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Field installation versus local integration of photovoltaic systems and their effect on energy evaluation metrics

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HIGHLIGHTS

- We evaluate life-cycle energy impacts of PV systems at different scales.
- We calculate the energy payback time, return factor and CO_2 emissions offset.
- Utilizing existing structures significantly improves metrics of flat-plate PV.
- High-efficiency CPV installations yield best return and offset per aperture area.
- Locally-integrated flat-plate systems yield best return and offset per *land* area.

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ABSTRACT

In this study we employ Life-Cycle Assessment to evaluate the energy-related impacts of photovoltaic systems at different scales of integration, in an arid region with especially high solar irradiation. Based on the electrical output and embodied energy of a selection of fixed and tracking systems and including concentrator photovoltaic (CPV) and varying cell technology, we calculate a number of energy evaluation metrics, including the energy payback time (EPBT), energy return factor (ERF), and life-cycle CO_2 emissions offset per unit aperture and land area. Studying these metrics in the context of a regionally limited setting, it was found that utilizing existing infrastructure such as existing building roofs and shade structures does significantly reduce the embodied energy requirements (by 20–40%) and in turn the EPBT of flat-plate PV systems due to the avoidance of energy-intensive balance of systems (BOS) components like foundations. Still, high-efficiency CPV field installations were found to yield the shortest EPBT, the highest ERF and the largest life-cycle CO_2 offsets—under the condition that land availability is not a limitation. A greater life-cycle energy return and carbon offset per unit *land* area is yielded by locally-integrated non-concentrating systems, despite their lower efficiency per unit module area.

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1. Introduction

Photovoltaic (PV) technologies have a pivotal role to play in the transition away from fossil fuel-based power generation. Solar radiation has a higher global power density than any other source of renewable energy (Smil, 2003), and PV systems in particular—because they are inherently scalable—can be integrated in a wide range of settings, from individual buildings to commercial-scale generating plants (Alsema, 1997). The considerable potential of direct solar conversion using PV is underpinned by expectations that solar energy will eventually become the most economical and sustainable solution for most energy applications, and the only viable alternative energy option throughout the world (Bradford, 2006).

At the same time, the process of PV manufacturing and installation (like any other anthropogenic activity) consumes energy and generates pollutants (Frankl et al., 1998). Studies over the past decade (Boyd and Dornfeld, 2005; Pacca and Horvath, 2002) have shown that while the carbon emissions resulting from PV power generation are an order of magnitude lower than for coal-fired plants, they are still significantly higher than for hydro-electric and wind generation. The overall energy efficiency of PV systems may therefore be improved not only by increasing their electrical output, but by reducing their embodied energy—which is consumed not only in the production of PV modules (including the specific solar cell), but in the other balance-of-system

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components such as supporting structures. The deployment of the PV system—be it building-integrated, requiring little or no additional support, or constructed in the open field—may thus have considerable importance for its net energy yield. In this study, we evaluate this impact via a case study of PV-supplied electricity for a region while considering different possibilities of system deployment.

The relative weight of embodied energy for the different components within a PV system's lifetime net energy yield may be quantified using Life-Cycle Energy Analysis (LCEA). The ratio of the total primary energy input to the yearly primary energy-equivalent generated by the system represents the energy payback time (EPBT) of the PV system, and a low EPBT is one measure of a PV system's appropriateness as an alternative to fossil fuel-based generation. Another measure is the Energy Return Factor (ERF) of the system, representing the ratio between the total energy generated by the PV system to the total energy consumed over its entire life cycle, and similar analyses can be made for greenhouse gases emissions, by evaluating the quantities of CO_2, SF_6, CF_4 and other greenhouse gases emitted in the PV system life-cycle and comparing these values to emissions from fossil fuel-based electricity generation options (Alsema, 1997).

The methods for performing such life-cycle analyses, including standardization in the definition of system boundaries and accounting procedures, have been refined over the last two decades (Alsema, 1997; Fthenakis and Alsema, 2006) and considerable progress has been made in the assessment of environmental impacts from PV systems. An opportunity for reducing the energy-demand footprint of PV systems is to exploit existing infrastructure, such as suitably pitched or flat roofs of buildings, for their installation—thereby avoiding energy-intensive concrete foundations and other BOS components. It has been suggested that distributed building-integrated photovoltaics (BiPV) may offer the most cost effective application of grid connected PVs and are likely to be "the first grid feeding PV systems to reach widespread commercialization" (McNelis, 1996). Oliver and Jackson (2001) found that BiPV may allow for savings in primary energy input of over 30% due to reduced transmission and distribution losses and lower BOS requirements, despite moderate increases in the inputs for the PV modules themselves. Similarly, Boyd and Dornfeld (2005) found significant drawbacks in employing ground-based installations, including 30–50% increases in air pollutant emissions relative to BiPV.

In addition to the potential savings offered by building-mounted PV through the avoidance of new support structures, access roads, fencing, and cabling, which can represent substantial costs (both monetary and energetic) at remote sites, other advantages over centralized ground-based PV have been cited as well (Oliver and Jackson, 2001). PV systems on buildings may produce electricity at or near the point of use, avoiding transmission and distribution of electricity and the costs and losses associated with this. As emphasized by Vardimon (2011) in a recent case study in Israel, producing energy in large solar power stations requires vast tracts of land and may necessitate an extensive upgrade of the power grid. It was shown that high-efficiency PV rooftop installations could produce a significant portion (the equivalent of 32%) of the national electricity consumption in the long run.

PV materials that are integrated into the building envelope can in some cases replace other cladding materials, such as waterproofing roof membranes or tiles, avoiding the costs of those products and thereby providing some offset to the considerable cost of PV as an energy source alone. Alternatively, placing panels above a building's rooftop can decrease the solar heating of the building and potentially yield significant moderation of its air-conditioning loads (Sick and Erge, 1996; Wang et al., 2006). Because of such multiple potential benefits, and due to the common limitation of available roof space, it is sometimes considered judicious to combine a variety of installation options within a given populated area, including shade structures and available open land as well as buildings per se.

Since the life-cycle performance of a PV system is naturally a function of its output as well as its input energy, the EPBT and related metrics are dependent on the conversion efficiency of the PV cell, and on the level of solar collection by the system as a whole. The intensity of solar incidence per unit area of PV cell (or module) may be enhanced by optimizing the panel's fixed orientation (i.e. tilt angle) or by employing single or dual-axis tracking, and additional gains may be achieved through optical concentration using mirrors and/or lenses. Concentrating photovoltaic (CPV) systems use less cell material than flat-plate collectors and have a higher conversion efficiency, significantly reducing the required cell area and overall cost (Der Minassians et al., 2006)—but they require 2-axis tracking and relatively wide spacing between collectors, and their potential for integration with buildings is limited. It is therefore relevant to gauge the system's net energy output with respect not only to the aperture area of the collecting device, but also to the area of land that is required for its operation.

Given the numerous technological and economic constraints which must be considered, it is clear that the viability of a PV installation can ultimately hinge on its geographical location. The Negev desert of southern Israel, which includes the Arava valley stretching from the Dead Sea to the Gulf of Aqaba (Eilat), is considered a prime location for large-scale solar generation, with its average horizontal annual insolation equaling 2150 kWh m^{-2} (Faiman et al., 2006)—as compared with 1700 kWh m^{-2} per year in Southern Europe and 1300 kWh m^{-2} per year in south Germany (Fthenakis and Alsema, 2006).

In this study, the Arava region (population ca. 4000) is used as a framework for a comparative life-cycle energy analysis of a variety of PV generating systems at three different scales, from the most localized (BiPV, or integration with individual buildings) to the most centralized (a commercial-scale field array). An intermediate-scale scenario of "urban-integrated" PV is also considered, in which available buildings, allied support structures (such as shading structures for parking and other open spaces), and open land within a given settlement are all utilized for PV installation.

2. Methodology

2.1. Evaluation process

Three distinctive scales and a number of PV technologies create a matrix of system possibilities, each of which requires the analysis of energy input (embodied energy) and output, from which in turn the other metrics can be derived. Fig. 1 schematically describes the process for determining the metrics for each combination of technology and type of deployment.

Eight different PV systems were chosen for this case study based on their commercial availability as well as the accessibility of their embodied energy data. Table 1 lists these PV systems with their key performance data and essential characteristics (such as temperature coefficient, positioning, and tracking strategy).

The determination of the energy output of each technology is performed by simulation while the embodied energy calculation relies on published data or on data provided by the manufacturer and takes into account the support structure of the system (metal frameworks are used throughout, though other options are available),

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