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Prospects of life cycle assessment of renewable energy from solar photovoltaic technologies: A review

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ABSTRACT

Life cycle assessment (LCA) is a comprehensive method used to investigate the environmental impacts and energy use of a product throughout its entire life cycle. For solar photovoltaic (PV) technologies, LCA studies need to be conducted to address environmental and energy issues and foster the development of PV technologies in a sustainable manner. This paper reviews and analyzes LCA studies on solar PV technologies, such as silicon, thin film, dye-sensitized solar cell, perovskite solar cell, and quantum dot-sensitized solar cell. The PV life cycle assumes a cradle-to-grave mechanism, starting from the extraction of raw materials until the disposal or recycling of the solar PV. Three impact assessment methods in LCA were reviewed and summarized, namely, cumulative energy demand (CED), energy payback time (EPBT), and GHG emission rate, based on data and information published in the literature. LCA results show that mono-crystalline silicon PV technology has the highest energy consumption, longest EPBT, and highest greenhouse gas emissions rate compared with other solar PV technologies.

1. Introduction

Climate change, impacts of mining fossil fuels, resource depletion, and energy shortage worldwide are the most pressing environmental concerns that need to be addressed in addition to the challenges in finding renewable energy solutions for the future. Among renewable energy resources, solar energy is the most abundant natural resource on earth. Solar energy is generated by converting sunlight into thermal or electrical energy powered by the application of photovoltaic (PV) devices. Solar energy is easily exploitable, clean, discreet, inexhaustible, long lasting, and reliable. These advantages make solar energy a key factor viable for meeting the world's growing electricity energy demand because of the increase in human population and infrastructure expansion.

Presently, the global market of solar PV technologies has exhibited impressive growth rates over the past decades. According to the International Energy Agency (IEA) [1] (change reference), by the end of 2016, at least 303GWs of solar PV have been installed over the world including grid-connected and off-grid installations as reported in Fig. 1. Continuous expansion of global PV market was observed from 2009 to 2016 which reflects the positive outlook of PV trend. Moreover, over 265 GW of cumulative PV have been installed in 25 countries under the IEA Photovoltaic Power Systems Programme (PVPS). China had the largest cumulative installed PV capacity, leads the global PV market with double growth from 43.5 GW in 2015 to 78.1 GW in 2016, followed by Japan at 42.8 GW, and Germany with 41.2 GW in 2016 as reported in Fig. 2 [1]. Other countries, such as the United States of America (USA) and India have installed PV systems more than 50% growth reported from 2015. The following countries for instance Italy, United Kingdom, France, Australia, and Spain, grew significantly and

Abbreviations: a-Si, amorphous silicon; BIPV, building integrated photovoltaic; BOS, balance of system; CdTe, cadmium telluride thin film; CIS, copper indium selenide thin film; DSSC, dye sensitized solar cell; EG-silicon, electronic silicon; EPBT, energy payback time; FTO, fluorine tin oxide; GHG, greenhouse gases; GWP, global warming potential; ITO, indium tin oxide; LCA, life cycle assessment; LCI, life cycle inventory; MG-silicon, metallurgical grade silicon; mono-Si, mono-crystalline silicon; multi-Si, multi-crystalline silicon; NER, net energy ratio; PET, polyethylene terephthalate; PR, performance ratio; PSC, perovskite solar cell; PV, photovoltaic; QDSSC, quantum dot sensitized solar cell; SiO_2, silicon dioxide; TCO, transparent conducting oxide; ZnO, zinc oxide

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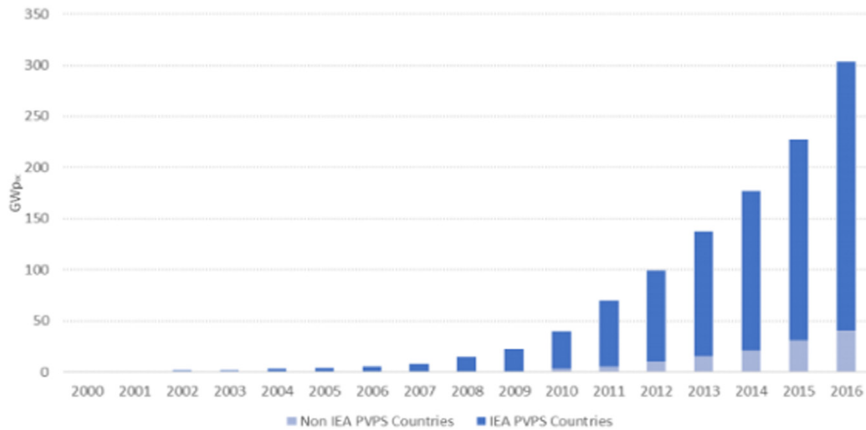

Fig. 1. Total PV installations for IEA PVPS countries and non IEA PVPS countries from 2002 until 2016 [1].

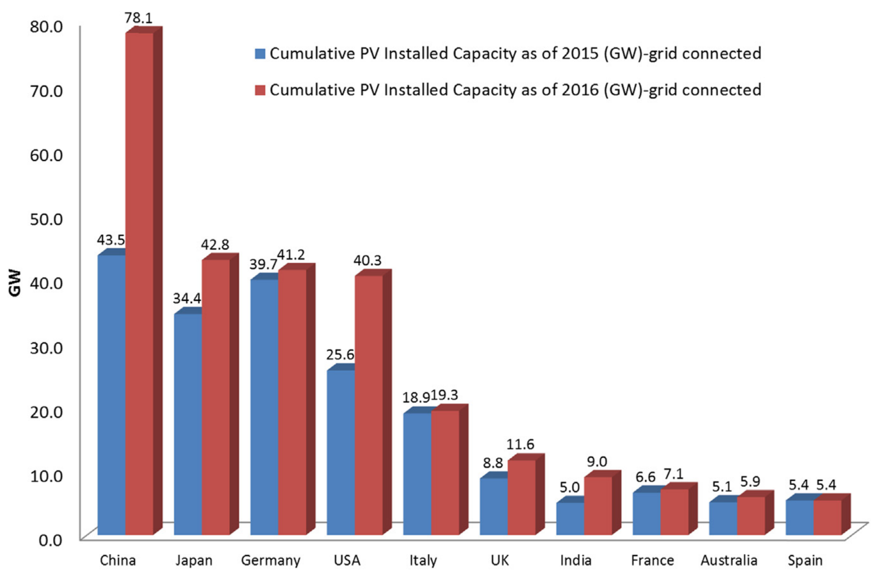

Fig. 2. Top 10 countries for total cumulative PV installed capacity as of 2015 and 2016.

have cumulative installed capacity of 19.3, 11.6, 7.1, 5.9, and 5.4 GW, respectively, as of 2016. Despite with this significant growth, solar PV technologies have considerable potential as renewable energy sources to meet the world's energy demand.

As of 2016, silicon solar cells have conquered 93% of global PV market [2] with highest conversion efficiency reported by the National Renewable Energy Laboratory (NREL) for mono-crystalline silicon (mono-Si) and multi-crystalline silicon (multi-Si) are 25.8% and 22.3% respectively, according to the solar cell efficiency chart in Fig. 3 [3]. The rapid growth in capacity are accompanied by the development of Chinese manufacturers and declining in capital expenditures [1,4]. The second generation of thin film solar cells, amorphous silicon (a-Si), cadmium telluride (CdTe) and copper indium selenide (CIS) reveal lower efficiencies than silicon solar cells with corresponding efficiency of 14.0%, 22.1% and 22.6%, respectively [3]. Impressive rapid growing of new emerging solar PV technologies such as dye sensitized solar cell (DSSC), perovskite solar cell (PSC), and quantum dot sensitized solar cell (QDSSC) in last decades have motivated research interests in these technologies toward simplest fabrication and cost effectiveness. According to NREL, the recent record efficiency of DSSC, perovskite and quantum dot solar cells are 11.9%, 22.1%, 13.4%, respectively. These potential candidates play significant role in global PV market even though the technologies presently in R&D stage. As the PV market grows, their development needs to be understood, and their present and future environmental and energy performances must be assessed. Thus, the life cycle assessment (LCA) of solar PV becomes crucial in determining their environmental performance over the past decades.

Up to present, there are few review papers on LCA of PV have been published [5–11]. Sherwani et al. (2010) [5] analyzed the LCA of silicon-based panels. The studied of Peng et al. (2013) [6] and Baharwani et al. (2014) [7] only considered the energy payback time (EPBT) and greenhouse gas (GHG) emissions of crystalline silicon and thin film PV modules. Darling et al. (2013) [8] and Lizin et al. (2013) [9] focused to review the environmental profile of organic PV. Furthermore, the LCA of silicon-based PV panels and balance of system (BOS) were reviewed by Gerbinet et al. (2014) [10]. Meanwhile, J.H. Wong et al. (2016) [11] only reviewed the embodied energy requirements of mono-crystalline and poly-crystalline silicon PV systems. The comparison of environmental impact of the new emerging technologies are not presented elsewhere. Therefore, this paper highlights to summarize up-to-date review and investigated a comparative LCA of different PV technologies including crystalline silicon, thin film and new emerging solar PVs such as DSSC, perovskite, and quantum dot-sensitized solar cell based on earlier studies. It is necessary to evaluate new emerging solar PVs in this review as large academic and industrial research relevance in these technologies while silicon and thin film modules were considered as there are extensively manufactured in the market.

Thus, the rational of this study is to compile and investigate the environmental impacts and problems of different solar PV technologies throughout their life cycle and explore improvement modifications of