Applied Energy 189 (2017) 245–256

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

A climate rationale for research and development on photovoltaics manufacture

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HIGHLIGHTS

- Current research underestimates climate impact of PV manufacturing GHGs.
- Radiative forcing quantifies time-sensitive climate impact of GHGs over PV lifecycle.
- GHG intensity of electricity used to manufacture PV is a significant climate hotspot.
- Climate benefit of low-carbon PV manufacture equivalent to 4% module efficiency gain.
- Manufacturing oriented R&D should complement R&D on module efficiency improvements.

ARTICLE INFO

Article history:
Received 6 September 2016
Received in revised form 9 December 2016
Accepted 10 December 2016

Keywords:
Photovoltaics
Climate impacts
Energy sustainability
Photovoltaics manufacturing

ABSTRACT

Photovoltaic (PV) power generation is critical to many climate policy goals, as PV electricity results in little or no greenhouse gas (GHG) emissions during use, utilities and governments view PV installations as a way to accelerate progress towards emissions reduction targets. However, typical analyses of the GHG implications of the PV lifecycle ignore inter-temporal effects, in which the initial GHGs emitted in PV manufacturing phase must be offset by avoided fossil-fuel combustion emissions during use. Thus, the overall climate benefits of PV are a function of both GHG efficiency of PV manufacture, and electricity generation efficiency of deployed modules during use. Improvements to PV manufacture result in immediate climate benefits, in contrast with improvements in module efficiency which may offset greater GHG emissions, albeit over decades of useful life.

This study presents a novel framework using the cumulative radiative forcing (CRF) metric to demonstrate the significant climate benefit of improving PV manufacturing processes predominantly located in GHG-intensive geographies and determines the equivalent increase in module efficiency that provide the same climate benefit. The findings show low-carbon PV manufacturing increases the life-cycle climate benefit by 20% and is equivalent to increasing the module efficiency from a baseline value of 17% to 21.7% and 16% to 18.7% for mono-Si and multi-Si modules, respectively. With commercial module efficiency having increased annually by only 0.25% over the last 12 years, the implication is that improving PV manufacturing may be more effective than module efficiency improvements for increasing the climate benefit of terawatt scale PV installations.

1. Introduction

Global photovoltaic (PV) installations are projected to exceed 1 terawatt as policy-makers strive to reduce global warming impacts of electricity production. For example, the SunShot Initiative launched by the United States Department of Energy proposes more than 630 GW of installed PV capacity by 2050 [1] and China is targeting 150 GW of installed capacity by 2020 [2]. The climate benefits of PV are determined by the displacement of non-renewable electricity sources during the use phase of the PV lifecycle, compared to the GHG emissions required to manufacture PV modules. Thus, improvements in the life-cycle GHG emissions of PV can take two forms (1) increasing module efficiencies to generate more electricity during use, and, (2) reducing GHG emissions associated with PV manufacturing processes.

To date, the dominant PV research and development (R&D) strategy is to improve life-cycle environmental and economic performance by increasing PV module efficiency [3,4]. A review

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http://dx.doi.org/10.1016/j.apenergy.2016.12.050
0306-2619/

and categorization of the 137 Department of Energy PV-related competitive awards from 2012 to 2016 shows that 48% of the R&D spend was allocated to increasing the module efficiency and 9% to improving the upstream PV manufacturing processes (Section 11 supplementary information). Furthermore, if only silicon technologies are considered (mono-Si, multi-Si and thin film Si), the R&D spend on projects focusing on improving PV manufacturing is 4%. In response to R&D, use phase efficiencies for commercial and emerging PV technologies have increased significantly over the last 3 decades [5], albeit at irregular rates [6]. Nonetheless, the upstream silicon feedstock purification processes necessary to produce high-efficiency modules continue to be energetically expensive, accounting for 40% of the energy consumed in manufacturing crystalline silicon modules [7]. Furthermore, as PV manufacturing increasingly migrates to locations sourced by GHG-intensive electric mixes, the GHG emissions of global PV manufacture may also increase. For example, China's contribution in the worldwide module production market has increased from 5% in 2005 to 69% in 2014 [8]. Therefore, current PV R&D efforts focusing on module efficiency improvements may forgo opportunities to enhance the climate and environmental performance of PV systems through manufacturing improvements, as well as derive concomitant benefits like reduced toxicity, better human health and safety [9] and decreased reliance on materials with limited availability [10–12].

Reducing the climate impact of upstream processes associated with PV technologies requires understanding the technology specific trends that drove historical improvements and using this to prospectively analyze the potential for further incremental improvements as intrinsic material and manufacturing limits are approached. For example, reduction in the silicon wafer thickness which drove past manufacturing improvements, may not be a viable strategy in the future as breakage and cracking rates in wafer manufacturing operations increase below a threshold thickness [13]. Additionally, it is necessary to compare the potential of hypothetical improvements in current PV manufacturing processes to those that may be available by increases to module efficiency that could achieve the same climate benefit. Because manufacturing occurs prior to use, such a comparison must account for temporal dimensions of radiative imbalances in the atmosphere [14–18]. Thus, for an equal mass of GHG emitted and offset, the climate impact of manufacturing emissions is greater than the global warming burdens avoided by the GHGs offset later in the use phase.

PV environmental studies quantify the PV manufacturing improvements using the GHG payback-time, energy payback-time or GHG intensity of PV electricity metrics. The energy payback-time is the time required by the PV module to generate the amount of energy utilized during manufacturing [7] [19–30]. The GHG intensity of the PV electricity is the ratio of the mass of GHG emitted during PV manufacturing and the electricity generated over the lifetime of the PV module [7,19–21,24,25,29,30]. The GHG payback-time is the time required for the PV module to displace (at the deployment site) the mass of GHG emitted during PV manufacturing [24,26]. While quantifying the energy and GHG trade-off over the manufacturing and the use-phase of the PV module, the aforementioned metrics do not account for the time-sensitive climate impact of manufacturing GHGs that are emitted earlier in the PV lifecycle than the GHGs avoided subsequently post-installation [16]. Therefore, existing PV environmental studies cannot inform the PV R&D policy on the actual magnitude of the climate gains to be achieved by reducing the manufacturing energy and GHG footprint. Although there have been recent reviews and harmonization studies on the GHG intensity of PV electricity [31,32] and research on optimally locating manufacturing and deployment sites for reducing the GHG and energy impacts during rapid growth phases of global PV installations [33,34], these stopped short of analyzing the potential for future gains in time-sensitive climate benefit of improving PV manufacturing. One study presented manufacturing trends over a shorter time frame of 5 years [35], but does not quantify the climate benefit of GHG and energy reduction in PV manufacturing processes using a time sensitive metric.

This paper addresses the above knowledge gap by presenting a novel framework to quantify the time-sensitive climate impact of GHGs emitted and avoided over the PV lifecycle, demonstrates the difference between using the GHG and the climate metric to inform R&D on increasing the climate benefit from PV, and analyzing if the climate benefit from PV manufacturing improvements are significant enough to motivate increased R&D on reducing the energy and material footprint of PV modules. Through analysis of significant manufacturing improvements in an environmental experience curve (Fig. 1), this research quantifies the climate benefit of PV manufacturing improvements using the time sensitive cumulative radiative forcing (CRF) metric [36]. The CRF metric is a time integrated measure of the radiative forcing (in Wm^{-2}) due to an imbalance in the incoming and outgoing infrared radiation in the atmosphere induced by a GHG emission and depends on the mass and timing of the GHG emission [37]. By calculating the net CRF benefit over the PV lifecycle as the difference between the CRF impacts of PV manufacturing emissions and the CRF benefit through the GHGs subsequently offset by PV electricity generation, this research determines the time-sensitive climate benefit of GHG emission reductions through PV manufacturing improvements. Further, this approach demonstrates that the conventional GHG metrics underestimate the climate benefits of PV manufacturing improvements (Fig. 2). To accelerate the development of less climate-intensive PV manufacturing pathways for the future, this work identifies CRF hotspots in existing PV manufacturing processes (Fig. 4). To demonstrate the significance of the climate benefit from manufacturing improvements, we calculate the equivalent increase in module efficiency delivering the same CRF benefit as addressing the manufacturing hotspots (Figs. 3 and 5) and compare this equivalent increase with the historical rate of increase in commercial module efficiency. Furthermore, based on the findings, we identify three PV manufacturing R&D strategies that can address the PV manufacturing hotspots and increase the climate gain from future PV installations that are expected to reach a terawatt scale (Section 3.6).

2. Methods

2.1. Data collection, harmonization and generation of PV manufacturing experience curve

To analyze temporal trends in the manufacturing energy embodied in a PV module, data from published PV studies must be harmonized for the primary energy required to produce one peak watt of a PV module (MJ/W_p) [7,19–21,26,35,38–109]. Four commercially dominant PV technologies – mono-crystalline silicon (mono-si), multi-crystalline silicon (multi-si), cadmium telluride (CdTe) and amorphous silicon – account for around 99% of the world PV market. A broad review results in 214 data points, covering energy requirements for raw material extraction, purification, fabrication of PV cells, and PV module assembly. However, data from studies with ambiguous system boundary definitions or assumptions for the material and energy used in PV production must be eliminated. For example, we discounted a data point from a study which did not mention if frames are included in the energy required to manufacture the module [81]. To avoid duplications, data points which were repeated across multiple studies are