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Strengthening the case for recycling photovoltaics: An energy payback analysis

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HIGHLIGHTS

- This study demonstrates potential opportunity for energy savings from recycling PV.
- As the efficiency increases, the EPBT savings from recycling decreases.
- Exhaustive material recycling reduces EPBT by 0.5 years for CdTe and 1.1 years for c-Si.
- Frameless designs decrease EPBT, may eliminate economic incentive for recycling.
- PV with shorter lifetime less likely to be collected, recycled, and reap EPBT benefit.

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ABSTRACT

The energy payback time (EPBT) of photovoltaic materials when recycled is analyzed. In particular we are interested in under what conditions recycling yields energy payback improvements equivalent to efficiency. The sensitivity to dynamic variables such as composition, efficiency, and recycling rate is also evaluated. We found that, in general, for all technologies, as the efficiency increases, EPBT savings from recycling decreases at a decreasing rate. This result suggests that greater EPBT savings are obtained for low efficiency module recycling, especially when considering framed modules whose aluminum materials make up between 50% and 70% of the embodied energy. Solar PV technologies have exponentially increasing production suggesting an equally growing future waste stream. No policy currently exists in the US for end-of-life management, collection, or recycling. This study demonstrates the potential opportunity for energy savings from recycling and pinpoints metrics that would be important to such a policy.

1. Introduction

Renewable energy technologies i.e. hydro, biomass, and solar have emerged to address the negative environmental impacts of increasing use of fossil fuels. Solar photovoltaics (PV) are an attractive renewable energy technology because they avoid significant carbon emissions during the use phase compared to non-renewables, have a long useful lifetime estimated at 20–30 years, and they take advantage of a stable and plentiful energy resource – the sun. In PV research and development, there is a strong emphasis on efficiency gains as one of the best strategies to increase the technology's economic and environmental attractiveness.[1] However, efficiency, while important, is only one strategy for reducing environmental impact and increasing energy savings. Recycling is another strategy with potential that has yet to be fully recognized due to the current lack of collection infrastructure and uncertain set of processing technologies. The use of secondary materials in production has the potential to reduce material energy intensity as well as improve economics by providing a less expensive material supply. This work explores under what conditions energy payback from increases in recycling is equivalent to increases in efficiency.

For a significant number of primary and secondary PV materials, LCA data is either incomplete or unavailable; for this reason we use cumulative energy demand data to evaluate energy payback. Energy payback time (EPBT) is the energy analogy to financial payback, it quantifies the time it takes for the energy produced after technology installation (in terms of primary energy equivalent) to equal the total energy required to produce it (including the energy burden of materials, manufacturing, collection, and disposal). For example, when solar PV technologies generate power they offset the energy spent to harvest the materials used in their production and manufacturing. Increasing efficiency improves

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[1] For example, the US Department of Energy DE-FOA-0000492 Foundational Program to Advance Cell Efficiency awarded over $19 million to research projects to advance PV efficiency.

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EPBT by increasing energy generation. Alternatively, increasing recycling can reduce the life-cycle energy spent to harvest and refine PV materials. Previous literature has widely used energy and CO_2 payback to quantify the environmental impacts of energy systems [1–6].

PV materials, especially those used in the absorber layer (e.g. Si, Te, Ge, In), consist of metals that have high cumulative primary energy demand compared to most materials, with the exclusion of precious metals (e.g. Pt, Au). Another factor that increases the energy burden of PV materials is the refining necessary to achieve a minimum purity required for performance. For example, the Siemens process refines silicon into semiconductor feedstock of up to 99.9999% purity in order to be used for PV and is estimated to account for 75% of a polycrystalline silicon (c-Si) PV module's total production energy [7]. Similarly CdTe semiconductor material for PV is assumed to be between five and six 9 purity in many life-cycle assessment (LCA) studies [8]. In addition to the high purity, some PV materials reflect a high processing energy because they are produced in low concentrations as a by-product of other mining such as Cu or Zn (e.g. Te, In, Ga, Ge) or require energy intensive production techniques such as electrolysis (e.g. Al production from bauxite). Because recycled materials require significantly less processing and refining compared to primary materials, the potential energy savings is significant for PV materials. On the other hand, as compared to bulk materials, the purity requirement for cell materials makes recycling more demanding in terms of cost and energy input.

While this work focuses on quantifying the energy savings potential through recycling, using secondary materials has other benefits for PV technology as well. One is the potential to significantly reduce costs; while scrap metals follow their primary commodity price, there is typically a discount of 10–80% depending on the scrap quality [9]. In addition, the use of secondary materials contributes to waste reduction by diverting materials from landfills and back into the market. A well-developed secondary material infrastructure also has the potential to mitigate scarcity issues [10]. Recent work has highlighted resource scarcity and criticality as a potential issue for PV materials like In, Ga, and Te [11,12]. While the research community is divided on how severe this issue may be, all can agree that future supply has a great deal of uncertainty due to a variety of factors including PV adoption, recycling policy, majority mine ownership and management, electronics demand, and price. Although future demand of PV will likely rapidly outpace supply from secondary sources, such potential energy, cost, and scarcity mitigation would still be significant for high utilization.

The PV technologies analyzed in this study each have unique processing, composition, and properties. Silicon-based technologies – i.e. polycrystalline and mono-crystalline silicon, are the most mature, one of the least expensive, and have one of the highest production efficiencies thus holding over 80% of the current market share. Thin-film technologies – i.e. cadmium telluride (CdTe), copper indium gallium diselenide (CIGS) and amorphous silicon (a-Si) – are named for their semiconductor layer thickness of just a few micrometers. Thin-films generally have more flexible applications due to their smaller size and ease of manufacturing, however they have lower efficiencies, as compared to traditional silicon-based PV. Emerging technologies such as organic PV, dye-sensitized, and multi-junction PV are still in development; they have the widest array of material compositions and therefore are not analyzed here. This analysis focuses on the most mature PV technologies: silicon-based and thin films.

Previous work suggests that recycling processes for silicon-based and thin-film PVs at end-of-life are technically possible [13–16], have economic benefits [17], and have significant contributions to reducing the life cycle impact [18,19]. Furthermore, literature also suggests that the recycling of the module frame [20], recycling silicon wafers for c-Si [7], and the recycling of Ag and Zn in transparent conductive oxides [21] has a significant impact on energy payback time. However, a comprehensive accounting for recycling's impact of all direct PV materials in the energy payback calculation has not been performed. This quantification would allow a fair comparison between developing recycling technologies and efficiency gains as strategies to reduce the environmental impact of solar technology. This study explores the impact of recycled content on the energy payback time of silicon-based and thin-film PV modules. The energy payback time (EPBT) of PV modules containing recycled materials is evaluated to show in which regimes improvements in recycling rates can demonstrate equivalent energy savings to improvements in efficiency. This analysis systematically compares silicon-based (i.e. c-Si) and thin-film (i.e. CIGS, CdTe, a-Si) PV technologies. Sensitivity of results to changes in module lifetime, composition, recycling rate, and configuration (i.e. ground-mounted, roof-mounted) are also investigated.

2. Methodology

2.1. Energy payback calculation

Energy payback is the ratio of energy input, E_I to energy output rate, $\dot{E}_O$ (1). The energy input to produce and manufacture each material, n, is determined by the cumulative primary energy demand, E_P, secondary energy, E_S, the composition, c, and recycling rate, r. The energy output was calculated using the solar insolation, H, performance ratio, PR, and a module efficiency, η. We assume a solar insolation of 1700 kW h/m^2/year – i.e. average solar radiation in southwest US and Spain – and system performance ratio for all technologies between 0.75 and 0.80 similar to [18,22–25]. However these results may vary with array orientation, tilt, and grid efficiency. [4].

$$\mathrm{EPBT} = \frac{E_I}{\dot{E}_O} = \frac{\sum_n c(1-r)(E_P) + r(E_S)}{PR\eta H} \qquad (1)$$

This way of describing energy payback is consistent with suggested LCA guidelines [26] which assumes that all of the manufacturing and production energy is primary (in the case of no recycling or $r = 0$) however we deviate from this assumption with the inclusion of a recycling rate and the secondary energy required to recycle PV materials. By using primary and secondary material cumulative energy demand for the energy input we explicitly include extraction, refining, production and recycling energy and omit operation, maintenance, assembly, end-of life transport, and indirect material use. We also deviate with suggested LCA guidelines by neglecting transmission and distribution losses from the grid which vary signifigantly by location. Typically the system components – e.g. frame, roof or ground mounting supports, inverter, cables – are included separately from the PV cell however in this analysis we define the module to include the frame, mounting array supports, interconnects and the PV cell. For lifetime, based on data from literature [27], CdTe, CIGS, a-Si, and c-Si technology degradation rates do not vary significantly and are consistent with 20–25 year product guarantees of power from major cell and module manufacturers. However literature suggests the mounting frame could have a lifetime three times that of the module [20].

2.2. Material Composition

This energy payback analysis includes all direct materials on a mass (kg) per module area (m^2) basis assuming a baseline configuration (Table 1). The module configuration and associated