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Internalizing land use impacts for life cycle cost analysis of energy systems: A case of California's photovoltaic implementation

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HIGHLIGHTS

- A framework to internalize land use impacts for life cycle costing of energy services is developed.
- The framework is demonstrated by applying it to a photovoltaic system implementation case study in California.
- Utility-scale ground mounted PV systems have the least life cycle costs compared to rooftop PV systems.
- Placing higher values on land use externalities could make ground mounted PV systems less favorable than rooftop systems.

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ABSTRACT

Solar photovoltaic (PV) is a rapidly growing electricity generation technology. The increasing penetration of this technology is facilitated by incentives and public policy support that are being offered by various jurisdictions. There are various options for installing photovoltaic systems, rooftop and ground mounted systems being the two common options. The choice between these options has been complicated by the tradeoffs between cost and land use impacts. In this paper we develop a framework that can be used to highlight and quantify the tradeoffs between costs and land using life cycle costs (LCC), life cycle land use footprints (LUF), and consequent land use impacts (LUI) across various options of implementing PV systems. We demonstrate the application of the framework using a hypothetical case study of implementing various options of PV systems in California. The results indicate that at 14.2 ¢/kWh, the utility-scale ground mounted option has the lowest LCC compared to residential and commercial rooftop mounted options. However, the utility-scale option has the highest land use footprint and land use impacts. The monitory value of the land use impacts from implementing utility scale ground mounted systems depends primarily on the type of associated ecosystems and the value people place on them. For the rooftop option in this case study to be preferred to the ground mounted option, the value of land use impacts would have to increase significantly.

1. Introduction

Photovoltaic (PV) systems are penetrating electricity markets at a rapid rate in several regions around the world. For example, between 2009 and 2010 the installed PV capacity increased by 131% globally and by 84% in the US [1]. California accounts for 47% of installed PV capacity in the US. In 2010 alone, 225 MW of PV was installed in California increasing its cumulative installed capacity to 1.02 GW (1.4% of California's electricity generation capacity in 2010) [1]. Increasing electricity demand, federal and state policies such as rebate programs, investment tax credits, net metering, favorable interconnection policies (operating, metering and interconnecting requirements that a generator has to meet to connect to a utilities distribution system), and rate structures have been key to the penetration of PV systems in California [2,3]. There are various options for installing photovoltaic systems, rooftop and ground mounted systems being two common options. The California government is providing incentives for both options; however, the investment decision between these options is complicated by tradeoffs between cost and land use impact. For example, incentives for rooftop PV system installations with a target of 3 GW operating in California by 2016 [4]. At the same time, the Bureau of Land Management (BLM) has allocated 619 million square meters of public land in the desert regions of Southern California for the development of solar energy systems. This has been critical to the deployment of utility scale ground mounted systems [5].

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However, there has been opposition to the use of public lands for these developments due to the impacts on ecological and cultural resources in these desert ecosystems [6,7]. The objective of this paper is to develop and demonstrate a framework that can be used to highlight and quantify the tradeoffs between costs and land impacts using life cycle costs (LCC), life cycle land use footprints (LUF), and consequent land use impacts (LUI) for various options of implementing PV systems.

LCC is a tool that can be used to estimate the cradle to grave costs associated with a product or a service [8]. LCC can also be used to compare a series of product or service alternatives and generally accounts for all costs arising from initial capital costs, recurring costs such as annual maintenance, non-recurring costs that occur irregularly such as replacement and repairs of system parts, end of life decommissioning and disposal costs as well as the time value of money [8–11].

Land use impacts of PV system implementations can be estimated using the total area required, the time of occupation of land, and the change in the quality of land for a particular activity (e.g., per kWh) [12]. The change in quality of land can be defined by how well land performs its "functions". These functions include (but are not limited to) erosion resistance, filtering, buffering capacity of the soil, ground water protection, buffering surface water (flood regulation), protection from impacts such as noise, biomass production, decomposition of organic matter, habitat for human and non-human life, and landscape quality (for example: scenic views, culturally important sites [13]).

Land use impacts from PV systems may result from site modifications such as clearing of vegetation, grading of land, redirecting water flow, fencing, creating access roads and pouring concrete pads to mount electrical equipment [14,15]. Impacts of such anthropogenic modifications in desert lands have been discussed in the literature by [16–21]. The impact of solar energy development on the desert ecosystem particularly endangered species such as the desert tortoise have begun to raise concerns among California residents [22]. California's deserts also have archeological and ethnological sites such as burial sites, trails that link resources to cultural sites, geoglyphs, rock art, and artifacts of early human settlement [23]. The potential deterioration of these sites from development of solar energy systems has also raised concerns [24]. Therefore, incorporating the value of land use impacts into the decision making process can provide a better understanding of the total cost of PV systems on society.

Ascribing a monitory value to the various qualities of land and the impact of their loss has been undertaken in environmental economic studies, using various methods. These methods include contingent valuation (willingness-to-pay) [25–28], travel cost methods [29,30], choice experiments [31], hedonic pricing [32,33], and value transfer methods [34].

Several studies have examined the life cycle costs of various options of implementing PV [11,35–38]. However, no study was found that makes a comparative assessment from a systems perspective (including transmission line losses and costs) while internalizing societal costs that occur from land use impacts. Furthermore, studies that have valued ecosystem services, as seen above, focus on the methods and assessment of ecosystem services and to date have not explored the implications of internalizing these impacts in a LCC. In addition, no study was identified that employed the valuation of ecosystem services to the total life cycle cost of various options for implementing PV systems.

2. Methods

The LCC/LUF/LUI framework presented in this paper is described and demonstrated through a case study that compares three options for deploying PV systems in California. These cases are the starting point for a sensitivity analysis to explore the tradeoffs between LCC and LUI results. The framework includes a detailed investigation of the land use footprint and impacts as well as methods to translate those impacts into financial costs (i.e., to internalize the externalities caused by this land use). Although the framework is developed with focus on PV implementation in California, it is flexible enough to be extended to other locations and to evaluate other technologies that face cost and land use tradeoffs.

The life cycle cost, land use footprint and land use impacts of three options for implementing PV systems to produce and deliver electricity to a residential neighborhood in an urban setting in Los Angeles, California are considered for this case study. These options are:

(1) The residential rooftop option where the PV system is installed on the roofs of the houses in a residential neighborhood in Los Angeles (L.A.), and each household consumes the electricity generated by the PV system on their roof (hereafter referred to as "*Residential option*");
(2) The commercial rooftop option where the PV system is installed on the roofs of commercial buildings in Los Angeles, and electricity produced is delivered to a residential neighborhood, in Los Angeles via a distribution system (hereafter referred to as "*Commercial option*"); and
(3) The utility scale ground mounted option where the PV installation is implemented in Blythe, a remote desert town in California and electricity generated is transmitted and distributed to the residential neighborhood in Los Angeles via a distribution system (hereafter referred to as "*Utility-scale option*").

In this study we consider the PV system to include both the PV installation and the transmission/distribution network required to deliver electricity to the end user. The PV installation includes PV modules and the balance of system components (includes inverters, protection systems, steel mounts, monitoring equipment, etc. [15]). The transmission network in this paper includes the transmission line, substations and distribution line. The framework developed is used to reflect what an end-user would pay for electricity generated from a PV system and includes the internalization of the value of the loss of land quality; loss of naturalness and its potential to be a carbon sink. In this analysis we do not consider administrative fees charged by utility companies.

We determine the system size by establishing the average expected output of utility-scale PV systems in California as reported by the CPUC's report on the status of RPS projects [39]. After accounting for transmission and distribution line losses (assumed to be 7%; [40]) we find that an average sized system will deliver 125 GWh/year to a residential neighborhood. Table 1 presents the key assumptions for a system that delivers 125 GWh/year for the three options, after accounting for line losses. We determine the array size or the number of modules required to generate the 125 GWh/year using the System Advisor Model (SAM) [41]. SAM is a software tool developed by the US National Renewable Energy Laboratory (NREL) that can be used to simulate the performance and make economic assessments of a range of renewable energy technologies including PV.

All of the key assumptions presented here are tested in the sensitivity analysis (discussed in detail in the results section and online Supplementary Information).

We also assume that there are no land use impacts from residential and commercial rooftop systems as they utilize rooftops of existing buildings. The land use footprint in the residential rooftop option is assumed to be zero. The commercial rooftop is in an