA technique is used to analyse the environmental impact of a product or multiple products, if a comparison is needed.

This paper represents a review of the environmental impact of different solar PV based systems by using LCA. The main question of this literature review paper is: What is the environmental impact of different solar PV based systems by using life cycle assessment (LCA)?

The life cycle assessment of three (most common) different Solar PV systems has been investigated: mono-crystalline (mc) PV systems, poly-crystalline (pc) PV systems and amorphous PV systems. Then the different results from existing research are compared and discussed. Figure 1 shows the three different PV systems investigated in this literature review paper: mono-crystalline (mc) PV system, poly-crystalline (pc) PV system and amorphous PV system.

Figure 1: Different PV systems. The picture shows the three most common PV systems: mono-crystalline, poly-crystaline and amorphous. Source: Solar Quotation http://www.solarquotation.com.au/blog/types-of-solar-panels-for-homes/

2 Methodology

To collect as many relevant articles as possible, mostly review papers are selected to use for this literature review paper. In these review papers are already different studies collected and reviewed.

The keywords used when searching for literature were: PV systems and life cycle assessment. Also the word: ''review'' was used when searching. These keywords describe the most important subjects of the literature. Literature focused on other renewable energy sources were excluded by using the keyword: PV systems.

In addition, a number of criteria is used to filter the literature. After entering the keywords this specific criteria was applied to assess the literature. All the documents listed below were excluded:

- documents published before 1995
- abstracts
- review documents without the framework of life cycle assessment methodology (ISO 14040 and 14044) mentioned
- documents without LCA results of: mono-crystalline (mc) PV systems, poly-crystalline (pc) PV systems and amorphous PV systems.

The most commonly used literature was retrieved from the database of sciencedirect (www.sciencedirect.com). Some of the sources come from the databases of universities, including the Technical University of Delft.

The data collection of the PV systems was focused on four parameters: efficiency (%), life time (yr), EPBT (yr) and GHG emissions (g- CO2-eq./kW he). The year and the location of the research has also been taken in account. Most of the data used in this literature review paper were gathered directly from summary life cycle tables. This data was filtered and then merged in new tables.

3 LCA of different PV systems

The data used for this literature review paper is mainly submitted by three different literature review papers, which reviewed over twenty different studies.

3.1 Mono-crystalline (mc) PV systems

Wilson and Young (1996) investigated two mono-crystalline PV systems. The energy payback time was investigated of the systems, which were applied in UK buildings. Wilson and Young (1996) concluded that their EPBTs were 7.4-12.1 years for an optimistic scenario.

Kato et al (1998) found for a mono-crystalline PV system a value of 8.9 years for the EPBT and 61 g CO2-eq./kWhe for the GHG emission. It was found that the energy requirement and the emission would decrease to two-thirds when the production scale expanded from 10 to 100 MW/yr.

Kannan et al (2006) found a value of 216 g CO2-eq./kWhe for the GHG emission, which is very high compared to the values of the other investigatios. In the study the EPBT and GHG emission of a mono-crystalline PV system with actual energy yield was investigated. The authors recommended three solutions in order to reduce the energy requirement:

- Improvement in manufacturing of the PV systems. Kannan et al (2006) found that the manufacturing of the modules accounted for 81% of the life cycle energy usage.
- Alternative material for supporting structure. Kannan et al (2006) found that the aluminium supporting structure accounted for 10% of the life cycle energy usage.
- Increase the efficiency

The study resulted in another entry which emphasised the need for improvement of the manufacturing. Kannan et al. (2006:562) found the following:

> ''Silver requirement for manufacturing solar PV modules could contribute to the depletion of silver resources. To meet 5% of the world electricity production from solar PV modules, their production would require about 30% of the current silver production. (Phylipsen and Alsema, 2009)''

Kannan et al (2006) also found that at the end of the lifecycle, the solar PV system generates a large amount of waste. Large-scale disposal of the Solar systems could be a problem in the future, as the rate of installation will increase.

Table 1 listed the reviewed results of the different studies on mono-crystalline PV systems. The differences were caused by different factors:

- manufactures and production methods of the modules used in the different studies
- methods used to achieve the results
- efficiency of the modules
- installation methods in the different studies
- different climates, countries and therefore different irradiation

Because of all these different factors it is not realistic to compare the results. There are too many variables. If a comparison is to be made, the variables should be taken into account. If the modules were tested on the same location and tested with the same method; then there may have been a realistic comparison.

Table 1: LCA results of Review of mono-crystalline PV systems

Author	**Year**	**Location**	**Efficiency (%)**	**Life time (yr)**	**EPBT (yr)**	**GHG emissions (g- CO2-eq./kWhe)**	**Source**
Wilson and Young	1996	UK	12.0	20	7.4-12.1	N/A	29
Kato et al.	1997	Japan	N/A	20	15.5	91	14
Kato et al.	1998	Japan	12.2	20	8.9	61	15
Mathur et al	2002	India	13.0	20	N/A	64.8	17
Alsema and Wild-Scholten	2005	South-European	13.7	30	2.6	41	3
Muneer et al	2006	UK	11.5	30	8	44.0	19
Kannan et al	2006	Singapore	7.3-8.9	25	5.87	217	13
Kannan et al	2006	Singapore	10.6	25	4.47	165	13
Alsema and Wild-Scholten	2006	South-European	14.0	30	2.1	35	4
Jungbluth and Dones	2007	Switzerland	14.0	30	3.3	N/A	12
Wild-Scholten	2009	South-European	14.0	30	1.75	30	28
Ito and Komato	2010	China	N/A	N/A	2.5	50	11

3.2 Poly-crystalline (pc) PV systems

Poly-crystalline (pc) PV systems have almost the same efficiency as mono-crystalline (mc) PV systems, but consume less energy during their life cycles. For this reason, the EPBT is shorter and the GHG emissions are lower for poly-crystalline (pc) PV systems (Peng, J. et al., 2013).

Ito et al. (2003) investigated large scale poly-crystalline PV systems at Gobi desert. It was found that the large scale installation resulted in a low value for the EPBT (less than 2 years) and a low value for GHG emission (12 g CO_2-eq./kWhe).

Table 2 listed the reviewed results of the different studies on poly-crystalline PV systems.

In the table is visible that there are two different values for the GHG emission of the study done by Pacca et al. (2007): 72.4 g CO_2-eq./kWhe and 54.6 g CO_2-eq./kWhe. Pacca et al. (2006:3323) found the following:

> ''The European grid has a comparatively lower CO_2 emission factor than the US grid. Also the primary energy to electricity conversion efficiency of the European grid is slightly higher than that of the US grid. The CO_2 emission factor for the US grid is 700 g CO_2-eq./kWhe, whereas the emission factor for the European grid is 480 g CO_2-eq./kWhe.The electricity to primary energy ratio in the US is 0.30, whereas the ratio in Europe is 0.33. These differences affect the life cycle CO_2 emission of the modules. ''

The differences in the table were caused by the factors that are mentioned in 3.1, but also the result which is described above (the differences between the European grid and the US grid).

3.3 Amorphous PV systems

Peng, J. et al. (2013) found that the performance of EPBT and GHG emission are better of Amorphous PV systems than of the crystalline PV modules. Amorphous PV systems have lower conversion energy than crystalline ones, but require less energy during lifecycle due to simple production technologies.

Nieuwlaar et al (1996) found that the frames used for the modules have a lot of influence on the EPTB. It was pointed out that the EPBT of frameless modules was below 2 years. Adding one more frame could increase the EPTB of the modules with more than half a year. Table 3 listed the reviewed results of the different studies on amorphous PV systems.

The differences in the table were caused by the factors that are mentioned in 3.1 and 3.2, but also the data if the PV modules were frameless or not. When the PV modules were frameless the EPTB were lower than the PV modules with a frame.

Table 2: LCA results of Review of poly-crystalline PV systems

Author	Year	Location	Efficiency (%)	Life time (yr)	EPBT (yr)	GHG emissions (g- CO2-eq./kW he)	Source
Phylipsen and Alsema	1995	South-European	13	25	2.7	N/A	23
Kato and Murata	1998	Japan	11.6	20	2.4	20	15
Alsema	2000	South-European	13	30	3.2	60	2
Ito et al	2003	China	12.8	30	1.7	12.0	9
Hondo	2005	Japan	10.0	30	N/A	53.4	8
Battisti and Corrado	2005	Italy	10.7	20	3.3	26.4	6
Tripanagnosto poules	2005	Greece	N/A	20	2.9	104	27
Alsema and Wild-Scholten	2006	South-European	13.2	30	1.9	32	4
Pacca et al	2007	US	12.92	20	5.7	54.6	21
Pacca et al	2007	US	12.92	20	5.7	72.4	21
Jungbluth and Dones	2007	Switzerland	13.2	30	2.9	N/A	12
Raugei and Bargigli	2007	South-European	14.0	20	2.4	72	23
Ito et al	2008	China	12.8	30	1.9	12.1	10
Ito et al	2008	China	15.8	30	1.5	9.4	10
Wild-Scholten	2009	South-European	13.2	30	1.75	29	28
Ito and Komoto	2010	China	N/A	N/A	2.0	43	11

Table 3: LCA Results of Review of amorphous PV systems

Author	Year	Location	Efficiency (%)	Life time (yr)	EPBT (yr)	GHG emissions (g- CO2-eq./kW he)	Source
Nieuwlaar et al	1996	Netherlands	10	20	N/A	47.0	20
Lewis and Keoleian	1997	USA	5	25	3.0	N/A	16
Alsema	1998	NW-European	6	N/A	3.2	N/A	1
Alsema	2000	South-European	7.0	30	2.7	50.0	2
Meier and Kulcinski	2002	US	5.7	30	N/A	39.0	18
Jungbluth and Dones	2007	Switzerland	6.5	30	3.1	N/A	12
Pacca and Sivaraman	2007	U.S.	6.3	20	3.2	34.3	21
Ito and Kato	2008	China	6.9	30	2.5	15.6	10
Wild-Scholten	2009	South-European	6.6	30	1.4	24	28

4 Conclusions

The environmental impact of three different PV systems was investigated in this literature review paper by using life cycle assessment. The main question of this literature review paper was: What is the environmental impact of different solar PV based systems by using life cycle assessment (LCA)?

This research resulted in the findings below:

- The EPBT of mono-crystalline PV systems vary from 1.75-15.5 years and the GHG emissions vary from 30-217 g CO_2-eq./kWhe.
- The EPBT of poly-crystalline PV systems vary from 1.5-5.7 years and the GHG emissions vary from 9.4-104 g CO_2-eq./kWhe.
- The EPBT of amorphous PV systems vary from 1.4-3.3 years and the GHG emissions vary from 15.6-50 g CO_2-eq./kWhe.
- Poly-crystalline (pc) PV systems have almost the same efficiency as mono-crystalline (mc) PV systems, but the EPBT is shorter and the GHG emissions are lower.
- The performance of EPBT and GHG emission are better of Amorphous PV systems than of the crystalline PV modules.
- The differences in the results of the systems were caused by different factors: manufactures, production methods, research methods, efficiency of the modules, installation methods, use of frames and different climates, countries, irradiation and grids.
- Large-scale disposal of the Solar systems could be a problem in the future, as we increase the rate of installation.
- A large scale installation can result in a lower value for the EPBT and a lower value for GHG emission.

Because of all these different factors, completely substantiated results can't be determined. However, the findings above show which factors play an important role in the environmental impact of PV systems. Improvement of PV systems is needed in order to reduce the environmental impact. The manufacturing process and the material need the most attention.

The various studies show that the irradiation of the tested location or country plays an important role in the environmental impact. For this reason PV systems may not be suitable everywhere. It is recommended to first analyse the location and then determine if installing the PV systems is suitable. It could be possible that applying another renewable energy source will result in a better solution for that specific location, for example the use of wind power.

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