Tradeoffs and Synergies between Biofuel Production and Large Solar Infrastructure in Deserts

Sujith Ravi,*† David B. Lobell,‡† and Christopher B. Field‡§

†Department of Environmental Earth System Science, Stanford University, 473 Via Ortega, Stanford, California 94305, United States
‡Center on Food Security and the Environment, Stanford University, Stanford, California 94305, United States
§Department of Global Ecology, Carnegie Institution for Science, Stanford, California 94301, United States

Supporting Information

ABSTRACT: Solar energy installations in deserts are on the rise, fueled by technological advances and policy changes. Deserts, with a combination of high solar radiation and availability of large areas unusable for crop production are ideal locations for large solar installations. However, for efficient power generation, solar infrastructures use large amounts of water for construction and operation. We investigated the water use and greenhouse gas (GHG) emissions associated with solar installations in North American deserts in comparison to agave-based biofuel production, another widely promoted potential energy source from arid systems. We determined the uncertainty in our analysis by a Monte Carlo approach that varied the most important parameters, as determined by sensitivity analysis. We considered the uncertainty in our estimates as a result of variations in the number of solar modules ha\(^{-1}\), module efficiency, number of agave plants ha\(^{-1}\), and overall sugar conversion efficiency for agave. Further, we considered the uncertainty in revenue and returns as a result of variations in the wholesale price of electricity and installation cost of solar photovoltaic (PV), wholesale price of agave ethanol, and cost of agave cultivation and ethanol processing. The life-cycle analyses show that energy outputs and GHG offsets from solar PV systems, mean energy output of 2405 GJ ha\(^{-1}\) year\(^{-1}\) (43% quantile values of 1940–2920) and mean GHG offsets of 464 Mg of CO\(_2\) equiv ha\(^{-1}\) year\(^{-1}\) (375–562), are much larger than agave, mean energy output from 206 (171–243) to 61 (50–71) GJ ha\(^{-1}\) year\(^{-1}\) and mean GHG offsets from 18 (14–22) to 4.6 (3.7–5.5) Mg of CO\(_2\) equiv ha\(^{-1}\) year\(^{-1}\), depending upon the yield scenario of agave. Importantly though, water inputs for cleaning solar panels and dust suppression are similar to amounts required for annual agave growth, suggesting the possibility of integrating the two systems to maximize the efficiency of land and water use to produce both electricity and liquid fuel. A life-cycle analysis of a hypothetical colocation indicated higher returns per m\(^3\) of water used than either system alone. Water requirements for energy production were 0.22 L MJ\(^{-1}\) (0.28–0.19) and 0.42 L MJ\(^{-1}\) (0.52–0.35) for solar PV–agave (baseline yield) and solar PV–agave (high yield), respectively. Even though colocation may not be practical in all locations, in some water-limited areas, colocated solar PV–agave systems may provide attractive economic incentives in addition to efficient land and water use.

INTRODUCTION

Energy production using fossil fuels is a major contributor to anthropogenic greenhouse gas (GHG) emissions and associated global warming.1 In this regard, low carbon emission technologies, such as biofuels and solar energy, may provide alternative pathways for sustainable energy production to meet the current and future energy requirements.2 Solar and biofuel technologies both use the energy from the sun, using photovoltaic (PV) conversion to electricity in the case of solar energy and harvesting plant biomass that can be processed as solid or liquid fuels in the case of biofuel energy.2 Even though renewable energy potentially provides several positive aspects, such as reduction of GHGs, reclamation of degraded land, increased energy independence, employment opportunities, acceleration of rural electrification, and improvement of the quality of life in developing countries,3–5 the deployment of large-scale renewable energy infrastructure may negatively impact land and water resources.6–8 Moreover, renewable energy technologies differ considerably in their effectiveness in specific geographic locations and in their environmental and socioeconomic impacts. Thus, to provide all of our energy needs, it is necessary to approach renewable energy development through a combination of complementary technologies to maximize returns on resource use and to minimize environmental impacts.1,2

Solar energy installations in drylands are on the rise, fueled by technological advances and policy changes.9 Drylands, with a combination of high solar radiation and availability of large areas unusable for crop production, are ideal locations for large solar installations. Drylands cover over 40% of the earth’s land...
Dust accumulation on solar panels is a major factor affecting power output from large solar installations, and annual loss estimates as a result of dust accumulation range from 5 to 35%.12–14 While there are many strategies to minimize dust accumulation on PV panels, washing panels with water remains the main approach in most systems.14 Ibrahim et al. demonstrated that washing panels every 2 months improved efficiency but still resulted in energy output 25% below the maximum possible and, hence, recommended a cleaning frequency of once a week for extreme arid climates.13 Thus, water for washing panels and dust suppression is potentially a major water demand and a large component of the water budget of solar facilities in desert regions,14 and it may place a major demand on the already scarce local water resources or may displace water allocated for domestic use or agricultural activities.

Although some of the water applied to panels is evaporated, much of it runs off the panels and into the desert soil. A pertinent question is therefore whether the moisture inputs are sufficient to maintain agriculture or biofuel production in water-limited regions. Most solar facilities are sited in marginal lands, which are unusable for most crops or pasture grasses. However, there is a growing interest to grow biofuel feedstocks in marginal lands that can be cultivated without competition for key resources for food crops.15–17 Biofuels are thought to be an integral part of the future energy mix,18,19 and several plant species have been identified and cultivated to use as feedstock for bioethanol production.15,20 Producing biomass feedstocks for bioethanol in drylands may be a way to partially meet the demand for renewable fuels without negative impacts on food production.2,15,21

Agave spp., perennial evergreen xerophytic plants, which have ecological and physiological adaptations to achieve meaningful yields on marginal lands, are a case in point.16,22,23 In particular, agave plants have high water use efficiencies as a consequence of using the crassulacean acid metabolism (CAM) photosynthetic pathway, which enable them to open stomata at night when evaporative demand is lower.21,22 Agaves are common in arid and semi-arid regions of the world, including the North American deserts, where they have been cultivated for fiber and alcoholic beverages for centuries.21,22 Even though maximum yields are limited to areas with precipitation exceeding 1000 mm, reasonable productivities occur in areas with precipitation in the range of 300–800 mm.15,16 Several characteristics of agave make them attractive as a biofuel crop in deserts. The list includes significant biomass production with little or no irrigation, tolerance to droughts and high temperature, ability to make use of small precipitation events or light irrigation, and high sugar and cellulose content (less energy to extract sugars and ethanol).16,21,22

Colocated solar energy and agave ethanol infrastructure 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 biofuel cultivation in existing large solar infrastructures, and simulating economic returns to improve livelihoods in rural areas. However, to explore the logistic and economic feasibility of integrated solar–agave biofuel systems, detailed life-cycle analyses are needed. Here, we conduct detailed life-cycle analysis for solar PV, agave-derived biofuel, and a hypothetical colocated solar–agave system to explore the tradeoffs and synergies (in the context of energy, water, and GHG emissions) between these two emerging land uses (Figure 1).

### MATERIALS AND METHODS

**Land Footprint and Water Use of Large Solar Installations.** To estimate the land footprint and water use in large solar installations in drylands, we compiled data from project-planning reports, from the California Energy Commission24 and Bureau of Land Management25 of large solar PV and concentrated solar power (CSP) projects in the south-
western United States, which are approved for construction or are already under construction. Our compilation covers both the land area used for the solar infrastructure and the right of way (ROW) land area allocated for additional support facilities, such as transmission lines and roads. For the land footprint and water use, our analysis included 28 large solar installations (13 PV, 10 parabolic trough CSP, and 5 central tower CSP). ROW land area for 10 solar installations were used to derive a linear relationship between land area under the installation and ROW allotted to the solar companies. The annual water uses for large solar facilities were partitioned into construction and operation phases, assuming a 30 year life for the installations. Water use in the construction phase is mostly for dust suppression from disturbed soils, and water use in the operation phase is for cleaning panels or mirrors. The data included 5 solar PV installations and 10 CSP installations (3 CSP parabolic trough with wet cooling, 3 CSP parabolic trough with dry cooling, and 4 CSP central tower) (details on solar technologies and methods are on page S3 of the Supporting Information).

Life-Cycle Analysis of Agave-Derived Ethanol. Fuel ethanol production from agave is not well-established, and we adopted the life-cycle analysis methodology followed by Yan et al., which is based on the production pathway used in the tequila industry in Mexico and the Brazilian sugarcane industry. The life-cycle stages for agave-derived ethanol are agave cultivation, harvest and transport, and ethanol production. In this scenario, the sugar extracted from agave juice is used for ethanol production, while the cellulosic residues are combusted in a co-generation system to provide process energy with excess electricity exported to the electrical grid. We take into account the life-cycle fossil energy use and GHG emissions for direct energy and material inputs, machinery, and buildings. We account for CO$_2$, CH$_4$, and N$_2$O as GHG emissions, with all emissions converted to CO$_2$ equivalents based on their 100 year global warming potential.

We consider an intensive cultivation scenario with high levels of fertilizer applications and soil amendments to reduce the harvest cycle to 6 years. Agaves are started from rhizomes, with a planting density of 3350 plants per ha$^{-1}$. Following Yan et al., the application rates of herbicides and pesticides are taken as average values reported for corn and sugarcane and the fertilizer application is 600, 40, and 240 kg ha$^{-1}$ (for a 6 year cycle) as nutrients of N, P, and K, respectively. In addition, ash from the combustion of bagasse and residue and filter cake from juice filtration during the biorefinery stage are also added as fertilizers. The mechanization level in the cultivation stage is assumed to be similar to the Brazilian sugarcane industry. (see pages S5–S13 of the Supporting Information.) Harvesting is assumed to be mechanical using modified whole-stick cane harvesters. Whole plants, including the sugar-rich stems and leaves, are harvested. Yield (above-ground dry matter) is a major unknown variable in agave cultivation, and reported yield measurements range from 10 to 34 Mg ha$^{-1}$ year$^{-1}$ for a precipitation range from 300 to 800 mm. However, higher yields are also reported around 42 Mg ha$^{-1}$ year$^{-1}$. For comparison, the average yields reported for corn and sugarcane are 10 Mg ha$^{-1}$ year$^{-1}$ (grain and stover) and 21 Mg ha$^{-1}$ year$^{-1}$ (sugar and bagasse), respectively. We consider three scenarios, low yield, baseline yield, and high yield, with annual yields of 10, 15, and 34 Mg ha$^{-1}$ year$^{-1}$, respectively. In the low-yield scenario, no irrigation is provided and the only water inputs are from precipitation (assumed to be 250 mm year$^{-1}$). In the baseline- and high-yield scenarios, irrigation is provided at a rate of 100 and 550 mm precipitation (annual) equivalent, respectively, in addition to background precipitation. In the baseline- and high-yield scenarios, stillage generated at the biorefinery stage is added as additional irrigation water and fertilizer.

Ethanol production equipment and processes are assumed to be comparable to those in a typical sugarcane ethanol plant. Agave stems and fresh leaves are used for ethanol production. The bagasse generated from the extraction process and the unused residual leaves are combusted to provide the process energy, and the surplus electricity is exported to the grid. The overall sugar utilization efficiency, which includes efficiency in extraction, hydrolysis, fermentation, and distillation, is assumed to be 80%. This efficiency is lower than the industry average value of 90% in the case of Brazilian sugarcane ethanol production, because commercial agave-derived ethanol processing pathways are not currently well-established. The first stage in ethanol production involves the use of diffusers to extract juice from uncooked agave stems and leaves. For this study, we consider the diffuser system instead of the mill system typically used in the sugarcane industry, because the diffuser system yields a higher sugar recovery percentage of 99%. In this stage, the major form of carbohydrate in agave (fructans) is converted to free sugars, such as fructose, which can later be fermented to produce ethanol. The energy use for the diffuser system and hydrated ethanol yield from sugarcane using the diffuser system are adopted from Yan et al. In this ethanol production scenario, enzymatic hydrolysis is adopted for agave juice, although a short thermal treatment (using the waste heat from the co-generation system) is used after enzymatic activities to accelerate the hydrolysis. Electricity is used for dehydration of ethanol and for stillage treatment. Stillage generation is assumed to be 12 L L$^{-1}$ of ethanol (see pages S5–S13 of the Supporting Information.)

The energy values and GHG offsets assigned to electricity export from agave are the life-cycle fossil fuel energy use and GHG emissions to produce this electricity based on the U.S. generation mix. Life-cycle fossil energy use and GHG emissions for the U.S. generation mix are 2.91 MJ and 193 g of CO$_2$ equiv MJ$^{-1}$ of electricity produced, respectively. The net GHG offsets for different yield scenarios of agave are calculated as the fossil fuel energy saved by manufacturing ethanol from agave compared to gasoline (94 g of CO$_2$ equiv to produce 1 MJ of gasoline) in addition to fossil fuel energy saved by exporting electricity by combustion of agave residues. In other words, the total GHG offsets include offsets by agave-derived ethanol displacing gasoline and surplus electricity displacing grid electricity minus the GHG emission resulting from the production of agave-derived ethanol and electricity.

Solar PV Life-Cycle Analysis. We considered a solar PV installation, because PV is the dominant technology for current and proposed solar installations. Further, there might be other logistic constraints for colocaiton of biofuels in CSP installations because of intensive infrastructure. The solar PV infrastructure is installed in a desert environment with an annual precipitation of 250 mm and a solar insolation of 2100 kWh m$^{-2}$ year$^{-1}$. We adopt the design configuration of a very large-scale PV power generation infrastructure described by Ito et al. This installation consists of a basic array of fixed flat plate systems with approximately 3500 multi-crystalline silicon [m-Si modules of 120 Wp (watt peak, maximum power in watts generated from a PV module under optimum conditions), with...
a module area of 1 m²) PV modules with an efficiency of 13%. The performance ratio (PR, defined as the ratio of energy output measured to energy output modeled, is a performance indicator of a solar infrastructure at a given location or environmental conditions) of this PV infrastructure is assumed to be 70%, which is typical of desert areas. The annual power generation is calculated as follows:

\[
\text{annual power generation (kWh year}^{-1}\text{)} = \text{solar insolation (kWh m}^{-2}\text{year}^{-1}\text{)} \times \text{efficiency} \times \text{module area (m}^2\text{)} \times \text{performance ratio}
\]

The materials and energy inputs and GHG emissions and outputs during life cycles of m-Si modules are considered from PV production plants. The life-cycle stages considered are manufacturing PV modules and balance of system (BOS) components, construction and operation, decommission, and recycling, assuming a life cycle of 30 years. Large-scale solar installations in deserts require balance of system components, such as module frames, mounting structures, grid connectors, concrete, and office facilities. The energy inputs for producing 1 MWp [megawatt peak, maximum power (in MW) generated from a module under optimum conditions] of m-Si module and BOS components total 31 333 GJ. The GHG emissions resulting from production of 1 kWh (kilowatt hour) of m-Si module and BOS components are 37 and 20 g of CO₂ equiv, respectively. 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 some additional pollutants and heavy metal emissions, including direct and indirect emissions of cadmium. The energy values and GHG offsets assigned to electricity produced by the solar PV infrastructure are the life-cycle fossil fuel energy use and GHG emissions to produce this electricity based on the U.S. generation mix (2.91 MJ and 193 g of CO₂ equiv MJ⁻¹ of electricity produced, respectively) (see page S14 of the Supporting Information).

To account for the dust or "soiling" impacts of solar power production, a derate rate of 0.3% per day was applied to the performance ratio for rainless periods, which extends over a period of 7 months per year. The washing frequency was once every week during the rainless periods (7 months) and once every month for the rest of the year. The water use for per washing event was adopted from the planning reports for large PV solar power projects in the southwestern United States (20 m³ ha⁻¹). Additional water application was used to suppress dust production from the soil. We assume that the total annual water requirement for dust management is approximately equivalent to 100 mm of annual precipitation. Water use for the construction of PV infrastructure is also included in the life-cycle water use. Water requirements for washing panels and dust suppression are provided in page S15 of the Supporting Information.

Integrated Solar Energy–Biofuel Systems. On the basis of the life-cycle analyses, we evaluated the potential to integrate solar infrastructure with agave feedstock cultivation. We also evaluated the economic returns (difference between annualized revenue and cost of installation (solar) or cultivation and ethanol processing (agave)) from solar PV (electricity) and agave cultivation (ethanol and electricity export). The wholesale electricity cost used in this analysis was $100 per MWh, and the lifetime (30 year) construction and operation costs were taken as $4 per Wp. Information on the cost of cultivation and ethanol processing from agave is scarce. In this study, we used cultivation costs of $1250, $1750, and $3250 ha⁻¹ for low-, baseline-, and high-yield scenarios of agave, respectively. The wholesale ethanol price used in this analysis was $2.75 per gallon (see pages S16 and S17 of the Supporting Information).

To illustrate the tradeoffs and synergies of colocating solar and biofuel infrastructures, we calculate the revenue generated (U.S. $) per cubic meter of water used in the San Bernardino County in California for agriculture, solar, and agave biofuel. San Bernardino County was chosen as an example to illustrate the potential to colocate solar and biofuel projects because this region has been identified as one of the major areas for large solar energy development. The region is characterized by an arid climate with around 250 mm of annual precipitation, and large areas are irrigated for crop and range production. We used the irrigated area and applied water estimates for various crops and their values (U.S. $) in 2003 from the California Department of Water Resources and United States Department of Agriculture (USDA), National Agricultural Statistics Service (NASS). The total value of all crops was divided by the total water applied to calculate the returns per amount of water used.

Sensitivity and Uncertainty Analyses. Sensitivity analysis was performed for solar PV installation and agave-derived ethanol. 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 output and GHG offsets) from its minimum to maximum value. We used the module efficiency, insolation, performance ratio, and number of modules ha⁻¹ for the solar PV infrastructure and overall sugar utilization efficiency and number of plants ha⁻¹ for the agave-derived ethanol system as input parameters (see pages S18–S21 of the Supporting Information).

We addressed the uncertainty in our analysis using a Monte Carlo simulation approach. The analysis was performed using the input values of the sensitive input parameters for solar PV and agave-derived ethanol, identified by sensitivity analysis. In addition, we also included the parameters that affect the revenue and returns from solar infrastructure and agave cultivation. The input variables considered for the solar installation were efficiency (11–15%), number of modules ha⁻¹ (2500–3500), installation cost ($3–4 Wp⁻¹), and the wholesale price of solar electricity ($0.08–0.12 kWh⁻¹). The input variables considered for agave-derived ethanol were the overall sugar utilization efficiency (70–90%), number of plants ha⁻¹ (2850–3850), cultivation and distillation cost ($1000–3500 ha⁻¹), and the wholesale price of biomass electricity ($0.08–0.12 kWh⁻¹). The input variables were assumed to be independent and were randomly selected from a uniform distribution, and the output simulation was repeated 10⁶ times. The maximum, mean, minimum, and quantiles (5% and 95%) of outputs for solar PV (outputs: energy input, energy output, GHG emissions, net GHG offsets, revenue, and returns) and the three yield scenarios of agave (outputs: energy input, total energy output, ethanol energy, electricity export, GHG emissions, net GHG offsets, revenue, and returns) were reported (see pages S22–S25 of the Supporting Information).
RESULTS AND DISCUSSION

Analysis of the solar installations in the southwest U.S. indicates that solar installations occupy significant land area and use a considerable amount of water for construction and operation (Figure 2). The land area required to install 1 MWp ranged from 1.8 to 3.8 ha (Figure 2a). The ROW area (e.g., for access roads and transmission lines) requested by solar companies is typically twice the actual area of the installed solar infrastructure (Figure 2a). The concentrated solar facilities with wet-cooling technology use high amounts of water compared to PV systems (Figure 2b), resulting in 10 times more water use compared to dry-cooled CSPs. In addition to that, CSPs require some process water and water for routine mirror cleaning and dust suppression (Figure 3). In the case of PV systems, water use for construction and operation phases is mostly for dust suppression and cleaning panels (Figure 3). Regardless of PV or CSP technology, water for dust management, either directly for washing dust from solar panels or indirectly for suppressing dust suppression from soils by adding moisture, is a major component of the total water use (Figure 3).

Sensitivity analysis indicated that the changes in the input parameters, efficiency and number of modules ha$^{-1}$ for solar PV...
and overall sugar utilization efficiency and number of plants ha\(^{-1}\) for agave, have significant impacts on the total energy output and GHG offsets (see more information on the analysis on pages S18–S21 of the Supporting Information). The solar insolation and performance ratio are not expected to change significantly as the panels are installed in a desert environment, such as southwestern U.S. (minor variations in solar insolation) and are cleaned routinely to minimize the impacts as a result of soiling (minor variations in PR). We have also included economic parameters in the uncertainty analysis: the installation cost of solar infrastructure and wholesale price of solar electricity for solar PV and the cultivation and distillation costs and the wholesale price of fuel ethanol. Even though there are several factors, which may affect the energy output and GHG offsets from solar PV and agave-derived ethanol, the factors that we considered are important in the case of colocation (see pages S22–S25 of the Supporting Information).

The Monte Carlo approach indicated an agave yield range from 8 to 12 Mg ha\(^{-1}\) (low yield), from 13 to 17 Mg ha\(^{-1}\) (baseline yield), and from 29 to 39 Mg ha\(^{-1}\) (high yield). The 5 and 95% quantile values are reported for all of the life-cycle model outputs. The maximum and minimum values of outputs are reported as error bars in Figures 4 and 5 and Table 1.

The life-cycle analyses show that energy output from the solar PV system [energy output of 2405 GJ ha\(^{-1}\) year\(^{-1}\) (1940–2920)] is much larger than that from agave, with a mean energy output of 206 GJ ha\(^{-1}\) year\(^{-1}\) (171–243) for high yield, 87 GJ ha\(^{-1}\) year\(^{-1}\) (73–103) for baseline yield, and 61 GJ ha\(^{-1}\) year\(^{-1}\) (50–71) for low yield (Figure 4). The energy ratio (energy output to input) was around 5.4 (5–6) for solar PV installation. For agave-derived ethanol, this ratio ranged from 3.3 (3.1–3.5), 3.2 (3–3.6), and 4.8 (4.4–5.2) for the low-, baseline-, and high-yield scenarios of agave. The energy ratios are consistent with existing life-cycle studies of large solar installations and agave-derived ethanol production.\(^{26,31}\)

The energy output from solar PV (mean) is 12, 28, and 40 times higher than that of high-, baseline-, and low-yield scenarios of agave. Despite the much higher rates of energy output...
A life-cycle analysis of a hypothetical colocation of solar PV and agave for San Bernardino County in California indicated higher returns per m3 of water used than either system alone (Table 2). The solar PV and agave both can achieve high revenues per m3 of water used compared to traditional agricultural crops. The revenues from solar PV per unit of water used were over 100 times higher than traditional crops, while the revenues from baseline- and high-yield scenarios of agave were 5 and 2 times higher, respectively. The lower revenue per unit of water consumed for the high-yield scenario of agave was attributed to high irrigation water input. However, we have to consider that installation costs are very high for solar infrastructures. Total returns on investment for solar PV, baseline-yield agave, and high-yield agave were 10, 1.3, and 1 times higher than the revenue of agricultural crops. Returns per m3 water use of these energy systems are higher than even the revenue per m3 water use of agricultural crops. Moreover, we can estimate the higher value of the liquid fuel compared to electricity (Table 1).

GHG emissions from the solar PV system [37 Mg of CO2 equiv ha−1 year−1 (45–30)] are much larger than those from agave, with GHG emissions of 4.7 Mg of CO2 equiv ha−1 year−1 (4.2–5.1) for high yield, 2.9 Mg of CO2 equiv ha−1 year−1 (2.6–3.2) for baseline yield, and 2.1 Mg of CO2 equiv ha−1 year−1 (1.9–2.4) for low yield (Figure 5). The GHG emissions from solar PV (mean) are 8, 13, and 18 times higher than those from the high-, baseline-, and low-yield scenarios of agave, respectively (Table 1). The GHG offsets from the solar PV system [464 Mg of CO2 equiv ha−1 year−1 (375–562)] are much larger than those from agave, with GHG offsets of 18 Mg of CO2 equiv ha−1 year−1 (14–22) for high yield, 6.8 Mg of CO2 equiv ha−1 year−1 (5.3–8.2) for baseline yield, and 4.6 Mg of CO2 equiv ha−1 year−1 (3.7–5.5) for low yield. GHG offsets (mean) resulting from electricity generation by solar PV are substantially higher than those from agave-derived ethanol, with offsets 26, 68, and 100 times higher than high-, baseline-, and low-yield scenarios of agave (Table 1).

To compare the land use efficiency for different biofuel feedstocks, we compared the life-cycle energy and net GHC emissions from agave-derived ethanol to ethanol derived from sugarcane, corn grain, and switchgrass even when we consider the low-yield scenario (Figure 5). The GHG offsets from the solar PV system [464 Mg of CO2 equiv ha−1 year−1 (375–562)] are much larger than those from agave, with GHG offsets of 18 Mg of CO2 equiv ha−1 year−1 (14–22) for high yield, 6.8 Mg of CO2 equiv ha−1 year−1 (5.3–8.2) for baseline yield, and 4.6 Mg of CO2 equiv ha−1 year−1 (3.7–5.5) for low yield. GHG offsets (mean) resulting from electricity generation by solar PV are substantially higher than those from agave-derived ethanol, with offsets 26, 68, and 100 times higher than high-, baseline-, and low-yield scenarios of agave (Table 1).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td>10,000</td>
<td>-1,000</td>
<td>1,000</td>
<td>2,000</td>
<td>5,000</td>
<td>10,000</td>
<td>-1,000</td>
<td>1,000</td>
<td>2,000</td>
</tr>
<tr>
<td>2015</td>
<td>15,000</td>
<td>-2,500</td>
<td>2,500</td>
<td>5,000</td>
<td>7,500</td>
<td>15,000</td>
<td>-2,500</td>
<td>2,500</td>
<td>5,000</td>
</tr>
<tr>
<td>2016</td>
<td>20,000</td>
<td>-4,000</td>
<td>4,000</td>
<td>7,000</td>
<td>10,000</td>
<td>20,000</td>
<td>-4,000</td>
<td>4,000</td>
<td>7,000</td>
</tr>
</tbody>
</table>

Table 1. Summary of Annual Life-Cycle Energy, GHG, Water, and Revenues from Agave and Solar PV

The S–95% quantile values are in parentheses. Calculated by subtracting the cost of installation/cultivation from the revenue.
In our analysis, the synergy between PV and agave stems from the fact that water addition for washing panels is beneficial for both the solar PV electricity output and agave yield. For example, we show that dust deposition can be a major factor affecting the economics of large solar infrastructures (annual loss of 15%) and, with proper dust control measures (routine cleaning operations), the losses can be reduced to under 1%. Other potential synergistic factors of integrated solar—agave systems include enhanced soil moisture availability to agave as a result of the concentration of rainfall (or water used for washing panels) by solar panels into the interspaces, reduced soil erosion by wind and water, and decreased dust emissions from disturbed soils as a result of moisture addition and vegetation (agave) cover. Moreover, many Agave spp. are known to benefit from an increase in the CO₂ concentration in the atmosphere and tolerate high temperatures (in the range of 60 °C) and recurrent droughts, which are expected to be more frequent in the future.45

Overall, colocated solar and agricultural infrastructure could (1) ensure efficient water use by sustaining biofuel production and maximizing power output form solar installations in deserts, (2) minimize dust generation, and (3) minimize impacts on natural areas by deploying biofuel cultivation in existing large solar facilities. Our results indicate that solar PV facilities use much less water compared to other energy technologies and traditional crops.43 In our analysis, the annual water requirement for energy production for the solar infrastructure was 0.43 L MJ⁻¹ (0.54—0.36) compared to 11.5 L MJ⁻¹ (13.7—9.5) and 26.7 L MJ⁻¹ (32.9—22.6) for baseline- and high-yield scenarios of agave, respectively. A life-cycle analysis of a hypothetical colocated indicated higher returns per m² of water used than either system alone. Water requirements to produce energy were 0.22 L MJ⁻¹ (0.28–0.19) and 0.42 L MJ⁻¹ (0.52–0.35) for solar PV—agave (baseline yield) and solar PV—agave (high yield), respectively. However, the water requirement for agave is low compared to agricultural and other biofuel crops, and agave can survive and produce significant biomass in nutrient-poor soils and adverse climatic conditions, thanks to their water-efficient CAM photosynthesis pathway.21,22 In particular, the baseline yield scenario for agave requires no additional water inputs other than the water required for operation of the solar infrastructure. In this scenario, even though energy outputs from agave-derived ethanol are much lower compared to the solar PV, they provide a more valuable (and easily transportable) form of energy in liquid fuels. Thus, in some dryland regions, colocated solar PV—agave systems may provide attractive economic incentives in addition to efficient land and water use.

In some existing solar facilities, it might be possible to integrate agave cultivation. Design modifications could be considered in future PV to better integrate agave cultivation. A major consideration is the spacing of PV panels (and number of modules ha⁻¹) in colocated systems, to account for the space requirements for plants and routine agricultural operations. Another consideration is the possible shading of solar modules by plants in colocated systems. In the case of agave, many cultivated species reach only a size of 1.5–2 m in 5–7 years and produce long flowering stalks (2–10 m) only after 6 years. In colocated systems, harvesting is expected to occur after 6 years when the agave plants are not tall enough to shade the panels. The intensive agricultural operations, such as planting, fertilizer application, and use of whole-stick cane harvesters, may have an impact on background dust emissions from these systems. In this study, we used the upper end values of water utilization for cleaning solar installations and dust suppression to account for water requirements for these additional impacts. The feasibility of colocation also depends upon availability of ethanol-refining facilities near the sites selected for colocation. Moreover, considerable uncertainties remain on the agave yield and the benefits of periodic water addition (light irrigation) and shading from the solar infrastructures in deserts. Colocation may not be practical in all locations, and further field studies are required to fully evaluate the advantages and disadvantages of colocation.

In the southwestern United States, solar deployments are increasing rapidly, with growing concerns about the fate of soil and water resources in these areas.46–48 The western United States accounted for half of all U.S. population growth in the past decade, creating additional demand for land and water resources.47,48 Moreover, the southwest has experienced rapid warming and recurrent droughts,45,49 further increasing the pressure on soil and water resources. In these water-limited areas, coupled solar infrastructure and biofuel cultivation could be established in marginal lands with low water use, thus minimizing the socioeconomic and environmental issues resulting from cultivation of biofuel crops in prime agricultural lands.

The United States Department of Energy estimates that around 850 000 ha of direct land transformation would be required to install the 2030 scenario of 302 GW of solar PV.36 Assuming that all of these areas could be integrated with agave ethanol production, around 1–2 billion gallons of fuel ethanol (and additional electricity exports) could be produced. Although this is a small percentage (3–6%) of the United States 2030 ethanol production target of 30 billion gallons,50 we have to consider that this ethanol is produced from marginal lands with no additional land transformation.

**ASSOCIATED CONTENT**

**Supporting Information**

Additional information regarding our approach and analysis (additional data, methods, assumptions, figures, tables, and references). This material is available free of charge via the Internet at http://pubs.acs.org.
The authors acknowledge the TomKat Center for Sustainable Energy at Stanford University. Symbols for Figure 1 are courtesy of the Integration and Application Network (ian.umces.edu/symbols).

REFERENCES

(42) California Department of Water Resources; http://www.dwr. water.ca.gov/

(43) United States Department of Agriculture (USDA), National Agriculture Statistic Service (NASS); http://www.nass.usda.gov/


