Co-location opportunities for renewable energy and agriculture

Applied Energy 165 (2016) 383–392

Contents lists available at ScienceDirect

Applied Energy

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

Colocation opportunities for large solar infrastructures and agriculture in drylands

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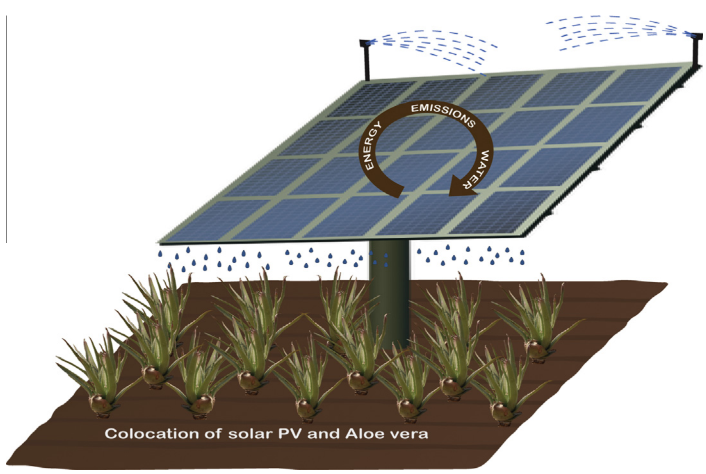
HIGHLIGHTS

- We explored the potential to colocate solar installations and agriculture.
- Water use at solar installations are similar to amounts required for desert plants.
- Co-located systems are economically viable in some areas.
- Colocation can maximize land and water use efficiency in drylands.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 29 June 2015
Received in revised form 13 December 2015
Accepted 17 December 2015

Keywords:
Renewable energy
Life cycle assessment
Water use efficiency
Land use
Food-energy-water nexus

ABSTRACT

Solar energy installations in arid and semi-arid regions are rapidly increasing due to technological advances and policy support. Although solar energy provides several benefits such as reduction of greenhouse gases, reclamation of degraded land, and improved quality of life in developing countries, the deployment of large-scale renewable energy infrastructure may negatively impact land and water resources. Meeting the ever-expanding energy demand with limited land and water resources in the context of increasing demand for alternative uses such as agricultural and domestic consumption is a major challenge. The goal of this study was to explore opportunities to colocate solar infrastructures and agricultural crops to maximize the efficiency of land and water use. We investigated the energy inputs/outputs, water use, greenhouse gas emissions, and economics of solar installations in northwestern India in comparison to aloe vera cultivation, another widely promoted and economically important land use in these systems. The life cycle analyses show that the colocated systems are economically viable in some rural areas and may provide opportunities for rural electrification and stimulate economic growth. The water inputs for cleaning solar panels are similar to amounts required for annual aloe productivity,

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http://dx.doi.org/10.1016/j.apenergy.2015.12.078

suggesting the possibility of integrating the two systems to maximize land and water use efficiency. A life cycle analysis of a hypothetical colocation indicated higher returns per m^3 of water used than either system alone. The northwestern region of India has experienced high population growth in the past decade, creating additional demand for land and water resources. In these water-limited areas, coupled solar infrastructure and agriculture could be established in marginal lands with low water use, thus minimizing the socioeconomic and environmental issues resulting from cultivation of economically important non-food crops (e.g., aloe) in prime agricultural lands.

1. Introduction

Population growth and increase in standards of living in the developing world have led to a rapid increase in energy demand [1]. At the same time, in the context of climate change mitigation, many governments worldwide have policies to increase the proportion of electricity delivered by low-carbon sources [2–4]. Solar electricity generation technologies have emerged as one of the fastest growing sectors due to rapid advances in affordable technology and policy support [2]. Solar energy deployment can provide several additional benefits such as reclamation of degraded land, employment opportunities, rural electricity access (off-grid systems), and improved quality of life in developing countries [5–7]. However, the deployment of large scale solar energy infrastructure may negatively impact land and water resources [8,9]. Hence a pertinent question for the future is how to meet the ever-expanding energy demand in the developing world with limited land and water resources in the context of increasing demand for alternative uses such as agricultural and domestic consumption [10,11].

The rapid expansion of large-scale solar installations in India is a case in point. Energy demand is rapidly increasing in India and the country has experienced severe power outages resulting from the interplay of several factors, including increasing demand, energy use for irrigation, and uncertainties in water availability induced by climate change [1,12]. In northwestern India, large solar installations are being established as part of the national and state renewable energy initiatives to meet the future energy targets [13,14]. In many of the "hotspots" identified for large solar installations, water resources are already scarce, such as in the Thar desert region of northwestern India [15,16]. The northwestern region of India (e.g., state of Rajasthan) has shown rapid increase in population over the last few decades creating additional demand for agricultural land and water resources [17–19]. Most of the proposed solar installations will be large photovoltaic (PV) systems, which can have a large land footprint (0.35 MW ha^{-1}) [8,9,13]. Although their water use per unit of generation is less than many other energy technologies (0.02 m^3 MW h^{-1}), due to their size they can use substantial amounts of water for construction and operation, mostly for cleaning PV solar panels and for dust suppression from disturbed soils [8,9,20].

The accumulation of airborne particulate matter or "soiling" can significantly impact the performance of PV systems in areas where rainfall is limited [21–23]. The construction and operation of large PV facilities in deserts may add additional disturbance to desert soils and enhance dust emissions. Further, increases in dust production related to climate change (e.g., increase in aridity), or disturbance (e.g., fires, grazing) to biological soil crusts [24,25] may render the dust management in large solar facilities in arid regions challenging. Considering the deleterious impact of dust-borne contaminants on regional air quality and human health, enhanced dust emissions related to the construction and operation of large solar installations may be a serious health hazard to consider [24,25]. For this reason, proper dust control strategies are necessary at large solar infrastructures in deserts to ensure efficient power generation and to minimize environmental impacts. In most PV facilities in arid regions, solar panels are routinely washed with water to maintain optimum power production [21,22,26]. The soiling of panels may result in 15–25% decline in annual electricity production and weekly cleaning of panels is recommended in many desert regions [23,26]. Studies have shown that water for washing panels and for dust suppression is a major component of water budget of many large solar infrastructures in desert regions [8]. In some areas with severe water scarcity, including areas in northwestern India, even the relatively small water requirements for solar PV installations (compared with other energy technologies) may place a major demand on local water resources or may displace water allocated for small-scale subsistence agriculture and domestic consumption. Most of the applied water runs off the panels and into the desert soil, and this moisture input may be sufficient to maintain some vegetation cover [8].

An emerging option being evaluated in the United States is the colocation of solar installations and vegetation [8,27] (Fig. 1a). Colocating solar infrastructure and agriculture (including bioenergy) crops would provide additional benefits such as dual income streams to farmers, employment opportunities at solar facilities for crop management, options for rural electrification, and electricity for processing agriculture products locally [8]. A major constraint for establishing colocated systems is identifying location-specific, physiologically and economically viable plants for colocation. Most solar installations are sited in arid and semi-arid regions characterized by low precipitation and poor soils, making them unsuitable for most food crops. However, there is increasing interest in growing high-value xerophytic plants (e.g., *Agave* spp., *Aloe* spp., *Opuntia* spp.) in marginal lands in arid and semi-arid regions that can be cultivated without competition for key resources for food crops [8,28,29].

Aloe vera, a perennial leaf succulent xerophytic plant with ecological and physiological adaptations to achieve economical yields on marginal lands [30,31], has potential for colocation with solar infrastructure. The genus *Aloe*, which includes more than 300 species, has been used for economical and medicinal purposes for centuries [31–33]. Aloe vera leaf contains a diverse array of compounds; over 200 active compounds (including minerals, amino acids and vitamins) and are utilized in several formulations and applications in diverse sectors [31,32,34]. Aloe vera cultivation offers numerous product diversification opportunities suitable for different climatic conditions and markets (e.g., aloe gel, aloe vera seeds, roots, aloin, cosmetics, health drinks, medicinal formulations, and biodiesel). The aloe gel, a colorless mucilaginous gel obtained from the parenchymatous cells in the leaf, is in high demand in the food and pharmaceutical industry, primarily as a major constituent in health drinks, natural medicines, and cosmetics [35]. The leaf gel is mostly composed of complex carbohydrates known for its medicinal values including effects on wound healing, anti-inflammation, and immune modulation [35]. Aloin, an anthraquinone contained in the leaf exudate, has several medicinal properties including blood purification, laxation, and diuresis [31,33].

Fig. 1. (a) Colocation of solar PV and vegetation in Colorado, USA. (b) Aloe vera cultivation in Rajasthan, India.

Aloes are under commercial cultivation over large areas in India (Fig. 1b), including the northwestern arid and semi-arid regions [36,37]. Several characteristics of aloes make them an attractive crop for colocation with solar infrastructure: short growth stature (0.3–0.6 m), significant biomass production with little or no irrigation, low maintenance, long crop cycle (5 years), availability of processing facilities and existing marketing chains, and high demand (and value) for aloe gel and gel-based products. Aloes are drought-resistant species with Crassulacean Acid Metabolism (CAM) photosynthetic pathway, which enable high plant water use efficiencies under desert conditions [28,38]. The plants establish very well in relatively poor soils and are known to grow well in partial shade (e.g., from solar panels) with no significant change in leaf productivity and gel quality [39–41]. Aloes have a thick shallow root system, which enables them to make use of light precipitation or irrigation (e.g., from water used for cleaning solar panels) [31,33].

Colocated solar and aloe vera (for gel production) installations could maximize the efficiency of water use in drylands by coupling water use for cleaning panels and irrigation, minimizing dust generation by increasing soil moisture and vegetation cover, minimizing impacts on natural areas by deploying crop cultivation in existing large solar infrastructures, and stimulating economic returns to improve livelihoods in rural areas. However, to explore the logistics and economic feasibility of integrated solar PV–aloe vera systems, detailed life cycle analyses are needed. Here, we conduct a detailed life cycle analysis for solar PV, aloe vera gel production, and a hypothetical colocated solar–aloe system to explore the tradeoffs and synergies (in the context of energy, water, and greenhouse gas emissions) between these two emerging land uses in northwestern India. We also examine the economics of these systems and the potential for improving rural livelihoods (employment generation, rural electrification).

2. Materials and methods

Life Cycle Analysis (LCA) is a commonly used tool for exploring the economic feasibility and environmental impacts of new technologies. Our analysis is based on a detailed life cycle analysis for a solar photovoltaic system, an Aloe vera gel production system, and a hypothetical colocated solar–aloe system to explore the tradeoffs and synergies between these two emerging land uses in northwestern India. In this study we adopted LCA methodologies used in existing comprehensive studies on solar PV and agricultural/biofuel production systems [8,42]. For Aloe vera, we used LCA methodologies to estimate the energy consumption, greenhouse gas emissions (GHG) and economic feasibility using different life cycle stages from cultivation to processing. For the LCA of solar PV installation, we used a comprehensive analysis to estimate the energy consumption, greenhouse gas emissions (GHG) and offsets, and economic feasibility. Our analysis includes all life cycle stages of solar PV – manufacturing PV modules and balance of system components (BOS), construction and operation, decommissioning, and recycling. Detailed description of LCA methodologies, input parameters and data sources are provided in the Supporting Information S1.

2.1. Life cycle analysis of aloe vera gel

The data required for life cycle analysis of aloe vera cultivation and gel processing are compiled from existing literature and from data collected during field visits to aloe vera farms and gel processing facilities in northwestern India. The life cycle stages for aloe vera gel production considered in this work are aloe cultivation, leaf harvest and transport, and gel production. In this scenario, the aloe vera leaves are harvested periodically and processed as gel. We take into account the life cycle fossil energy use and greenhouse gas emissions for direct energy and material inputs, machinery and buildings. We account for CO_2, CH_4, and N_2O as GHG emissions with all emissions converted to CO_2 equivalents based on their 100-year global warming potential [8,42,53,54].

We consider two commercial scale cultivation scenarios of five-year cycle—baseline yield scenario and high yield scenario—with moderate levels of fertilizer/manure applications and irrigation. Aloe vera grows well in loamy to sandy loam soils and is sensitive to waterlogged conditions. The plants flourish well in a semi-arid environment with 300 mm of annual rainfall typical of northwestern India and are under commercial cultivation. The plants are established by planting root suckers. The number of plants ha^{-1} ranges from 15,000 to 55,000. The commercially important species in India is *Aloe barbadensis* Miller (AL-1 variety). We adopt a conservative planting density of 22,500 plants ha^{-1} based on the established cultivation practices and data available from commercial aloe vera farms in northwestern India [43,44] (see Supporting Information S1).

The application of fertilizers and manures varies with soil type, crop management, and climatic factors. We chose values based on the general fertilizer recommendation for commercial aloe cultivation in India [43,44]. In this study we use 50:50:50 kg ha^{-1} for nitrogen, phosphorus, and potassium fertilizers (basal dose) as nutrients, respectively. For the high yield scenario, a top dressing of an extra 25 kg ha^{-1} of nitrogen is provided from the 2nd year onward. The plant responds very well to application of farmyard manure, and is applied at the rate of 15 Mg ha^{-1} $year^{-1}$. In northwestern India, a botanical pesticide and slow release N fertilizer known locally as neem cake is added to control termites and to improve soil quality. Termites indeed can be an issue in some areas during the early stages of crop establishment [36,37]. The use of plant protection chemicals is not usually recommended as aloe products commonly used in cosmetics and health foods. However, in the case of leaf spot disease occurrence, fungicide application is recommended in some areas.

The level of mechanization is very low in northwestern India [45], as the farm holdings are relatively small. In this study we considered some level of mechanization for large commercial aloe cultivations. Energy for farm operations—ploughing (twice before planting), fertilizer/manure application, and transportation—is assumed to come from diesel [45,46]. The embedded energy for production and use of agricultural implements and farm machinery is considered in the life cycle analysis. Planting, weeding, and harvesting are assumed to be done manually. In the case of high yield scenario, the leaf residue from the gel processing plant is applied to the soil as mulch/manure (see Supporting Information S1).

Aloe vera can be cultivated both under rain-fed and irrigated conditions. The plants can generate economic yields with an annual rainfall of around 300–500 mm, and can tolerate some degree of drought [32,36,37]. Light irrigations immediately after planting and during summer months will ensure better leaf production and gel quality. In the baseline yield scenario, plants are irrigated twice immediately after planting and 6 additional times during the summer season corresponding to once per month for six months. For the high yield scenario, plants are irrigated twice immediately after planting and 24 additional times during the summer months corresponding to once per week for six months. Several studies have indicated that the high leaf biomass and gel quality are obtained by light irrigation in short weekly intervals [33,47]. Irrigation water requirements were collected from aloe vera farmers in northwestern India. Water is manually applied at the rate of around 20 m^3 per week (water volume per irrigation event) ha^{-1} (22,500 plants). Irrigation water is normally groundwater and the power source is electricity (see Supporting Information S1).

The harvesting starts 15 months after planting and there are at least three harvests per year. From years two through five, two to four mature leaves from each plant are removed at harvest. Economical harvest can be done up to the fifth year of planting. Harvesting is a labor-intensive process. Average yield from commercial aloe cultivations is around 50 Mg ha^{-1} $year^{-1}$ fresh leaf weight [43,48,49]. Higher yields in the range of 75–100 Mg ha^{-1} $year^{-1}$ are reported in the literature. In this study we assumed a high yield scenario (fresh leaf weight) of 55 Mg ha^{-1} $year^{-1}$ and a baseline yield scenario of 27 Mg ha^{-1} $year^{-1}$ (see Supporting Information S1).

Leaves show loss of biological activity a few hours after harvest, so leaves are processed within 12 h of harvesting. The processing stages for gel manufacturing are: leaf cleaning, leaf filleting, gel extraction, filtration, homogenization, addition of preservatives, pasteurization, cooling, and bottling/storage of gel/gel juice [35,50]. The manual leaf filleting process involves cutting open the leaf from the sides and separating the gel from the outer part of the leaf (leaf rind). Even though automated whole-leaf processing methods are available, the manual leaf filleting process ensures better separation of pulp and minimizes the presence of undesirable phenolic compounds from the leaf rind in the final gel product. The gel juice output is around 30% of the fresh leaf weight. In this life cycle analysis, we accounted for the embedded energy and GHG emissions from transportation of leaves from farm to the processing facility (diesel energy), processing machinery (e.g., washing unit, pulping unit, extractor, homogenizer, and mixers), buildings, chemicals and lubricants, and the electricity for gel processing (see Supporting Information S1).

2.2. Solar PV life cycle analysis

We considered a solar PV installation, as PV is the dominant technology for current and proposed solar installations. Moreover, there might be other logistic constraints for colocation of crops in concentrated solar power installations (CSP) due to intensive infrastructure. The considered solar PV installation is installed in a desert environment, typical of northwestern India, with an annual precipitation of 300 mm and a solar insolation of 2000 kWh m^{-2} $year^{-1}$ [16,51]. This installation consists of a basic array of fixed flat plate systems with approximately 3250 multi-crystalline silicon (m-Si) PV modules of 120 Watt-peak (Wp), a module area of 1 m^2, and an efficiency of 15% [52]. The annual power generation is calculated via the HOMER model[1] utilizing a solar resource of 5.80 kWh m^{-2} day^{-1} for Northwestern India. Additional details are available in the Supporting Information S2. The materials input and energy input, and greenhouse gas emissions and outputs during the life cycles of m-Si are considered from PV production plants. The life cycle stages considered are manufacturing PV modules and balance of system components, construction and operation, decommissioning, and recycling [53] assuming a life cycle of 30 years. Large-scale solar installations require balance of system components like module frames, mounting structures, grid connectors, concrete, and office facilities. The energy inputs for manufacturing one MWp of m-Si module and balance of system components total 31,333 GJ [52,54]. The GHG emissions for manufacturing the module and balance of system components are 37 and 20 g CO_2e kWh^{-1}, respectively, over an expected 30 years of useful life of a module [53,54]. We also consider the energy used for operation of the PV infrastructure, mainly for the routine cleaning of panels. In this study we do not consider additional pollutant emissions. Electricity generation by solar PV results in substantial GHG offsets – by the reduction in GHG emissions resulting from electricity generation by renewable technologies compared to conventional fossil-based electricity generation. We used the GHG emissions from electricity generation in India for calculating the offsets resulting from solar PV-based electricity generation. The life cycle fossil fuel energy use and GHG emissions to produce this electricity is based on the Indian electricity generation mix of 3.4 MJ and 278 g CO_2e MJ^{-1} [55] of electricity produced respectively (see Supporting Information S2).

[1] HOMER (Hybrid Optimization of Multiple Energy Resources) software models micropower systems with single or multiple power sources. HOMER finds the least cost combination of components that meet electrical and thermal loads by simulating thousands of system configurations, optimizing for lifecycle cost, and generating results of sensitivity analyses on most inputs.

The cleaning frequency assumed is once every week during the rainless periods (8 months) and once every month for the rest of the year (total of 36 cleaning events per year). This cleaning schedule is ideal for arid regions to minimize reductions in electricity output resulting from dust deposition [8,21,22]. The water use per washing event is 20 m^3 ha^{-1} per wash for cleaning panels and water for dust suppression from soil. Water requirements for panel washing and dust suppression are provided in the Supporting Information S2. We assume that the total annual water requirement for dust management is equivalent to 72 mm (2 mm per event) of precipitation. Water use for the construction of PV infrastructure is also included in the life cycle analysis (see Supporting Information S2).

2.3. Integrated solar energy–aloe vera systems

Based on the life cycle analysis of a stand-alone solar PV system and aloe vera cultivation, we investigated the potential to integrate these two emerging land uses in northwestern India to identify the synergies and tradeoffs of colocation. We also conducted detailed economic analyses of colocated systems and the potential of these systems to improve rural livelihoods in northwestern India.

2.4. Sensitivity and uncertainty analyses

Sensitivity analysis (one-at-a-time local sensitivity analysis) was performed for solar PV installation and aloe vera cultivation. We defined a base case of the parameters considered, identified a range of uncertainty for each parameter, and then tested the effect of changing each parameter (on energy input/output and GHG emissions/offsets) from its minimum to maximum value. We used the module efficiency, irradiation, performance ratio and number of modules ha^{-1} for the solar PV infrastructure and overall leaf to gel conversion rate and number of plants ha^{-1} for the aloe vera gel system as input parameters (see Supporting Information S3).

We addressed the uncertainty in our analysis by using a Monte Carlo simulation approach. The analysis was performed using the input values of the most sensitive input parameters for solar PV and aloe vera gel, identified by sensitivity analysis. The input parameters considered for solar installation were efficiency (range of 14–16%) and number of modules ha^{-1} (3000–3500). The input variables considered for aloe vera gel were the overall leaf to gel conversion rate (25–35%) and number of plants ha^{-1} (20,000–25,000). The input variables were assumed to be independent and were randomly selected from a uniform distribution. The output simulation was repeated 10^4 times. The maximum, mean, minimum, and quantiles of outputs for solar PV (outputs: energy input, energy output, GHG emissions, and net greenhouse gas offsets) and the two yield scenarios of aloe (outputs: energy input, GHG emissions) were reported (see Supporting Information S3).

2.5. Economic analysis

An economic analysis was conducted to compare landowner returns on single land use to combined land use, both for grid-tied and off-grid cases. The analysis considered five project designs or land use scenarios, each evaluating the economic return to a 5-ha plot in Rajasthan. The land use scenarios considered are Aloe only, Off-grid PV only, Grid-tied PV only, Off-grid Combined and Grid-tied combined. This economic analysis assumes that the landowner is an individual, rather than a business, and thus is ineligible to capture cash benefits from tax-related incentives such as accelerated depreciation. Furthermore, the analysis assumes that the PV system is used for a variety of uses, not solely for agriculture; thus, subsidies for irrigation-related electricity demand are not considered.

2.5.1. Agriculture-related assumptions

Each model scenario that involved aloe cultivation (scenarios A, D, and E) uses the same input assumptions. Each hectare can support 22,500 aloe plants, with each plant capable of producing 2 kg of finished product (aloe gel) per year (resulting in 50,000 kg of processed aloe ha^{-1} $year^{-1}$). At a market price of 150 Indian Rupees (INR) per kilogram for aloe gel, this results in revenues of INR 7.5 M ha^{-1} $year^{-1}$. Planting costs are INR 75,000 per hectare, while annual crop maintenance costs are INR 37,000 per hectare. The aloe plants can be harvested 3.5 times per year beginning in year two. Planting costs occur in year one of the plant's life while crop maintenance costs and revenues occur in years two through five. Immediately after the five-year cycle, new plants are grown, and this plant cycle is repeated during the 30-year evaluation period. The model assumes that all 5 ha are cultivated on the same schedule, rather than rotating between hectares to smooth cash flow. Initial capital costs of INR 2 M and INR 1 M are incurred for machinery and buildings, respectively; annual operation and maintenance costs are of INR 600,000. The annual cash flow profile associated with aloe production (in scenarios A, D, and E) is shown in the Supporting Information S4.

2.5.2. Solar PV assumptions

The solar PV analyses assume a default power density of 400 kW/ha, totaling 2 MW for the 5-ha plot. Two different scenarios were considered for the solar PV analysis: a grid-tied and off-grid system. The off-grid systems assumed that the PV system would offset diesel consumption (valued at INR 14.7 per kWh or U.S. dollar \$0.25 per kWh) for three types of consumers: site-based agricultural electricity consumption, residential consumption, and non-residential (or commercial) consumption. Therefore, the consumption of each of these consumer classes is valued at what they would have paid to consume diesel-based electricity.

For grid-tied cases, the analysis used prevailing retail electricity rates and solar feed-in tariff (FiT) for Rajasthan (Supporting Information). The grid-tied cases assume that the landowner would build a PV system of the same capacity as above (400 kW ha^{-1} or 2 MW total) and sell all electricity generated to the local grid. This implies that residential and commercial consumers would purchase directly from the grid and are therefore not reflected in the grid-tied cases. The landowner would receive FiT payments for all kilowatt-hours sold to the grid and purchases electricity for agricultural production at the agricultural rate for electricity. In this analysis we did not account for the cost subsidies provided by governmental agencies for installing large solar infrastructures in this region.

The system design specifications were developed using HOMER, a cost optimization tool. The HOMER model optimized a system design that kept PV capacity constant across scenarios in order to provide a meaningful comparison. Cash flow profiles for the off-grid and grid-tied cases are shown in Supporting Information S4. The resulting output combines capital costs (of PV technologies, batteries, inverters, and a diesel generator to provide consistent production), total production costs, and annualized values for replacement costs and operations and maintenance (which explains why the cash flow profiles below appear to be smooth).

3. Results and discussion

The total energy inputs for solar PV infrastructure (412 GJ ha^{-1} $year^{-1}$ and gross GHG emissions of 39.6 Mg CO_2e ha^{-1} $year^{-1}$) are several times higher than the aloe vera baseline yield (28.14 GJ ha^{-1} $year^{-1}$ and 2.01 Mg CO_2e ha^{-1} $year^{-1}$) and high yield (52.59 GJ ha^{-1} $year^{-1}$ and 4.06 Mg CO_2e ha^{-1} $year^{-1}$) scenarios of aloe vera cultivation (Figs. 2 and 3, Table 1). However, solar

PV has an average energy output of 2590 GJ ha^{-1} $year^{-1}$ and gross GHG offset of 736 Mg CO_2e ha^{-1} $year^{-1}$. The energy ratio (energy output to input) was around 6:1 for solar PV installation (Table 1). The energy ratios are consistent with existing life cycle studies of large solar installations in desert regions. The water requirements for cleaning solar PV installation were higher than the water requirements for baseline and high yield scenarios of aloe vera.

Results of the economic analysis indicate that in grid-tied cases, the landowner would receive more benefits by simultaneously pursuing both productive uses of the land. Economic benefits are additive when combining land uses because there is no reduction in PV capacity by cultivating aloe in the same area, due to panel spacing restrictions of PV installations. Combining projects with positive net present value (NPV) leads to greater combined NPV. In this case, the grid-tied PV scenario has a positive NPV, so combining this land use with aloe cultivation yields a higher total project benefit. Off-grid (or microgrid) PV projects tend to have much higher capital costs, which occur early in the project's life and heavily impact the discounting of project benefits. This is the primary reason for the significantly negative NPV for the off-grid scenarios. Capital costs for off-grid PV are INR 351 M compared to INR 191 M for a grid-tied system of this type. Combining aloe cultivation with off-grid PV improves the landowner's NPV, but is still negative in terms of revenues. The NPV of each scenario is shown in Fig. 4 (calculated at a 10% discount rate throughout the analysis).

Fig. 5 shows the landowner's cash flows profiles for each of the five cases. It is important to note that the only negative cash flows periods occur during construction of the PV plant. Similarly, in the aloe-only case, cash flow is negative each year there is a replanting. In the combined land use scenarios, the cash flow is never negative after construction suggesting that this scheme may also provide more resilient aggregate cash flow to the landowner.

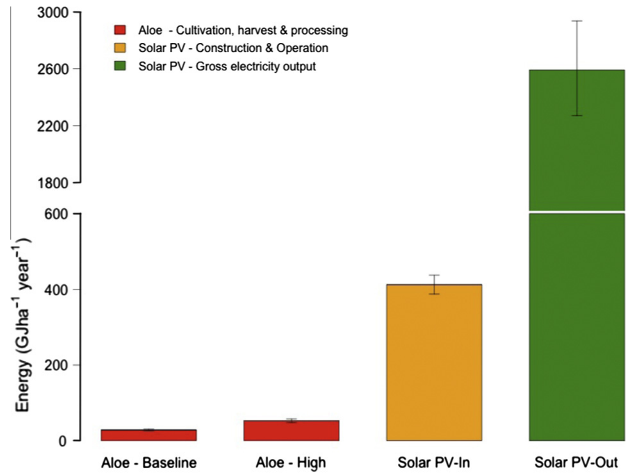

Fig. 2. Life cycle energy inputs and outputs of solar PV and aloe vera cultivation. The error bars represent the uncertainty in our analysis as determined by Monte Carlo analysis in which the most important parameters, as determined by sensitivity analysis, were varied.

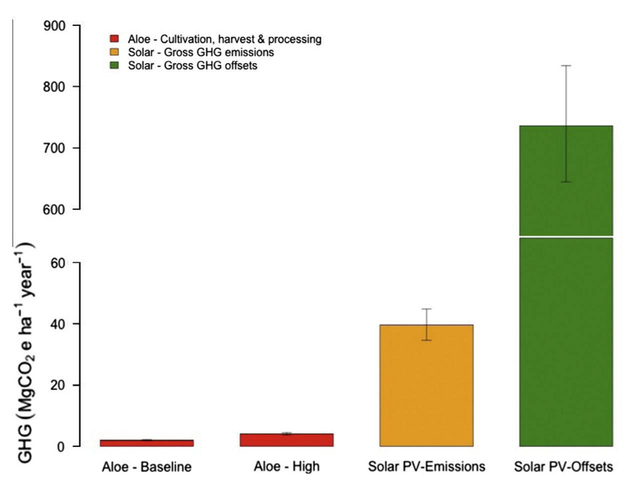

Fig. 3. Life cycle GHG emissions of aloe vera cultivation and gross GHG emissions and offsets of solar PV. The error bars represent the uncertainty in our analysis as determined by Monte Carlo analysis in which the most important parameters, as determined by sensitivity analysis, were varied.

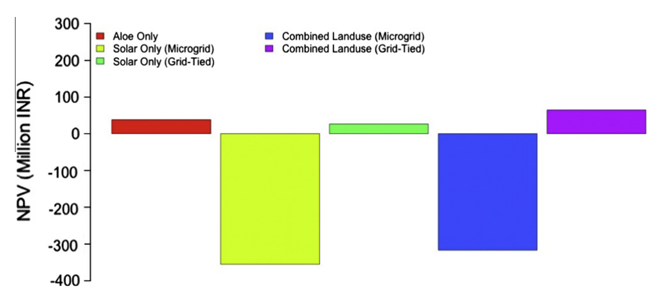

Fig. 4. Net present value of five land use scenarios (10% discount rate over 30 years).

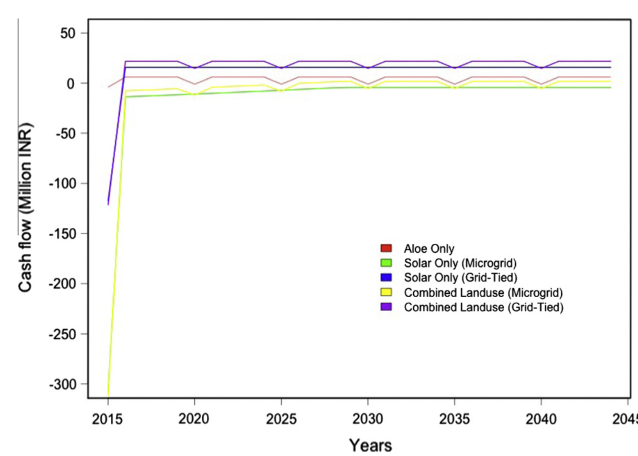

Fig. 5. Cash flows of five land use scenarios.

Table 1
Summary of annual life cycle energy and GHG from solar PV and aloe vera gel (5–95% quantile values are in brackets).

Land use	Gross energy output (GJ ha^1 y^{-1})	Gross GHG offsets (Mg CO_2e ha^{-1} y^{-1})	Energy input (GJ ha^{-1} y^{-1})	GHG emissions (Mg CO_2e ha^{-1} y^{-1})
Solar PV	2592 (2365–2828)	735 (671.8–803.1)	413 (389.6–435)	39.6 (35.7–43.2)
Aloe-high yield	–	–	52.6 (48.3–56.9)	4.1 (3.7–4.4)
Aloe-baseline yield	–	–	28.1 (26.1–30.3)	2.01 (1.8–2.2)

Aloe cultivation is a highly productive use of the land, while the solar scenarios are less so on an NPV basis. As mentioned above, the grid-tied PV case delivers a positive NPV, while the off-grid case is negative. This is largely because capital costs in year one are much larger for the off-grid cases due to the additional expense of batteries for the PV system. An impact that counteracts this effect is that off-grid kilowatt-hours are valued at INR 14.7 per kWh while grid-tied kilowatt-hours are valued at the FiT of INR 8.75 per kWh. However, timing effects from discounting have a greater impact on the resulting NPV. In both cases, though, including aloe as a productive land use improves the NPV to the land owner, increasing the grid-tied PV plant from INR 40 M to INR 66 M, and the off-grid plant from INR −355 M to INR −315 M, as seen in Fig. 4.

Sensitivity analysis indicated that the changes in the input parameters—efficiency and number of modules for solar PV and overall sugar utilization efficiency and number of plants for aloe—have significant impacts on the total energy input, gel production, and GHG offsets.

The Monte Carlo approach indicated that the aloe fresh leaf yield (annual) ranges from 24 to 30 Mg ha^{-1} for the baseline scenario and 48–60 Mg ha^{-1} for the high yield scenario. The maximum and minimum values for outputs are reported as error bars in Figs. 2 and 3 (see Supporting Information S3).

The results presented above consider reference case input values. In order to incorporate uncertainty and evaluate sensitivity to individual model inputs, a 10,000 trial Monte Carlo simulation was conducted. NPVs for each of the five cases were defined as outputs for sensitivity analysis, and Fig. 6 shows the range of results of each given ±20% ranges for selected inputs. Uncertainty ranges were defined where information was available for specific inputs. The frequency distributions below provide a glimpse of how certain the NPV results are. For example, the off-grid scenarios consistently show negative NPV values, whereas the grid-tied PV-only scenario could show negative or positive NPV values, depending on inputs.

In addition to showing the range of possible outputs, the Monte Carlo analysis can reveal how sensitive an output is to a given input. This is typically displayed with a tornado chart, which shows the most sensitive inputs for each of the scenario NPV results (see Supporting Information S4). These tornado charts provide a meaningful comparison of the input sensitivities because all uncertainty ranges are identical. In general, prices and consumption are the most sensitive variables for both PV and aloe scenarios. Capital costs were excluded from the sensitivity analysis because they were modeled outside of the economic model in HOMER, so the relationships between capital costs and capacity and production would not hold in this economic model if included in the sensitivity analysis. If included in the sensitivity analysis, capital costs would be much more sensitive, both because they are significant relative to other cash flows and because they occur in year one.

In addition to the Monte Carlo analysis, an evaluation was conducted to examine the impact of a 10% reduction in PV capacity that could result from combining land use. For this assessment, only the PV capacities in the two combined land use scenarios were reduced by 10% from 400 kW ha^{-1} to 360 kW ha^{-1}. Interestingly, the NPV decreases in the microgrid case, but marginally increases in the grid-tied combined land use case. This is primarily due to system design. In order for a microgrid to support a certain load at lower PV capacity, battery capacity should be increased, thereby offsetting some of the cost reduction from capacity decreases. In a lower load case (1500 kWh day^{-1} versus 1700 kWh day^{-1}), the NPV of the microgrid case increases to INR 56 M. This implies that the microgrid scenario is very sensitive to system design and therefore cost.

In our analysis of colocation, the synergy between solar PV system and aloe vera cultivation stems from the fact that the water inputs for cleaning solar panels are similar to amounts required for annual aloe production, suggesting the possibility of integrating the two systems on the same plot of land to maximize land and water use efficiency. The life cycle analyses show that the colocated systems are economically viable in some cases and may provide opportunities for rural electrification and stimulate economic growth. A life cycle analysis of a hypothetical colocation system in northwestern India indicated higher economic returns per m^3 of water used than either system alone, an important consideration in an arid area. We considered the output from the uncertainty analysis of the average aloe yield scenario and average solar PV

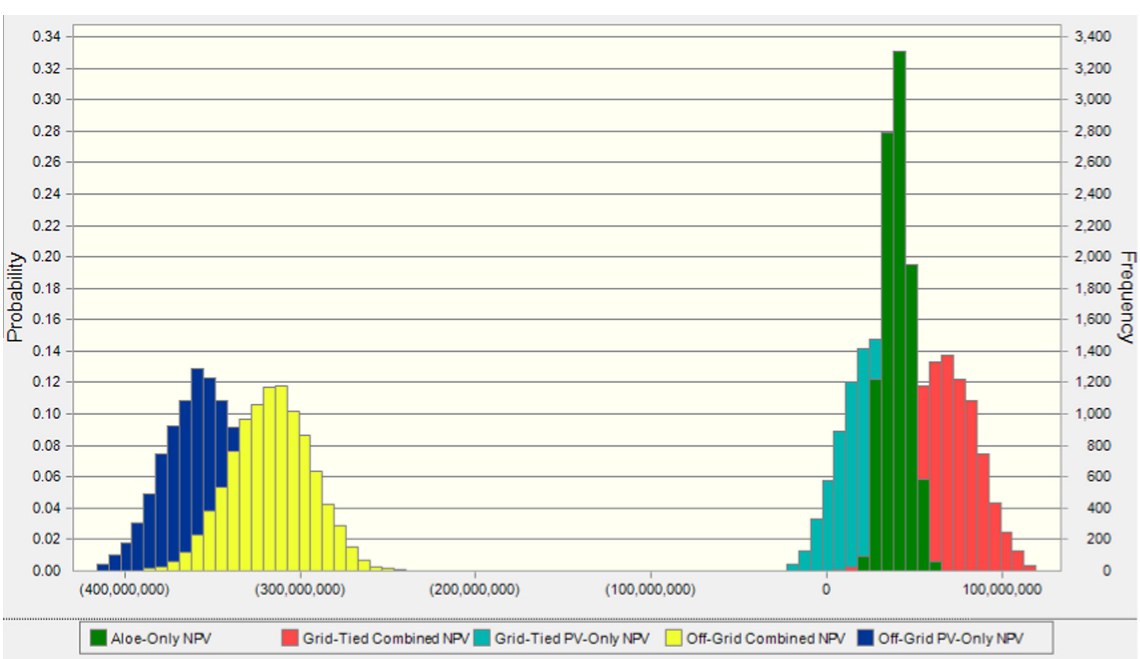

Fig. 6. NPV frequency distributions from Monte Carlo analysis (10,000 trials) where the *x*-axis represents NPV in INR.

to estimate the economics range of different land use scenarios (see Supporting Information S4). When water productivity is expressed in terms of net benefits (INR m^{-3}) the aloe vera cultivation (low yield scenario for leaf production only at INR 2 kg^{-1}) [43,44] resulted in much higher returns m^{-3} of water used (INR 60 for the baseline yield scenario) compared to agricultural crops in the region (INR 2–12) [56]. The results from our economic analysis indicate that the processing of aloe to gel leads to a substantial increase (over 10 times) in water productivity compared to the aloe leaf production only scenario. The water productivity of solar PV installation (grid-tied) by far exceeds other land uses (over 250–1500 times normal agricultural crops in the region) and when colocated with aloe cultivation (for gel production) the water productivity and economic benefits are much higher (30% higher), highlighting the synergies of colocation. In the case of micro grids, the colocation leads to an even higher increase in returns (40% higher), indicating that colocation may have the potential to make some offgrid systems profitable. The benefits will be substantially higher if we account for subsidies provided by governmental organizations for installing large solar installations, particularly in the case of micro grids.

Colocated systems may provide several co-benefits. In rural areas not connected to the electricity grid, colocation of aloe cultivation with standalone solar infrastructures has the potential to stimulate economic growth by aiding in rural electrification and creating stable employment opportunities for agricultural laborers (e.g., in cultivation and processing of aloe or other local agricultural commodities). Studies have indicated that electricity availability is a significant driver of development in rural areas by stimulating economies, providing job security, and improving health and education [57,58]. The labor requirements for large solar infrastructures are mostly concentrated during the construction phase. The colocation of agriculture with solar facilities may provide continuous employment opportunities for routine agricultural operations (farm labor and processing).

Colocation of solar PV and agriculture in rural areas may provide several new and feasible technologies for solar energy applications in the agricultural sector [59,60]. Common applications of solar energy in agriculture include solar irrigation systems, photovoltaic heating and refrigeration systems, solar-based processing units for agriculture commodities, and solar greenhouses [59,60]. In rural areas not connected to the grid, solar water pumps provide an environment friendly alternative to diesel pumps with high emissions [59,61]. Solar-powered desalination systems can be used to provide irrigation water in some arid regions with limited access to fresh water resources [62]. Further, rural electrification provides rural farming communities easy access to up-to-date agriculture-related information and weather forecasts, thereby enabling faster adoption of improved crop and water management practices. Overall, colocation may contribute to sustainable agriculture and rural development [59,61].

Colocating crops in solar facilities may help to control soil erosion by wind and water by maintaining an effective ground cover (aloe), improving soil moisture in surface soil and potentially reducing dust emissions from disturbed soils and improving air quality in the region [25]. Moreover, solar panels may result in enhanced moisture availability to aloe plants by channeling or concentrating rainfall on to the interspaces, thereby amplifying the background precipitation for plants. Partial shading by solar panels may provide benefits to aloe plants grown in desert conditions with high available solar radiation [39]. Further, CAM plants like aloe vera are known to benefit from increase in atmospheric CO_2 and are tolerant to droughts and high temperatures, which are expected to be more frequent in the future [38].

Colocation may not be practical in all locations, and further field studies are required to fully evaluate the advantages and disadvantages of colocation [62]. We acknowledge that before field level implementation of large colocated systems, long-term field experiments are needed to fully understand the benefits and synergies of colocation in different regions. For example, considerable uncertainties remain on aloe yield under colocated conditions and the impact of periodic water addition (from washing panels) and partial shading on aloe vera leaf yield and gel quality. Reliable estimates of leaf yield and gel characteristics (quantity and quality) of various aloe cultivars are critical for establishing the long-term economic and logistic viability of commercial aloe vera gel production. Another factor that needs consideration is determining the optimum packing density for solar modules and the optimal planting density for aloe vera. The spacing of solar modules is an important factor because it impacts the space requirements for plants and routine agricultural operations. Even though colocation might be possible in some of the existing solar PV installations, design modifications (and additional costs) might be needed to fully accommodate the colocation of aloe vera. The success of these systems depends on the timely availability of planting materials, gel processing machinery, and the ability to provide technical guidance to local farmers. The life cycle assessment and ecological benefits depend also on the electricity source used for cultivation practices such as irrigation. For example, in scenarios where the farmers sell PV-sourced electricity to the local grid and buy electricity at the agricultural rate, the environmental benefits depend on the source of the electricity used for cultivation practices.

4. Conclusions

Colocated solar and aloe vera infrastructure could: (1) ensure efficient land and water use (both PV cleaning water and precipitation) by sustaining agricultural production in marginal lands and maximizing power output from solar PV; (2) increase area of high value crops and thereby minimize the socioeconomic and environmental issues resulting from cultivation of high value non-food crops (e.g., aloe) in prime agricultural lands; (3) stimulate rural economies by creating employment and providing opportunities for rural electrification; and (4) improve regional air quality by reducing soil erosion and dust emissions from large solar infrastructures. The water requirement for aloe vera cultivation is low compared to other agricultural crops, and aloes can survive and produce significant biomass in nutrient poor soils and in adverse climatic conditions. In northwestern India, solar deployment is increasing rapidly, with growing concerns on the fate of land and water resources in this region. This study indicates that there is potential to integrate high value crops with these large solar installations with no additional land or water use.

Based on an optimistic scenario of solar expansion in India, there is potential to install 100 GW in the next decade [63]. This expansion will translate into over 250,000 ha of direct land transformation, mostly in the arid regions of northwestern India. Assuming that all these areas could be integrated with aloe vera cultivation, over 7–14 million tons $year^{-1}$ (base and high yield scenarios respectively) of aloe vera leaves could be produced, with no additional water use or land transformation. Colocation of high-value crops may make the off-grid solar PV systems economically viable in certain configurations, thereby providing co-benefits including rural electrification, reduced diesel consumption (and associated reductions in GHG emissions), and employment generation. The northwestern state of India (Rajasthan), identified as the one of the hotspots for solar energy development in India, has a population of over 70 million with access to only 1% of India's water resources. The region has experienced high population growth (10%) in the past decade (2001–2011), creating additional demand for land and water resources. In these water-limited areas, colocated solar infrastructure and aloe cultivation could be established in marginal lands with low water use, thus minimizing the socioeconomic and environmental issues resulting from cultivation of non-food crops (e.g., aloe) in prime agricultural lands.

Acknowledgements

The Joint Institute of Strategic Energy Analysis (JISEA – IRAAP), TomKat Center for Sustainable Energy at Stanford University, Council on Environment, Energy & Water (CEEW). This work was supported by the Joint Institute for Strategic Energy Analysis (JISEA). JISEA is operated by the Alliance for Sustainable Energy, LLC, on behalf of the U.S. Department of Energy's National Renewable Energy Laboratory, the University of Colorado-Boulder, the Colorado School of Mines, the Colorado State University, the Massachusetts Institute of Technology, and Stanford University. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes. Some symbols used in the graphical abstract are courtesy of the Integration and Application Network (ian.umces.edu/symbols).

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2015.12.078.

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