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Review on life cycle assessment of energy payback of solar photovoltaic systems and a case study

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Abstract

This paper aims to examine the environmental performance of the multi-crystalline (multi-Si) photovoltaic installations by conducting a life cycle assessment (LCA) of a typical 1-Megawatt on-grid ground-mounted solar power station in China. An energy payback time calculation will be presented with some further suggestions. After a thorough study of the LCA of solar power station, the boundary of the goal is clearly presented, making it feasible to study the total input and the annual output of the system. Specifically speaking, the total energy input, including the energy input of the module manufacturing and the energy input of balance of system (BOS) is 19.5548 x10^6 MJ, while the annual energy output is calculated to be 8.328 x 10^6 MJ. Thus the energy payback time (EPBT) is 2.3 years, revealing the conclusion that the establishment of the solar power station would contribute to a clean usage for more than 27 years, given the assumption of a 30-year operation period. Therefore, the solar power station is much more environmental friendly compared to the traditional fossil fuel systems.

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Keywords: *Photovoltaic system, Multi-Si, Life cyle assessment, Energy payback time.*

1. Introduction

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The accelerating development of the economics and the exponential growth of the world population have witnessed the increasing demand of the energy, catalyzing the speed of burning of traditional fossil fuels. At the same time, the vast consumption of fossil fuels could also cause a series of serious environmental problems such as global warming, air pollution, acid rain and so on [1]. Therefore, people have been seeking for the alternative sustainable and renewable energy technologies, especially photovoltaic (PV), to cope with the challenges of energy shortage and environmental pollution [2].

Solar power, no matter using photovoltaic (PV) directly or using concentrated solar power (CSP) indirectly, is the conversion of sunlight into electricity, in which photovoltaic convert light into an electric current using the photovoltaic effect [3]. There is no fossil energy consumption and greenhouse gas (GHG) emission during its operations, theoretically, thus solar power seems to be environmental friendly comparably [4]. However, when the whole life cycle assessment is taken into consideration, including the solar cell manufacturing processes, PV module assembly, balance of system (BOS) production, material transportation, PV system installation and retrofitting, and system disposal or recycling, it actually incurs significant amount of energy input. As a result, a life cycle assessment (LCA) is often introduced at such situation to scientifically investigate the whole picture of the environmental impact of such a PV system installation, elaborating by the commonly used factor of energy payback time (EPBT) [1].

According to the Handbook of Life Cycle Assessment, LCA is usually defined as the "compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life time", meaning that it aims to evaluate the whole environmental burden with consideration of the entire input and output process at all stages over a product's life time [5-8]. The methodology of LCA generally consists of four main sectors: the goal and scope definition, inventory analysis, impact assessment and interpretation as shown in the following figure 1 to form an entire framework [9].

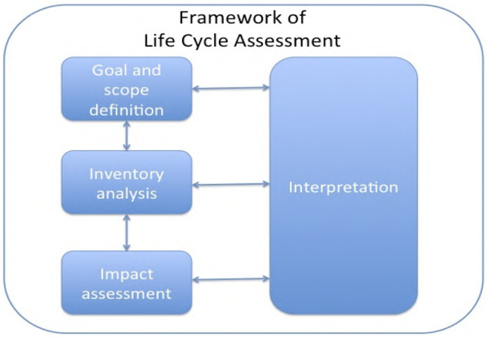

Figure 1
Framework of Life Cycle Assessment

Some scholars have already conducted the LCA analysis on the PV application of solar power installations, and results could be found that PV-based electricity generation systems generate significantly lower GHG emissions than the traditional fossil fuel stations, and the difference could be as high as 89% if the PV-based electricity generation systems are connected to the grid [10]. To further investigate the environmental impact of the PV stations, a closer study of LCA will be conducted, and this paper would primarily use the EPBT indicator to demonstrate the issue.

EPBT is defined as the years a PV system has to operate in order to recover the energy input, both from the manufacturing of modules and the energy requirement of the balance of system (BOS). The calculation of EPBT can be presented as Eq. (1):

$$EPBT = E_{input} / E_{output} = (E_{PV} + E_{BOS}) / E_{output} \quad (1)$$

Where, E_{input} equals to the energy input during the module life cycle (which includes the energy requirement for manufacturing, installation, energy use during operation, and energy needed for decommissioning) plus BOS components (which includes the support structures, cabling, electronic and electrical components, inverters) (Mj). E_{output} is the annual primary energy savings due to electricity generation by PV system, (MJ) [11].

2. Life cycle assessment for PV systems

2.1 Goal and scope definition

Considering the current circumstance of PV installations in China, this paper aims to choose a typical 1-MW on-grid ground-mounted multi-Si PV station in China, consisting of 4568 pieces of modules. Since the multi-Si columns are sawn into wafers with a square size of $156x156mm^2$ [12], while a single panel is made up of 60 pieces of solar cells with tiny spaces between. The correspondent data is presented in the following Table 1:

Table 1
The correspondent data of the 1-MV multi-Si PV station

Capacity	Module type	Rated Power	Cell Area (m^2)	Number of Cells	Cell Area per Module (m^2)	Unit Module Area(m^2)	Total Cell Area (m2)	Total Module Area(m^2)
1 MW	Multi-Si	270Wp	0.024336	60	1.46	1.65	6670	7537.2

2.2 LCA boundaries of the multi-Si PV modules

The whole LCA of the multi-Si PV modules could be divided into two parts: the manufacturing of PV panel and BOS which includes inverter, controller, junction box, cabling, array support, battery, etc. During the manufacturing of PV module stage, the silica sand is firstly purified by reducing quartz, obtaining the metallurgical grade silicon (MG-silicon), which would be further purified into electronic silicon (EG-silicon) by Siemens process or more preferably, into solar-grade silicon (SoG-silicon) by modified Siemens process. The EG-silicon and SoG-silicon are then mixed to form the silicon feedstock that would be molten and cast into molds to form polycrystalline blocks, which could directly produce the multi-Si wafers. After the wafer sawing, the next step is cell production, followed by the final PV panel or laminate manufacturing. The difference between PV panel and the laminate is that the former one has an additional aluminum from which could be used to strengthen and mount the module, unlike laminates which are commonly used on the BIPV buildings. Therefore, in our study, PV panel will be our final product of manufacturing. Figure 2 reveals the LCA boundaries of the multi-Si PV station.

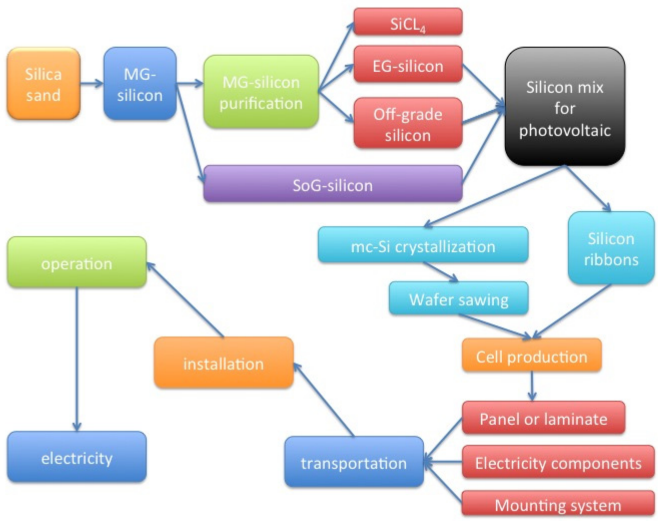

Figure 2
LCA boundaries of the multi-Si PV station

2.3 Energy requirement in the life cycle of multi-Si PV stations

As early as in the 1970s, scholars already did researches to investigate the life cycle and energy payback time for the solar cells production using the technics at that time, resulting in an EPBT of more than 20 years [13]. In the early 1990s when the crystalline silicon PV stations were firstly introduced and installed, scientists began conducting the life cycle assessment of the environmental impact. Thanks to the continuing improvement of the PV production technologies, the adoption of the lower energy estimate in the process of the preparation of the silicon feedstock, the reusing and recycling of the materials as well as the better value chain management, the energy requirement of the per unit crystalline silicon has decreased dramatically from over 10,000 MJ to less than 3000 MJ. Since the energy requirement for the PV panel would not only be contributed by the silicon part but also due to the aluminum frame, Alsema and Wild-Scholten's study would be adopted as the reference here, where the total energy requirement per unit area of the multi-Si panel is 3210 MJ_p, with 270 MJ_P reflecting on frame [14]. However the energy input for module has significantly dropped in the recent years, thus this figure would be more properly assumed to be 1000MJ_p. Please see the detailed energy requirement in each process in the Table 2.

Apart from the manufacturing of the PV modules, the rest of the components in the whole life cycle of the construction of the PV stations, known as BOS, should also be considered when calculating the energy requirement. As different applications of PV systems, such as on rooftop, BIPV, ground field, on-grid or stand-alone ones, would witness quite differentiate consumptions of BOS components such as array support and battery, this paper would simply assume that the PV system would be on-grid ground-mounted with one-time replacement of inverter in the middle of the operation period. According to this assumption, Alsema et al. Alsema and Wild-Scholten pointed out that the BOS energy requirement would reach the astonishing 100 MJ/m^2 thanks to the huge amount of concrete and steel used for the supporting system. The other critical energy requirement component is inverter, which would consume 503 MJ_p/m^2 [15].

Another factor is the transportation process, and assumptions have been made that the unit energy requirement for this was estimated to be 2-5 MJ/t/km, the average weight per m^2 of panel is 15kg [16], and the average transportation distance would be 300km in China. Therefore the total weight of the panel in this case would be 100.05t, and the average energy requirement of the transportation would be 105,052.5 MJ, adopting the average unit energy requirement of 3.5 MJ/t/km.

The life cycle energy requirement data is summarized in the following Table 2.

Table 2
The life cycle energy requirement summary

Component	**Si feedstock production**	**Wafer process**	**Cell production**	**Module assembly**	**Frame**	**Supporting + cabling**	**Inverter**	**Transportation**
Per Unit (**MJ_p/m^2**)	1000	550	400	500	270	100	503MJ/kw*	13.9
1-MW (**MJ_p**)	$6.67x10^6$	$3.6885x10^6$	$2.668x10^6$	$3.335x10^6$	$1.8 x10^6$	$0.667 x10^6$	$0.6213x10^6$	$0.1050525x10^6$

*The unit here is MJ/kw. When converted into the common unit here in this table, this figure shall be 93.14 MJ/m^2.

2.4 Energy output and the EPBT time for a 1-MW multi-Si PV station

In dessert areas of China where large ground mounted PV stations are established, for example, the Gobi Desert of China, the annual irradiation rate (AIR) is estimated to be 2017 $kWh/m^2/yr$ [17] (that is, 7261.2MJ/ m^2/yr), with estimated electricity conversion efficiency (E_e) to be 17.5%. The system performance ration could be 0.835 according to the measurement at the grid connection side [18]. The total efficient area (Area) of the PV station is 7261.2 m^2. Therefore the annual solar power electricity generation (E_{output}) would be calculated using the following Eq. (2):

$$E_{output} = AIR \times E_e \times Area = 7261.2\ MJ/\ m^2/yr \times 7537.2m^2 \times 17.5\% \times 0.835 = 8.328 \times 10^6\ MJ/yr \qquad (2)$$

According to Eq. (1):

$$EPBT = E_{input} / E_{saved} = (E_{PV} + E_{BOS}) / E_{output} = 19.5548 \times 10^6\ MJ/ 8.328 \times 10^6\ MJ/yr = 2.3\ yrs$$

3. Discussions and Conclusions

The paper conducted a LCA of a 1-MW on-grid ground-mounted multi-Si PV system in China, demonstrating the overall energy input and annual energy output of such system with an energy payback time of 2.3 years. The findings and further study suggestions are summarized as below:

1) Although the primary energy input of the manufacturing of wafer, cell and solar panels is significant, adding the massive energy consumption during the BOS process, the establishment of the solar power station is still environmental friendly compared to the traditional fossil fuel systems, with an EPBT of 2.3 years in this case study.
2) Taken 30 years as the operational period of PV stations, there will be 27.7 years of net energy saving in its whole life cycle.
3) The result in this study could be somehow theoretical, due to the lack of data of the BOS components and the transportation energy input components other than PV panels. Also, the calculation did not include the operational energy input, which could be relatively high in the dessert area in China where heavy cleaning and fitting workload on modules might be required.
4) A sensitivity analysis could be made in future studies to see how the EPBT result is varied according to the different locations.
5) The data used in this study when calculating the energy input is relatively old, meaning that the result would be pessimistic to some extent.
6) The estimated electricity conversion efficiency used in this paper is the figure several years ago, so the calculation of the first-year electricity generation could be noticeably lower than the empirical result. However, the fading effect is not taken into consideration due to the simplicity intention, the overall electricity generation could be a proper reflection of the reality. Nevertheless, a further closer study should be carried to justify this issue.

Nomenclature

A	E_{input}	the overall energy input during the whole life cycle
B	E_{PV}	the energy input on the manufacturing of PV modules
C	E_{output}	the annual electricity generation of the PV system
D	E_{BOS}	the energy input of the balance of system

References

[1] Jingqing Peng, Lin Lu*, Hongxing Yang,. Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic system. *Renewable and Sustainable Energy Reviews* 2013;**19**:255-74.

[2] Nishimura A, Hayashi Y, Tanaka K, Hirota M, Kato S, Ito M, et al. Life cycle assessment and evaluation of energy payback time on high-concentration photovoltaic power generation system. Applied Energy 2010;87:2797–807.

[3] Solar Cells and their Applications Second Edition, Lewis Fraas, Larry Partain, Wiley, 2010, ISBN 978-0-470-44633-1 , Section10.2.

[4] Jinqing Peng, Lin Lu. Investigation on the development potential of rooftop PV system in Hong Kong and its environmental benefits. Renewable and Sustainable Energy Reviews 2013; 27: 149-162.

[5] ISO International Standard 14040, 1997E. Environmental management – Life cycle assessment - Principles and framework. International Organisation for Standardisation (ISO), Geneva.

[6] ISO International Standard 14041, 1998E. Environmental management - Life cycle assessment - Goal and scope definition and Inventory analysis. International Organisation for Standardisation (ISO), Geneva.

[7] ISO International Standard 14042, 2000E. Environmental management - Life cycle assessment - Life cycle Impact assessment. International Organisation for Standardisation (ISO), Geneva.

[8] ISO International Standard 14043, 2000E. Environmental management - Life cycle assessment - Life cycle Interpretation. International Organisation for Standardisation (ISO), Geneva.

[9] Sherwani AF, Usmani JA, Varun. Life cycle assessment of solar PV based electricity generation systems: a review. Renewable and Sustainable Energy Reviews 2010;14:540–4.

[10] Fthenakis V M, Kim H C, Alsema E, Emissinos from phtovoltaic life cycles[J]. Evironmental Science & Technology, 2008, 42(6): 2168-74.

[11] Kim, HC, Fthenakis, VM. Life cycle energy demand and greenhouse gas emissions from an amonix high concentrator photovoltaic system. In: Conference Record of the 2006 IEEE 4th World Conference on Photovoltaic Energy Conversion; 2006. pp. 628–631.

[12] Wild-Scholten, MJ, Alsema, EA. Environmental life cycle inventory of crystalline silicon photovoltaic system production: status 2005/2006. (Download from /http://www.ecn.nl/docs/library/report/2007/e07026-LCI data-cSiPV-pubv2_0.xlsS).

[13] Hunt, LP Total energy use in the production of silicon solar cells from raw materials to finished product. In: Photovoltaic Specialists Conference. 12th, Baton Rouge, La., November 15–18; 1976.

[14] Alsema, EA, Wild-Scholten, MJ. Reduction of the environmental impacts in crystalline silicon module manufacturing. In: Proceedings of the 22nd European Photovoltaic Solar Energy Conference and Exhibition. Milan Italy, 2007; p. 829–836.

[15] Pacca S, Sivaraman D, Keoleian GA. Parameters affecting the life cycle performance of PV technologies and systems. Energy Policy 2007;35:3316–26.

[16] Alsema EA. Energy requirements of thin film solar cell modules—a review. Renewable and Sustainable Energy Reviews 1998;2:387–415.

[17] Ito M, Kato K, Komoto K, Kichimi T, Kurokava K. A comparative study on cost and life-cycle analysis for 100 MW very large-scale (VLS-PV) systems in deserts using m-Si, a-Si CdTe and CIS modules. Progress in Photovoltaics Research and Applications 2008;16:17–30.

[18] Jahn U, Nasse W. Operational performance of grid-connected PV systems on buildings in Germany. Progress in Photovoltaics Research and Applications 2004;12(6):441–8..

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