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Effects of radiative forcing of building integrated photovoltaic systems in different urban climates

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ABSTRACT

Recent years have witnessed a remarkable reduction in solar-panel costs, such that low-efficiency, low-cost photovoltaics (PV) currently prevail over more complex, high-efficiency technologies. Although solar-energy-generating installations provide a renewable energy source often considered emission-free, a number of externalities are frequently ignored that favor technologies with a reduced efficiency as long as they are available at lower cost. Whenever PV systems are installed, the absorption properties of the surface are changed and less sunlight from the Earth's surface is reflected into space. By including this radiative forcing in the form of the Earth's surface reflection coefficient *albedo* (α), we take these externalities into consideration in the overall equivalent global warming potential (GWP) of a PV system. Three different effects need to be considered when changing the absorption properties of the Earth's surface: (1) global albedo impact, (2) regional atmospheric heat islands, and (3) locally heated surfaces. The unintended radiative forcing adversely affects the net efficiency of building-integrated solar installations in warm urban climates, as more energy is required for cooling to ensure human comfort. The total GWP of four different PV technologies was examined for three different urban climates, temperate, moderate, and warm. To minimize the system energy payback time (EPBT) it is most sensible to install high-efficiency solar-energy systems outside cities and urban developments in locations with high annual irradiance. Only when taking radiative forcing into environmental and economic considerations is it expected that solar-technology development will correct its trajectory away from low-cost systems and toward high-efficiency installations with lower overall GWP.

1. Introduction

Immediately after the public demonstration of a solar module powering a radio transmitter in 1954, this achievement was heralded as the beginning of a new era promising almost limitless harnessing of the sun's energy (Chapin et al., 1954; Perlin, 2004). In reality, however, this prospect has largely been hampered by cost constraints (Lewis, 2007). Consequently, much effort has been invested primarily in reducing the cost of solar power to make it economically competitive with fossil fuels and nuclear energy (DOE, 2015).

As the solar spectrum is a wideband radiation spectrum, it has an inherently limited efficiency when fully absorbed and directly converted by a single photovoltaic (PV) junction (Shockley and Queisser, 1961). For this reason, conversion in multiple PV junctions or selective absorption is the only viable way to achieve high conversion efficiencies. Particularly multi-junction solar cells have proved to be expensive, which has limited their deployment to date.

Technologies with a reduced efficiency are favored as long as they are available at lower cost, with the result that the development of more complex technologies with higher efficiencies has been delayed. This approach, however, may be challenged when taking into account the externalities examined in the present contribution. Whenever solar absorbers are installed, radiative forcing occurs, which ultimately increases global temperatures (Forster et al., 2007; Nemet, 2009; Barron-Gafford et al., 2016). Life-cycle analyses (LCAs) disregard these effects, which should be evaluated analogously to the embodied energy in order to determine a technology's total global warming potential (GWP) and system energy payback time (EPBT). By including radiative forcing in the form of the Earth's surface reflection coefficient albedo (α), this conjunction is made possible. Here, the albedo of a surface is defined as the ratio of the radiation reflected by that surface to the total incident irradiation upon it, whereby α varies from 0 (no reflectivity) to 1 (perfect reflectivity).

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Three different effects must be considered when changing the absorption properties of the Earth's surface and decreasing its albedo (Fig. 1). First, less sunlight is reflected into space, which has a direct impact on global climate. Second, regional atmospheric conditions are affected, which may generate heat islands and concomitant space-conditioning (heating and cooling) demand for buildings. Third, exposed surfaces heat up considerably under insolation and warm the supporting structures and buildings, which leads to an additional localized space-conditioning demand on the scale of an individual building. The latter effect is notably present for building-integrated PV (BIPV). To evaluate the GWP and EPBT for solar-energy systems, these effects have to be added to the embodied energy determined from LCAs.

A previous study incorporated radiative forcing effects induced by the deployment of PV systems by setting up a radiation balance for the incoming and outgoing radiation of the Earth's atmosphere (Nemet, 2009). In another study the effects of atmospheric heat islands induced by the deployment of PV systems were investigated (Taha, 2013). While not all externalities have been considered in these studies, the substitution of fossil fuel by PV systems was still shown to be largely beneficial in both cases. In particular, previous studies have omitted the local heating of buildings in their analyses and did not address the variety of PV technologies with different performance and life-cycle impact characteristics.

In this study, the environmental externalities according to Fig. 1 are quantified, for the first time also including the change in energy consumption due to space-conditioning loads induced by the deployment of PV systems. Further, different PV technologies with efficiencies ranging from low to high are evaluated using this methodology. The results provide insight into the overall environmental impact of PV technologies. The methodology will help guide policy selection and implementation recommendations for PV deployment with respect to system efficiency and installation location in order to harvest solar power with minimal environmental impact.

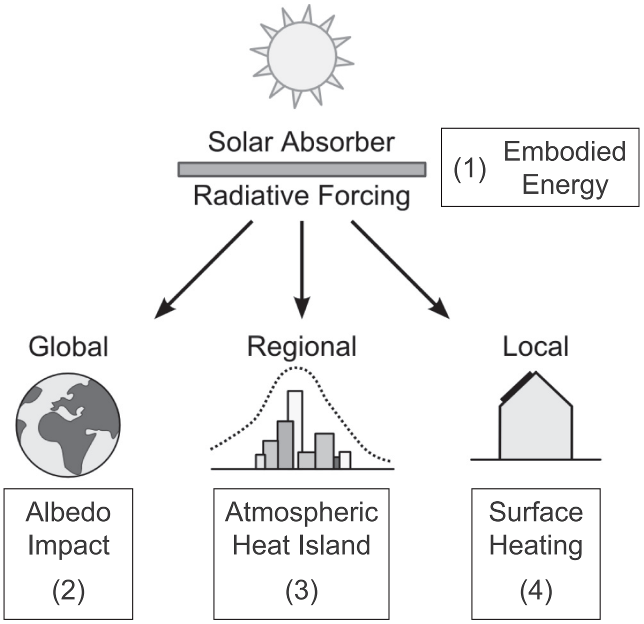

Fig. 1. The environmental externalities of PV systems are classified into (1) Embodied Energy associated with manufacturing and deployment, (2) Albedo Impact due to the radiative forcing of dark solar absorber surfaces on the Earth's surface, (3) Atmospheric Heat Island which describes the additional energy required for cooling of buildings due to the urban heat island effect, and (4) Surface Heating which describes the additional energy required for cooling of buildings due to the local heating of roofs covered with dark solar absorbers.

2. Methods

In the following, an analysis is presented where roofs with built-in opaque solar absorbers ($\alpha = 0.05$) are compared to white roofs ($\alpha = 0.90$). An albedo of 0.9 represents an upper limit for a whitewashed exterior finish (Taha et al., 1988), while the former value varies slightly for different PV technologies but is rather consistent. Solar technologies that do not absorb the entire solar spectrum, such as dye-sensitized solar cells or cells covered by a diffusing surface, may have different albedo values, but as this does not change the ratio of the electrical energy conversion efficiency to absorption substantially, the main findings of this study will prevail. The albedo of an aged white roof may be as low as 0.55 (Sproul et al., 2014), which still represents a substantially more reflective surface than a solar absorber in line with the present discussion. Further, the albedo values were considered constant and independent of the angle of incidence. Secondary effects due to reflected radiation, such as radiation entrapment in the urban canopy, were are not considered as these require assumptions about the specific installation geometry and surface properties of the urban environment, which would lead to a loss of generality of the analysis.

An approach to calculate the overall GWP (in CO_2-eq/MW h) and EPBT (in years), GWP_{PV} and $EPBT_{PV}$, for different PV technologies that absorb the entire solar spectrum is introduced which incorporates the individual contributions of (1) embodied energy (subscript LCA) (Fthenakis and Kim, 2011; Fthenakis and Kim, 2012), (2) global albedo impact (subscript α) (Akbari et al., 2012; Burg et al., 2014), (3) regional atmospheric heat island (subscript UHI) (Barron-Gafford et al., 2016), and (4) local surface heating (subscript s) (Akbari et al., 2001):

$$GWP_{PV} = GWP_{LCA} + GWP_{\alpha} + GWP_{UHI} + GWP_{s} \tag{1}$$

$$EPBT_{PV} = EPBT_{LCA} + EPBT_{\alpha} + EPBT_{UHI} + EPBT_{s} \tag{2}$$

The equivalent CO_2 emissions of the GWP relate to the total electricity production (in MW h) of the PV system during its life time. The EPBT determines the energy break-even point in years considering all environmental externalities.

The production of new PV is energy intensive and creates greenhouse gas (GHG) emissions during raw material extraction and purification, panel manufacturing and module installation. The embodied energy is determined by LCAs, which include material and energy flows of the module, frame and balance of system. LCA studies are used to extract these reference GWP values, *Ref.* GWP_{LCA} (Table 1) (Fthenakis and Kim, 2011; Fthenakis and Kim, 2012). Besides the materials and energy balance, the employed LCA data takes into account assembly and installation, maintenance and operation as well as end-of-life disposal of the installations without recycling or re-purposing of materials. Out of the four PV technologies considered herein (Table 1), high-concentration photovoltaics requires a tracking structure, which comprises a concrete foundation, pedestal, hydraulic drive and motor, and has been shown to account for 38% of primary GHG emissions for a typical installation (Fthenakis and Kim, 2011, 2012). The other three PV technologies are assumed to be non-tracking and are therefore not subject to the associated embodied energy demand. Alternative uses of land (in the case of HCPV) or roofs (all other PV technologies) were not considered in this study. As the GWP results are dependent on the life time power production, they must be put into relation with the installation location Global Horizontal Irradiance (GHI), *Location GHI*, through the reference values used in the LCA study, *Ref. GHI*. The GWP based on embodied energy of PV systems, GWP_{LCA}, is equated in the following manner: