Tradeoffs and synergies between biofuel production and large solar infrastructure in deserts

Supporting Information

Sujith Ravi,[a] David B. Lobell[a,b] and Christopher B. Field[ca]*

[a] Department of Environmental Earth System Science, Stanford University, 473 Via Ortega, Stanford, CA 94305, USA. Tel: 00 1703 581 8186; E-mail: sujith@stanford.edu; dlobell@stanford.edu

[b] Center on Food Security and the Environment, Stanford University, Stanford, CA 94305, USA.

[c] Department of Global Ecology, Carnegie Institution for Science, Stanford, CA 94301,USA. E-mail: cfield@ciw.edu

28 Pages

6 Figures

12 Tables

<u>Contents</u>

Land footprint and water use of solar installations

To estimate the land footprint and water use of large solar installations in drylands, we compiled data from project planning reports - from California Energy Commission[1] and Bureau of Land Management[2] - of large solar Photo Voltaic (PV) and Concentrated Solar Power (CSP) Projects in the southwestern United States which are approved for construction or are already under construction.

The solar PV technology involves the use of a semiconductor material (e.g. Silicon) to convert sunlight into electricity. The PV systems can range from small-scale residential systems to large utility scale systems. The CSP system involves the use of mirrors to concentrate sunlight to produce intense heat energy, which is used to produce electricity as in a conventional thermoelectric power plant (using a conventional steam turbine). The CSP systems, mostly installed as utility scale systems, will involve a cooling system where the cooling agent can be air (dry cooled) or water (wet cooled). Parabolic trough, the dominant CSP technology, uses parabolic mirrors to focus sunlight and to heat up the fluid in the receiver pipe located along the focal point of the trough. Power tower technology (Central Tower) uses a field of mirrors to focus sunlight onto a central tower receiver, which has a heat transfer fluid. The intense heat is used to generate electricity using a conventional steam turbine. The major advantage of CSP technologies is that they allow the efficient storage of energy[3].

Our compilation covers both the land area use for the solar infrastructure and the right of way land area (ROW) requested by the solar companies for additional support facilities like transmission lines and roads. The annual water uses for large solar facilities were partitioned into construction and operation phases, assuming a 30-year life for the installations.

The solar installations considered are located (under construction or approved for construction) in the states of California, Arizona and Nevada. For the land area and water use of solar installations, the data included 28 large solar installations in the Southwestern United States ranging from 100 MW to 1000 MW (13 PV, 10 CSP with Parabolic trough, 5 CSP with Tower). The data on the Right of Way 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 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, 3 CSP parabolic troughs with dry cooling and 4 CSP central towers.

Life Cycle Analysis

To explore the logistic and economic feasibility of integrated solar - agave biofuel systems we conduct detailed life cycle analysis for agave-derived biofuel, solar PV and a hypothetical co-located solar-agave system to explore the tradeoffs and synergies (in the context of energy, water, and greenhouse gas emissions) between these two emerging land uses. **Figure S1** represents the conceptual framework of the life cycle analysis and the lifecycle stages considered.

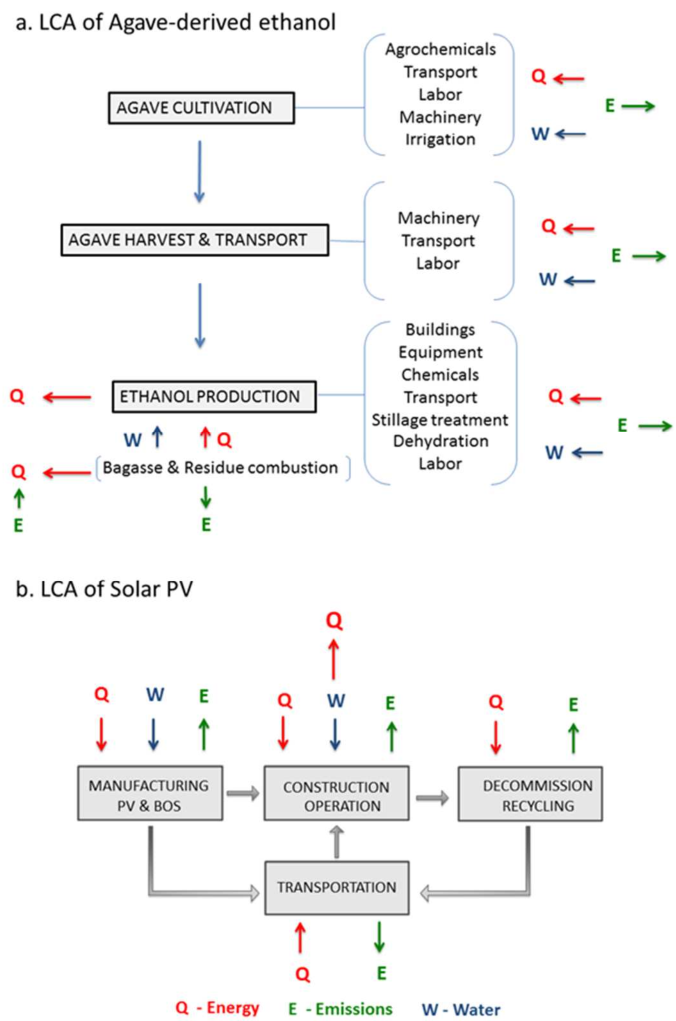

Figure S1. Life cycle analysis (energy, emissions and water) of agave-derived ethanol (a) and solar PV (b).

Life cycle of agave-derived ethanol

We adopted the biofuel production & life cycle analysis methodologies followed by Yan et al., (2011), Macedo et al., (2008) and Farrell et al., (2006) [4,5,6], which are based on the production pathways used in the tequila industry in Mexico and the Brazilian sugarcane industry (**Figure S2)**. We implemented the life cycle model in R (R: a language and environmental for statistical computing and graphics by R Foundation for Statistical Computing, Vienna, Austria, 2013).

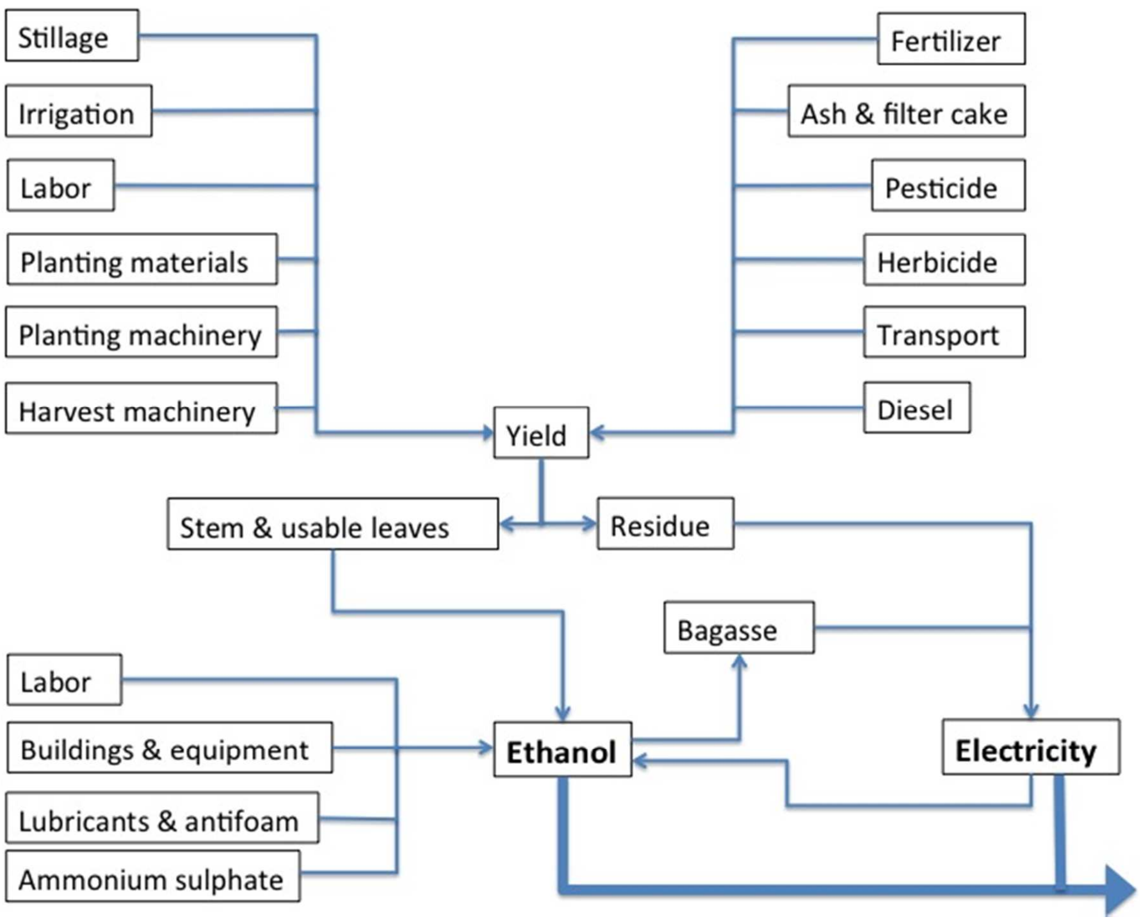

Figure S2. Stages consider in the life cycle analysis of agave-derived ethanol.

The life cycle stages for agave-derived ethanol are agave cultivation, harvest and transport, and ethanol production. The sugar extracted from agave juice is used for ethanol production while the cellulosic residues are combusted in a cogeneration system to provide process energy with excess electricity exported to the electrical grid.

Cultivation stage: We considered the embedded energy and GHG emissions from fertilizers and agrochemicals. We also considered the diesel energy and GHG emissions resulting from transport of agrochemicals and fertilizers (including ash and filter cake). Farm inputs include fertilizers (Nitrogen, Phosphorus and Potassium), agrochemicals (pesticide and herbicide), ash & filter cake (as fertilizers) and planting material. In addition, stillage is applied to baseline and high yield scenarios[5]. Transport energy and GHG emissions involves diesel use (embedded energy and GHG of diesel fuel). Soils in southwestern US are generally not acidic, so lime application is not required. The cultivation stage of agave also includes embedded energy and GHG of machinery and diesel fuel consumption. The energy and emission factors for farm labor energy use and planting material are also considered. In addition, for the high and baseline yield scenarios of agave we included the energy and GHG emissions resulting from irrigation. We used the Kansas State University Irrigation Energy (electricity) Cost Comparison Program[7] (A program to compare the cost of irrigation energy options). Application rate and energy requirements for stillage application (for high and baseline yield scenarios) were adopted from Yan et al (2011).[5] The data used for the cultivation stage are provided in **Table S1**.

Harvest and transport stage: Yield at harvest (fresh and dry yield of stem, usable leaves and residue) was calculated based on the data provided in **Table S2**. In this stage we considered the energy and emissions resulting form diesel use for mechanical harvesting and transport to ethanol processing plant. The data used in the harvest and transport stage are provided in **Table S3**.

Ethanol processing: The sugar extracted from agave juice is used for ethanol production while the cellulosic residues are combusted in a cogeneration system to provide process energy with excess electricity exported to the electrical grid. In this stage we considered cooking, milling, fermentation and distillation.[5] We considered the energy and GHG from chemicals (ammonium sulphate), lubricant and antiform used in the processing stage and diesel use to transport the chemicals. Ammonium sulphate is added as a nutrient in the fermentation process during ethanol production[5]. We consider the embedded energy and GHG emissions from building, equipment and labor used in the processing stage. The GHG emissions from bagasse and residue combustion are also considered. The bagasse generated and unused leaves are combusted to produce electricity. The cogeneration system supplies all the process energy, and the excess electricity is exported to the electrical grid. The data used in the ethanol processing stage are provided in **Table S4**.

Energy

$$\textit{Input energy}_i = \textit{Agave cultivation}_i + \textit{Harvest \& Transport}_i + \textit{Ethanol production}_i$$

$$\textit{Agave cultivation}_I = \sum \textit{(Embedded energy of agrochemicals)} * \textit{(Application Rate)} + \sum \textit{(Transport energy (fuel) for agrochemicals \& soil amendments *application rate)} + \textit{Farm labor energy} + \textit{Farm machinery energy} + \textit{Embedded energy of seed.}$$

$$\textit{Harvest \& Transport}_i = \textit{Harvest energy} + \textit{Transport energy}$$

Ethanol production$_i$ = Embedded energy of ammonium sulphate + Transport energy (fuel) for ammonium sulphate + Embedded energy of Lubricants and antifoam energy + Embedded energy for buildings and equipment + Ethanol processing labor energy.

Output energy$_i$ = Ethanol energy + Electricity export

*Ethanol energy = ethanol produced (liters) * 21.2 (MJ)*

Electricity export = Electricity surplus from ethanol processing + electricity generated from surplus residue and bagasse.

Greenhouse gas emissions (GHG)

GHG emissions$_{ghg}$ = Agave cultivation$_{ghg}$ + Harvest & Transport$_{ghg}$ + Ethanol production$_{ghg}$

Agave Cultivation$_{ghg}$ = $\sum$ (Embedded GHG of agrochemicals) + $\sum$ (GHG from transport of agrochemicals & soil amendments) + GHG from Farm labor energy use + Embedded GHG of Farm machinery + GHG from fuel use of machinery + Embedded GHG of seed.

Harvest & Transport$_{ghg}$ = Harvest$_{ghg}$+ Transport$_{ghg}$

Ethanol production$_{ghg}$ = Embedded GHG of Ammonium sulphate$_{ghg}$+ GHG from transport (fuel) of ammonium sulphate + Embedded GHG of lube and antiform$_{ghg}$+ Embedded GHG of building & equipment$_{ghg}$+ GHG from bagasse & residue combustion$_{ghg}$

Life cycle fossil energy use and GHG emissions for the US generation mix (mean) are 2.91 MJ and 193 gCO_2e per MJ of electricity produced respectively[5]. 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 (94g CO_2 e to produce one MJ of gasoline) in addition to fossil fuel energy saved by exporting electricity by combustion of agave residues.[4,5] 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.[4,5]

$$GHG\ offsets_{electricity\ export} = 0.193\ (Kg)\ *\ electricity\ export\ (MJ)$$

$$GHG\ offsets_{ethanol} = 0.094\ (Kg)\ *\ ethanol\ energy\ (MJ)$$

$$Total\ GHG\ offsets = (GHG\ offsets_{ethanol} + GHG\ offsets_{electricity\ export}) - GHG\ emissions_{ghg}.$$

Table S1: Data used for life cycle analysis (cultivation stage) of agave-derived ethanol over a 6-year cycle (from Yan et al 2011)[5].

Cultivation				
	Agrochemicals	Application rate ($Kgha^{-1}$)	Embedded energy ($MJ\ Kg^{-1}$)	Embedded GHG ($Kg\ CO2eKg^{-1}$)
	N	600	56.9	11
	P_2O_5	91.6	9.3	1.61
	K_2O	289.2	7	0.71
	Herbicide	15	356	25
	Pesticide	1.08	358	29
Machinery Diesel Fuel	550.1 liter ha^{-1}			
Machinery Embedded energy	592.3 $MJha^{-1}Year^{-1}$			
Transport of agrochemicals	200 Km^{-1}			
Ash and filter cake application	5000 Kg ha			
Transport of ash and filter cake	25 Km			
Truck fuel efficiency	0.019 liter $Mg\text{-}Km^{-1}$			
Energy content of diesel	37.8 MJ $liter^{-1}$			
Life cycle energy use of diesel	1.15 $MJMJ^{-1}$			
GHG emissions from diesel	86g $CO2_eMJ^{-1}$			
Embedded energy of seed and FGHG of seed as a share of the total cultivation	2.7%			
Farm labor energy use	0.046 $MJMJ^{-1}$ ethanol			
GHG emission factor from farm labor energy use	54 g CO_{2e} ha^{-1} $year^{-1}$			

Table S2. Data used to estimate agave yield estimation (from Yan et al 2011)[5].

Plant age of 6 years	Portion	Fresh Biomass (Kg)	Dry Biomass (Kg)	Sugar content (%)		Fiber content Dry (%)	Ash content Dry (%)	Water content (%)
				Fresh	Dry			
Stem	Usable	40.3	12.1	24	80	16	4	70
Leaves	Usable	31.23	6.87	6.6	30	61	9	78
	Residue	13.66	6.83	0	0	87	13	50

Table S3: Data used for harvest and transport stage (calculated from data in Table S2).

	Low yield	Baseline yield	High yield
Fresh stem yield (Mgha^{-1})	94	135	319
Fresh usable leaves yield (Mgha^{-1})	73	105	245
Fresh residue yield (Mgha^{-1})	32	46	108
Total harvested fresh biomass (Mgha^{-1})	198	285	674
Diesel fuel use in harvesting (liter Mg^{-1})	1.59	1.59	1.59
Agave transport distance (KM)	25	25	25

Table S4. Data used for ethanol production (from Yan et al 2011)[5].

Item	Value
Theoretical sugar yield from fresh agave	164 Kg Mg-1 agave
Theoretical ethanol yield from sugar	0.51 Kg Kg-1 sugar
Overall sugar utilization efficiency	90%
Ethanol yield	95.3 Liter Mg-1 agave
Bagasse and residue generation (50% moisture)	337.3 Kg Mg^{-1} agave
Bagasse and residue consumed to supply all process energy (50% moisture)	231.0 Kg Mg^{-1} agave
Electricity surplus from hydrated ethanol production	172 MJ Mg^{-1} agave
Electricity use in dehydration	0.05 MJ $liter^{-1}$ ethanol
Electricity use in stillage treatment	0.29 MJ $liter^{-1}$ ethanol
Electricity surplus after all internal consumption of ethanol	139.6 MJ Mg^{-1} agave
Efficiency of electricity generation from bagasse and reside	30%
Energy content of Bagasse and residue	7.53 MJ
Additional electricity generated from surplus bagasse and residue	240.2 MJ Mg^{-1} agave
GHG emissions from bagasse and residue combustion	1.874 g CO_2e Mg^{-1} agave
Ammonium sulphate use	10 g Kg^{-1} sugar
Ammonium sulphate embedded energy	11.92 MJ Kg^{-1}
Ammonium sulphate embedded GHG	2.31 Kg CO_2e Kg^{-1}
Transport distance of ammonium sulphate	200 Km
Lubricants and antifoam energy	0.366 MJ Mg^{-1} agave
Lubricants and antifoam GHG	34.75 gCO_2e Mg^{-1} agave
Embedded energy for buildings and equipment	4.4 MJ MJ^{-1} ethanol
Embedded GHG for building and equipment	444 g CO_2e Mg^{-1} agave
Ethanol processing labor energy use	0.006 MJ MJ^{-1} ethanol

We assumed that bagasse consists of fibrous material and has moisture content of 50% and the energy content of bagasse and residue to be 7.53 $MJKg^{-1}$ (Yan et al 2011)[5]. Assumes that 1 Mg of fresh agave includes 0.565 Mg of stem and 0.436 Mg of usable leaves.

Life cycle analysis of Solar PV

We considered a solar PV installation, as PV is the dominant technology for current and proposed solar installations. Further, there might be other logistic constraints for colocation of biofuels in CSP installations due to intensive infrastructure. As per the Department of Energy (DOE) projects 90% of the future installations will be solar PV. Also there are other issues of colocation with solar thermal power plants due to intensive onsite infrastructure. US Department of Energy (2012) predictions for the sunshot scenario are 303 GW of PV and 28 GW of CSP for 2030 [3].

The data for LCA of solar PV was derived from Ito et al 2007, Raugei et al. 2007, Fthenakis and Kim, 2011[8,9,10]. Solar insolation of 2100 Kwh/m2/year, typical of North American deserts. The installation consists of a basic array of fixed flat plate systems with approximately 3500 multi-crystalline silicon (120 Wp m-Si) PV modules (approximate module area of $1m^2$) with an efficiency of 13% (an output of 420 KWp ha^{-1}) [8]. The performance ratio of this PV infrastructure is assumed to be 70%, which is typical of desert areas[11]. The annual power generation is calculated as follows.

Annual Power Generation = solar insolation X efficiency X module area X performance ratio

Energy and greenhouse gas emission from PV

Adopted the values from Ito et al 2007, Raugei et al. 2007; Fthenakis and Kim, 2011[8,9,10].

The energy inputs for producing one MWp (megawatt-peak) of m-Si module and balance of system components total 31333 GJ[8]. This included PV modules, array support, foundation, cable, transportation, transmission, and other components. The GHG emissions resulting from production of one KWh of m-Si module and balance of system components are 37 and 20 gCO_2e respectively[9,10].

Energy of cleaning panels was assumed to be similar to irrigation energy requirements for agave.

To account for the decline in power output due to dust deposition we adopted the derate model developed by Kimber et al (2006) [12] based on experimental observations from large solar PV installations in the south western United States. We used a derate rate of 0.3%[12] in performance ratio per day for rainless periods (7 months).

Water use for cleaning panels

We complied the existing (but limited) information on water requirements for large solar installations from project planning reports of proposed large solar infrastructures around the world. There is no information available for schedule of washing panels. The water requirements per washing event ranged from 18000 (Israel, personal communication) to 43000 liters (US) MW_p^{-1} or ~9000 to 22000 liters ha^{-1}. We adopted the values from a solar installation in the southwestern United States[1,2].

In this study we used the water requirements for washing as 20000 literha^{-1}, which is equivalent to 2 mm of rainfall per panel cleaning event. We adopted a washing schedule of once every week for dry periods of the year (7 months, 28 washes) and once a month for rest of the year (5 months, 5 washes). Additional water equivalent to 1 mm rainfall was used to for dust suppression by adding moisture to soil (twice a month for 7 months and 6 times for the remaining 5 months). In addition to this, there are water inputs (14 mm per year) along with stillage application. Solar PV infrastructures also use minor amounts of water of maintaining additional facilities, potable water etc. Total water application for cleaning is approximately equivalent to 100 mm (annual) of rainfall.

Energy requirement for water application is assumed to be similar for irrigation in the case of agave cultivation. We assume that the total water use for operation of a PV infrastructure with dust control to be 100 mm rainfall (annual) equivalent.

Agave cultivation & Ethanol processing costs

Table S5: Cultivation cost of Agave (from Nunez et al 2011 and Crago et al 2010) [13,14].

Scenario	Ethanol (l)	Cultivation	Ethanol processing cost	Total cost
Low yield	2353.43	800	541.28	1341.28
Baseline yield	3390.45	1100	779.80	1879.80
High yield	8003.25	1500	1840.74	3340.74

In our analysis we use an agave cultivation and ethanol processing cost of $1250, $1750 and $3250 for low, baseline and high yield scenario.

Installation and operation cost of solar PV

We assumed an installation & operation cost of 4$ W_p^{-1} (range of 3-5 $\$W_p^{-1}$) [15,16,17,18].

Table S6. Installation cost of solar PV used in this study.

Installation cost $\$W_p^{-1}$	Cost ha^{-1}	$\$/ha^{-1}/year^{-1}$	$\$ha^{-1}year^{-1}$
6	2520000	84000	
5	2100000	70000	
4	**1680000**	**56000**	**10885**
3	1260000	42000	
2	840000	28000	

Wholesale price of Electricity & Ethanol

The wholesale electricity price (mean) used in this analysis was 100$ MWh^{-1} (range of 80 to 120) [15,16,17,18] and the life time (30 year) construction and operation costs (mean) were taken as $4 $\$W_p^{-1}$ (3 - 5 $\$W_p^{-1}$). [15,16,17,18] The wholesale ethanol price used in this analysis was 2.75$ $gallon^{-1}$ [19]. The wholesale cost of electricity (mean) for electricity exported from combustion of bagasse and residue is assumed to be $100 MWh^{-1} (range of 80-120 $ MWh^{-1}). [20,21]

Sensitivity and uncertainty analysis

Sensitivity analysis

Sensitivity analysis (one-at-a-time local sensitivity analysis) was performed for solar PV installation and agave-derived ethanol. We defined a base case of all the parameters considered, identified a range of uncertainty for each parameter and then tested the effect of changing each parameter from its minimum to maximum value. We use module efficiency, insolation, performance ratio and number of modules per ha for the solar PV infrastructure and overall sugar utilization efficiency and number of plants per ha for the agave-ethanol system as input parameters. The input parameters and ranges for the sensitivity analysis are provided in **Table S7**.

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 agave - have significant impacts on the total energy output and greenhouse gas offsets. For the solar PV the difference in total energy output for maximum and minimum values of efficiency (11 % and 15%) and number of modules (3000 and 4000) was 741 and 688 $GJha^{-1}year^{-1}$, while the difference for green house gas offsets were 145 and 135 Mg CO_2e $ha^{-1}y^{-1}$ respectively (**Figure S3 and S4**). In the case of agave-derived ethanol (baseline yield scenario) the difference in total energy output for maximum and minimum values of sugar utilization efficiency (70 and 90%) and number of plants per ha (2850 and 3850) were 18 $GJha^{-1}year^{-1}$ and 26 Mg CO_2e $ha^{-1}y^{-1}$, while the difference for net greenhouse gas offsets were 1.6 and 2.3 Mg CO_2e $ha^{-1}y^{-1}$ respectively (**Figure S5 and S6**).

Table S7. Input parameters for sensitivity analysis

	Input parameters	Min	Mean	Max
Solar PV	Efficiency (%)[8]	11	13	15
	Number of modules ha^{-1} [8]	3000	3500	4000
	Performance ratio (%)[11]	65	70	75
	Insolation ha^{-1} [8,11]	2000	2100	2200
Agave derived ethanol				
	Number of plants ha^{-1} [5, 22]	2850	3350	3850
	Sugar utilization efficiency (%)[5,6]	70	80	90

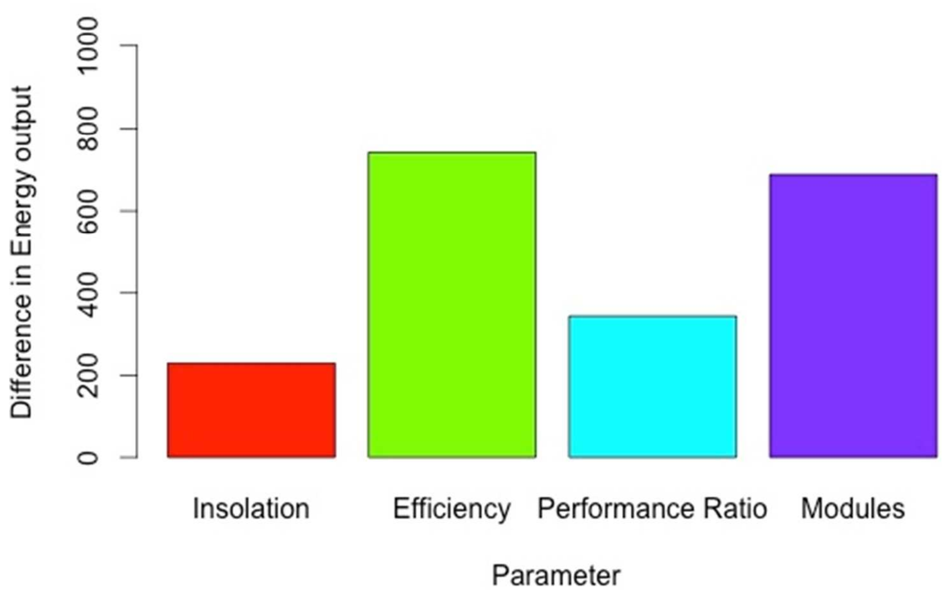

Figure S3. Sensitivity analysis for solar PV: Change in energy output ($GJha^{-1}y^{-1}$).

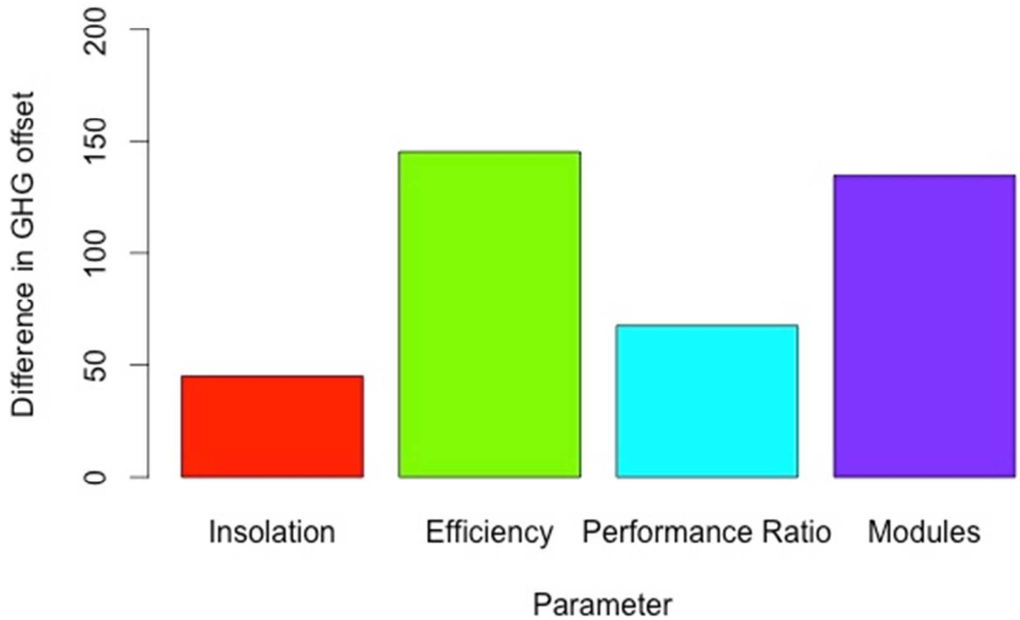

Figure S4. Sensitivity analysis for solar PV: Change in GHG offsets (MgCO2e $ha^{-1}y^{-1}$).

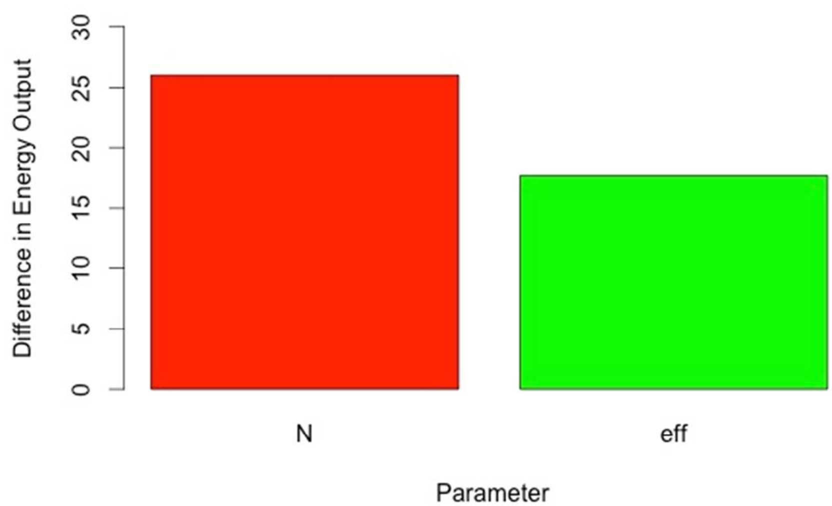

Figure S5. Sensitivity analysis for agave-derived ethanol (baseline yield): Change in total energy output ($GJha^{-1}y^{-1}$). N- number of plants per ha, eff- overall sugar utilization efficiency.

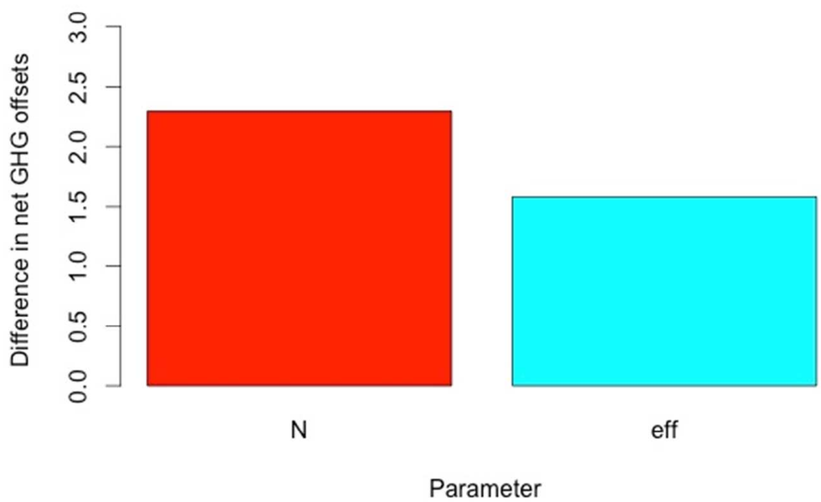

Figure S6. Sensitivity analysis for agave-derived ethanol (baseline yield): Change in net GHG offsets ($MgCO2_e$ $ha^{-1}y^{-1}$). N- number of plants per ha, eff- overall sugar utilization efficiency.

Uncertainty Analysis

We addressed the uncertainty in our analysis by using a Monte Carlo simulation approach. The analysis was performed using the input values of the two most sensitive input parameters as identified by a sensitivity analysis. The input parameters considered for solar installation were efficiency (range of 11 to 15%) and number of modules per ha (2500 to 3500). The input variables considered for agave derived solar were the overall sugar utilization efficiency (70 to 90%) and number of plants per ha (2850 to 3850). The input variables were assumed to be independent and were randomly selected from a uniform distribution and the output simulation was repeated 10^4 times. The maximum, mean, minimum and quantiles of outputs for solar PV (outputs: energy input, energy output, green house gas emissions and net greenhouse gas offsets) and the three yield scenarios of agave (outputs: energy input, total energy output, ethanol energy, electricity export green house gas emissions and net greenhouse gas offsets) were reported. The input parameters and ranges for the Monte Carlo analysis are provided in **Table S8**.

Table S8. Input parameters for Monte Carlo Analysis

	Input parameters	Range
Solar PV	Efficiency[8]	11 to 15%
	Number of modules ha^{-1} [8]	3000 to 4000
	Installation cost[15,16,17,18]	3 – 4 $\$W_p^{-1}$
	Wholesale electricity cost [15,16,17,18]	0.08 – 0.12 $\$Kwh^{-1}$
Agave derived ethanol		
	Number of plants ha^{-1} [5,22]	2850 to 3850
	Sugar utilization efficiency[5,6]	70 to 90 %
	Cultivation cost* [13,14]	1000-3500$\$ha^{-1}$
	Wholesale price of ethanol[8]	2.5 to 3 $\$gal^{-1}$
	Wholesale electricity cost[20,21]	0.08 – 0.12 $\$Kwh^{-1}$

*In this study we used a cultivation cost range 1000-1500 (low yield), 1500-2000 (baseline yield), 3000-3500 (high yield) $\$ha^{-1}$.

The detailed results of the Monte Carlo Analysis are provided in **Tables S9-S12**.

Table S9. Monte Carlo analysis for solar PV

Quantile	Energy output GJ ha^{-1} $year^{-1}$	Energy input GJ ha^{-1} $year^{-1}$	GHG emission Mg CO_2 e ha^{-1} $year^{-1}$	GHG offsets Mg CO_2 e ha^{-1} $year^{-1}$	Revenue $	Returns $
0%	1750	387	27	338	40403	-26126
2.50%	1889	390	29	365	47308	-12998
5%	1940	394	30	374	49796	-9859
25%	2195	418	34	424	58510	1938
50%	2394	450	37	462	66394	10607
75%	2611	480	40	504	74569	19607
95%	2909	506	44	561	86584	32739
97.50%	2985	509	46	576	90347	36728
100%	3170	513	48	612	104192	51716

Table S10. **Monte Carlo analysis for agave** (high yield scenario)

Quantile	Energy input GJ ha^{-1} year^{-1}	Energy output GJ ha^{-1} year^{-1}	Ethanol energy GJ ha^{-1} year^{-1}	Electricity export GJ ha^{-1} year^{-1}	GHG emission Mg CO_2 e ha^{-1} year^{-1}	GHG offsets Mg CO_2 e ha^{-1} year^{-1}	Revenue $	Returns $
0%	38	158	127	31	4.2	14	4776	1417
2.50%	39	167	135	31	4.2	15	5409	2129
5%	39	171	138	31	4.2	15	5593	2309
25%	41	190	156	33	4.4	17	6241	2989
75%	45	222	183	39	4.9	20	7405	4156
95%	47	243	203	41	5.1	22	8204	4965
97.50%	47	248	207	41	5.1	22	8434	5213
100%	48	260	219	42	5.2	23	9373	6273

Table S11. Monte Carlo analysis for agave (baseline yield scenario)

Quantile	Energy input GJ ha^{-1} year^{-1}	Energy output GJ ha^{-1} year^{-1}	Ethanol energy GJ ha^{-1} year^{-1}	Electricity export GJ ha^{-1} year^{-1}	GHG emission Mg CO_2 e ha^{-1} year^{-1}	GHG offsets Mg CO_2 e ha^{-1} year^{-1}	Revenue $	Returns $
0%	23.8	67	54	12.9	2.56	5.02	2011	115
2.50%	24.2	71	57	13.1	2.59	5.38	2287	479
5%	24.4	73	59	13.3	2.61	5.53	2365	553
25%	25.4	80	66	14.1	2.73	6.24	2647	885
75%	27.9	94	78	16.5	3.03	7.41	3121	1395
95%	28.9	103	86	17.4	3.15	8.21	3466	1769
97.50%	29.1	105	88	17.5	3.17	8.41	3573	1875
100%	29.6	110	93	17.7	3.21	8.85	3943	2426

Table S12. **Monte Carlo analysis for agave** (low yield scenario)

Quantile	Energy input GJ ha^{-1} $year^{-1}$	Energy output GJ ha^{-1} $year^{-1}$	Ethanol energy GJ ha^{-1} $year^{-1}$	Electricity export GJ ha^{-1} $year^{-1}$	GHG emission Mg CO_2 e ha^{-1} $year^{-1}$	GHG offsets Mg CO_2 e ha^{-1} $year^{-1}$	Revenue $	Returns $
0%	16.1	47	37	9.0	1.86	3.42	1400	29
2.50%	16.4	49	40	9.1	1.88	3.64	1590	244
5%	16.5	50	41	9.2	1.89	3.75	1642	316
25%	17.3	56	46	9.8	2.00	4.20	1834	559
75%	19.4	65	54	11.4	2.27	4.98	2167	942
95%	20.2	71	60	12.1	2.37	5.52	2408	1214
97.50%	20.4	73	61	12.1	2.39	5.66	2480	1299
100%	20.8	76	64	12.3	2.42	5.97	2726	1662

References

(1) 1. California Energy Commission Webpage; http://www.energy.ca.gov/.

(2) Bureau of Land Management Webpage; http://www.blm.gov/.

(3) U.S. Department of Energy, *SunShot Vision Study*, DOE/GO-102012-3037, 2012; http://www1.eere.energy.gov/solar/pdfs/47927.pdf.

(4) Farrell, A. E.; Plevin, R. J.; Turner, B. T.; Jones, A. D.; O'Hare, M.; and Kammen, D. M. Ethanol can contribute to energy and environmental goals. *Science* **2006**, *311*, 506–508.

(5) Yan, X.; Tan, D. K. Y.; Inderwildi, O. R.; Smith, J. A. C.; King, D. A. Life cycle energy and greenhouse gas analysis for agave-derived bioethanol. *Energy Environ. Sci.* **2011**, *4*, 3110–3121.

(6) Macedo, C.; Seabra, J. E. A.; Silva, J. A. E. R. Green house gases emissions in the production and use of the ethanol from sugarcane in Brazil: The 2005/2006 averages and a prediction for 2020. *Biomass Bioenerg*. **2008**, *32*, 582–595.

(7) Kansas State University Irrigation Energy (electricity) Cost Comparison Program. Web page. The program can be downloaded at this site: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CEIQFjAA&url=http%3A%2F%2Fwww.agmanager.info%2Fcrops%2Fbudgets%2Fproduction%2FKSU%2520Irrigation%2520Energy%2520Cost.xls&ei=qp_9UK_OCKbNiwLawIDYAg&usg=AFQjCNGE9Dg5bhNMaKHycwrYLFiOVcRvew&bvm=bv.41248874,d.cGE

(8) Ito, M.; Kato, K.; Komoto, K.; Kichimi, T.; Kurokawa, K. A comparative study on cost and life-cycle analysis for 100 MW very large-scale (VLS-PV) systems in deserts using m-Si, a-Si, CdTe, and CIS modules. *Prog. Photovoltaics*. **2008**, *16*, 17–30.

(9) Raugei, M.; Bargigli, S.; Ulgiati, S. Life cycle assessment and energy pay-back time of advanced photovoltaic modules: CdTe and CIS compared to poly-Si. *Energy* **2007**, *32*, 1310–1318.

(10) Fthenakis, V. M.; Kim, H. C. Photovoltaics: Life-cycle analyses. *Sol. Energy*. **2011**, *85*, 1609–1628.

(11) Kawajiri, K.; Oozeki, T.; Genchi, Y. Effect of temperature on PV potential in the world. *Environ. Sci. Technol*. **2011,** *45,* 9030–9035.

(12) Kimber, A.; Mitchell, L.; Nogradi, S.; Wenger, H. Conference Record of the 2006 IEEE 4th World Conference on Photovoltaic Energy Conversion. 2, 2391-2395, 2006., http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4060159.

(13) Nunez, H.; L. F. Rodriguez, and M. Khanna, Agave for tequila and biofuels: an economic assessment and potential opportunities. *GCB Bioenergy*. **2011***, 3*, 43-57.

(14) Crago, C. L.; Khanna, M.; Barton, J.; Giuliani, E.; Amaral, W. Cost competitiveness of sugarcane ethanol in Brazil relative to corn ethanol in the US. *Energy Policy* **2010**, *38*, 7404-7415.

(15) Solar Cell Central, Solar electricity costs, Webpage http://solarcellcentral.com/cost_page.html.

(16) *Open energy Information* Website; http://en.openei.org,last

(17) Goodrich, A.; James, T.; Woodhouse, M. *Residential, commercial, and utility scale Photovoltaic (PV) systems in the United Statees: Current drivers and cost reduction opportunities*, pp.64, NREL report No.TP-6A20-53347, National Renewable Energy Laboratory, Golden, Colorado, **2012**.

(18) Barbose, G.; Darghouth, T.; Wiser, S. R. Weaver, Tracking the sun VI, An historical summary of the installed price of Photovoltaics in the United Stated form 1998 to 2012, Lawrence Berkeley National Laboratory, **2013**.

(19) United States department of Agriculture, Livestock and grain market news, National Weekly Ethanol Summary, **2012**, http://www.ams.usda.gov/mnreports/lswethanol.pdf.

(20) Biomass for power generation and CHP, IEA Energy Technology Essentials, OECD/IEA **2007**.

(21) Renewable energy technologies: Cost analysis series, Biomass for power generation, volume 1:Power sector issue1/5, International Renewable Energy Agency Working paper, **2012**.

(22) Davis, S. C.; Dohleman, F. G.; Long, S. P. The global potential for Agave as a biofuel feedstock. *GCB Bioenergy*, **2011**, *3*, 68–78.