Alternatives to Utility-Scale Solar on agricultural lands: Adoption potential and impacts of utility-scale and agrivoltaic solar on permanent and marginal cropland

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Abstract

The expansion of the adoption of solar energy is a promising development that will meet energy needs while reducing greenhouse gas emissions through renewable energy production. We provide a comprehensive economic analysis of the potential of U.S. agriculture to meet solar development targets using utility-scale PV and agrivoltaic solar systems, and the impact such adoption will have on crop production and farmer profitability. We show that even to meet the high 1.6TWac capacity generation using only cropland, only a fraction of ag land is needed under utility solar. We show that utility solar has the smallest footprint in terms of developed land compared to other solar system setups so developers adopt in each balancing authority can site utility solar where site and transmission LCOE is lowest. When considering marginal land only for solat siting, the location of solar development is more spread out and further away from transmission lines, raising costs. Additionally, some balancing authorities may not have enough marginal agricultural land to provide solar development sites. However, targets can be reached by developing only marginal agricultural land within each or neighboring balancing authority. In considering agrivoltaics, we find that Ag/PV splits are cheaper than traditional agrivoltaics as they do not have a higher CAPEX and maintain farmland around solar developments. However, Solar/Farm split developments may be spread out and not near the cheapest locations. Traditional agrivoltaics lead to higher costs for developers and the lowest net addition to farmers. Utility and AV Optimistic do not need much land, so developers adopt in each eGRID where site LCOE is lowest.

Designing Payments to Induce Low Carbon Sustainable Aviation Fuel Production in U.S. Croplands

1.1 Introduction

Solar energy deployment in the United States continues to be the largest share of all new electricity-generating capacity additions since 2019 (48% in 2022), with over 10.2 GWac added in 2022 (Davis et al., 2023). The contribution of solar electricity to US power generation to the national energy capacity is projected to increase from 3.4% in 2022 (Bolinger et al., 2023) to 45% by 2050, generating 1.6 TWac (*Solar Futures Study*, 2021).

The expansion of the adoption of solar energy is a promising development that will meet energy needs while reducing greenhouse gas emissions through renewable energy production (Creutzig et al., 2017; Millstein, Wiser, Bolinger, & Barbose, 2017; Victoria et al., 2021). Utility-scale photovoltaic solar systems (Utility PV) are the dominant solar setup in the US, accounting for 71.3% of all solar deployment (Bolinger et al., 2023). Utility PV systems are ground-mounted plants connected to the electric grid larger than 5MWac (Bolinger & Bolinger, 2022; Bolinger et al., 2023). Land best suited for Utility PV are those with high insolation, relatively flat ground, connections to the electric grid, proximity to developed areas, access to roads, light winds, moderate temperatures, and low humidity (Adeh, Good, Calaf, & Higgins, 2019; Goldberg, 2023; Walston et al., 2021). Additionally, ideal sites are free of preexisting infrastructure, hazards, and biodiversity, reducing the cost and barriers to developing Utility PV (Goldberg, 2023; Hernandez, Hoffacker, & Field, 2015). As farmland requires many of the same land features for crop production, ideal land for solar development, especially in the Eastern Interconnection electric grid, may overlap with high-yielding cropland in the rainfed region of the US (Adeh et al., 2019). This overlap in land suitability has given rise to fears that such an expansion of solar development will utilize large amounts of cropland (Sorensen et al., 2022), significantly affecting aggregate crop production and farmer profits.

Solar adoption is highly appealing for individual farmers as solar lease payments are generally several times higher than profits from growing almost any crop (Grout & Ifft, 2018; Mwebaze et al., 2024; Wiser, Bolinger, & Seel, 2020). From the solar developers' perspective, lease payments account for less than 5% of all costs[1], allowing lease payment offers to be adjusted to be higher than crop returns (Hirth & Steckel, 2016; Mwebaze et al., 2024; Wiser et al., 2020). Farmers avoid agricultural-related yield risk by forgoing crop cultivation (Bookwalter, 2019; Grout & Ifft, 2018) and receive guaranteed lease payments for the solar system's life, typically between 20-30 years (Wiser et al., 2020). Additionally, if solar is adopted on farmland, it spares land with more biodiversity, such as land with wildlife or conservation value, for solar development (Hernandez et al., 2015). However, significant community opposition is to adopting utility-scale solar on farmland (Lopez et al., 2023; Susskind et al., 2022). Farmers who adopt solar on their lands would be giving up their current way of life (Goldberg, 2023; Sorensen et al., 2022). Large-scale adoption of solar would also remove large swaths of high-yielding farmland from crop production (Grout & Ifft, 2018), threaten food security (Goldberg, 2023; Sorensen et al., 2022), and increase competition for arable land (Grout & Ifft, 2018; Marshall-Chalmers, 2023). One solution to preserve high-quality agricultural land is to site solar energy development on land that may not be highly profitable to farmers (Calvert & Mabee, 2015; Crawford, Bessette, & Mills, 2022; Katkar, Sward, Worsley, & Zhang, 2021; Marshall-Chalmers, 2023; Moore, Graff, Ouellet, Leslie, & Olweean, 2022). Developers could consider leasing out only cropland with low profitability for food crop production (economically marginal cropland)(Jiang, Guan, Khanna, Chen, & Peng, 2021;

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[1] Estimated expenses (Mwebaze et al., 2024) for a 25.9 MW Utility PV in Champaign, IL for 25 years with a time discounting of 6.5% with $29.7 x 10^6 for capital, $3.8x10^5 per year for operating, $1.56x10^5 per year for electricity transmission, 2.9x10^4 per year for vegetation management, and $8x10^4 per year for lease payments. In this case, capital and operation costs account for more than 85% of expenses, and lease payments account for less than 5%.

Yang, Cai, & Khanna, 2021). In such a case, farmers may reduce the profit lost through foregone crop production. However, marginal land availability in some regions may be low (Jiang et al., 2021) or may be located further from transmission lines, resulting in higher costs to solar developers.

Solar developers may also consider alternative solar system setups that allow for co-locating agricultural and solar sites (agrovoltaic systems) and maintaining a portion of row crop production while generating energy. Under agrovoltaic setups, farmers can continue growing row crops on a portion of their land while receiving consistent revenue through lease payments from solar developers. Agrivoltaic systems may, however, be more costly to solar developers due to increased capital and installation costs due to increased height and inter-panel spacing to accommodate commercial farm equipment (Ramasamy et al., 2022; Schindele et al., 2020). Increased inter-panel spacing for agrivoltaic systems reduces their generation potential per unit of land. It increases electricity generating costs relative to utility PV (Macknick et al., 2015). However, even under agrivoltaic system setups, not all land may be used for crop production, as some land must be dedicated to solar panel mounts and buffer areas around panels, reducing the total cropped acreage of a field (Du et al., 2024). Further, shading from panels adjacent to (and in some cases, over) crops will reduce the amount of sunlight available to crops through shading, generally reducing row crop yield (Du et al., 2024; Laub, Pataczek, Feuerbacher, Zikeli, & Högy, 2022). Further, agrivoltaic systems may not be compatible with growing taller crops such as corn, which typically average between 8 and 9 feet (Berti et al., 2021; Williams, Dodds, Buehring, Dhillon, & Henry, 2021; Xie et al., 2021; Yin, McClure, Jaja, Tyler, & Hayes, 2011). As continuous corn and corn-soybean rotations make up large portions of US cropland (Jiang et al., 2021), these croplands would be incompatible with agrivoltaic systems. Agrivoltaic systems with higher panel height to accommodate taller crops will have higher capital costs (Macknick et al., 2015). Alternatively, developers may also consider splitting solar project lands so utility-scale solar panels are adopted on only a portion of a field and row crops are grown on the rest (Ag/PV split) (Mwebaze et al., 2024). An Ag/PV split setup will ensure solar developers can achieve utility-scale panel density without increased cost due to increasing panel height and costly equipment. Farmers benefit from an Ag/PV split by not losing yield due to panel shading and will receive lease payments for the solar portion of their land. However, such setups will require more total land (developed and farmland combined) to achieve the same power generation level as a utility-scale solar system. As each alternative solar system setup differs in costs, panel density, power generating potential, land requirements, and the spatial pattern of solar adoption to reach energy targets under each alternative solar system setup, along with its effect on crop production and farmer profitability, are unknown.

We aim to assess the economic adoption potential of solar development and its impact on US agriculture. First, we determine solar developer costs and spatial adoption potential in meeting solar energy targets by adopting utility-scale PV on US farmland. We consider how adoption differs when development is allowed on all cropland or restricted to only marginal cropland and whether solar adoption on marginal cropland alone is enough to meet solar energy targets. We then determine the effect of Utility-scale PV adoption on aggregate crop production and farmer profitability, accounting for forgone profit from row crop production and additional lease payments from solar development. Next, we consider whether alternative configurations of solar systems, such as agrivoltaic setups and Ag/PV split setups, differ in land requirements, spatial adoption patterns, and effect on farmer profitability in meeting the same solar energy targets. For agrivoltaic setups, we account for crop yield changes on cropped land from shading, reduction of available cropped land within a farm/solar development due to co-locating agriculture with solar development, and restrict land availability to those croplands that meet the requirements of each agrivoltaic setup.

A growing body of literature examines US solar potential to meet energy targets (Brown & Botterud, 2021; Denholm et al., 2022; Hartmann et al., 2016; Heath et al., 2022; Larson et al., 2021; Lopez et al., 2023; Shum, 2017; Sorensen et al., 2022). Much of this literature estimates the potential of Utility PV solar adoption on particular types of land, for example, on contaminated lands (Hartmann et al., 2016; Heath et al., 2022), lands with no land-use ordinances (Lopez et al., 2023), and cropland, pastureland, grassland, and others (Sorensen et al., 2022). We contribute to this literature by providing a comprehensive economic analysis of the potential of US agriculture to meet solar development targets using only farmland. Our aim in considering only farmland is to show the extent of cropland that could be converted to solar to meet power generation needs. Our analysis considers various constraints on cropland use (all cropland, marginal cropland only) and solar system setups (utility-scale PV and various AV setups). Further, our analysis accounts for spatial heterogeneity in solar energy generation potential and solar deployment costs across solar system setups. Further, in considering the economic impact solar adoption on farmland will have on crop production and farmer profitability, we account for spatial differences in crop production costs and prices, crop and rotation choices, and effects of each solar system on cropped acreage and yield reduction due to shading.

1.2 Methods and Materials

We undertake this analysis by using a stylized integrated numerical simulation framework that links a crop economic model with a biogeochemical model (DayCent), a spatio-temporal solar economic model (Renewable Energy Potential (reV)), and satellite land usage data (USDA-NASS Cropland Data Layer (CDL)).

In order to identify ideal cropland suitable for solar system siting, we use 30 meter pixel level satellite land usage data (USDA-NASS Cropland Data Layer (CDL)) to determine land usage in terms of crop production. Pixel level analysis of satellite data on land use from 2008 to 2015 by Jiang et al. (Jiang et al., 2021) is used to determine land classification in terms of pixels that are permanently cropland or in an out of cropland use (Jiang et al. classify marginal land pixels as marginal land with confidence and uncertainty, signifying how confident they are that the pixel is marginal cropland). Agricultural land included are corn and soybean cropland that are either permanent cropland (land identified as permanent cropland and growing either corn or soybean in 2021) and idle marginal lands (land determined to be either certain or uncertain marginal land and idle in 2021) and meets the criteria for Utility-scale PV adoption use (with land slope being under 10 degrees and has access to electricity gridlines). We leave out permanent cropland identified as crops other than corn and soybean due to lack of large scale adoption and uncertainty of returns and suitability with agrivoltaics. We show In Figure 1 the spatial distribution of permanent cropland (Figure 1(a), 769 Million Hectars (Mil Ha)), Marginal land with confidence (Figure 1(b), 36 Mil Ha), Marginal land with uncertainty (Figure 1(c), 247 Mil Ha), and all cropland suitable for solar development (Figure 1(d), 1051 Mil Ha).

We simulate county-level yields conventional crops (corn and soybean) using the biogeochemical model DayCent under two permutations of rotation types (corn-corn and corn-soybean) at intervals of 4 kilometers. We consider corn-soybean and continuous corn rotations in counties where satellite data show soybean cultivation and consider only continuous corn in counties where satellite data shows no soybean cultivation. Conventional crops are planted and harvested annually over the life of the solar system. Conventional crop costs for each rotation option are calculated at the county level using quantities and prices provided by state extension service budgets. Input quantities for conventional crops based on rotation choice are compiled from state-level extension documents, with input costs and crop prices obtained from the National Agricultural Statistics Service (NASS) and literature. Conventional crop costs are constructed for each rotation and tillage option at the state level using crop budget quantities and prices provided by state extension services. These include chemicals, seeds, harvesting, storage, drying, and inputs. As under agrivoltaic systems, shading may affect yield, we model the effect of solar shading using the Ecosys crop model across the rainfed US at intervals of 25 km. We follow a methodology similar to Majeed et al., (2023) to determine row crop rotation by determining which rotation is more profitable at a county level. Parameters for inflation and farmer time discounting are assumed to be exogenous, and their ranges are obtained from the literature.

We calculate Levelized Costs of Energy generation (LCOEs), Levelized Costs of Transmission (LCOTs), generation capacity, and the breakeven energy prices needed at the 25 kilometer level for each solar system setup (Utility-scale PV, Reference AV, Optimistic AV, and Ag-PV split) while accounting for spatial heterogeneity in solar energy generation potential and costs using the Renewable Energy Potential (reV) model which conducts a techno-economic NREL System Advisor Model (SAM) and solar data from the National Solar Radiation Database (NSRDB). We limit energy generation to be based on electricity demands within each Balancing Authority Area level following Heath et al. 2022, using geographical data from the NREL ReEDs. We use the demand input into the model on a regional basis for each balancing authority. We also determine, following Heath et al (2021) the expected adoption of solar up to 2050. We consider electricity production two-year interval given by the SFS. In our mode, once the demand capacity is reached for a particular BA for a given year and the limit is only increased if demand increases in subsequent years. We estimate the potential magnitude and spatial pattern of solar adoption and the energy prices needed to meet government solar energy targets while accounting for energy transmission constraints. We compute changes in crop production due to changes in yield while accounting for spatial heterogeneity in crop yields in cropped land and loss of crop-able land. Farmer profitability is calculated while considering the foregone crop profit and land rent received, spatial heterogeneity in crop costs and prices, and spatial choices of crop choices and rotations. Our analysis is conducted for twenty-five years for each solar system set up to represent the solar system lifetime for exogenous degrees of time preferences and inflation rates.

1.3 Simulation Results

Our results show that the energy price required for Utility-scale PV and Ag-PV systems is the lowest at $ 63 per Megawatt hour ($ MWh-1), whereas agrivoltaic systems cost 95 $ MWh-1 for Reference AV and $ 130 MWh-1 for Optimistic AV, implying that agrivoltaic systems may not be adopted at a large scale by solar developers who would prefer PV systems. Additionally, Utility-scale PV systems provide higher overall power generating capacity relative to alternative solar system setups due to the dense usage of solar panels. For example, Utility-scale PV can meet 2050 solar targets by using only 1.6 million hectares (Mil. Ha.) of land (less than 0.5% of total cropland area). In contrast, Reference AV systems would require 4.1 Mil. Ha. to achieve similar targets. Further, when considering yield losses due to shading, Reference AV systems would require more cropland to become unusable (2.1 Mil. Ha.) than Utility-scale PV. Reference AV will also have the largest value of farm profits foregone, at $3,250 Mil., followed by PV reference at $2,000 Mil., Ag-PV split at $1,900 Mil. and Optimistic AV with $1,600 Mil. However, farmers will also receive between $3,400 and $4,500 Mil. in land lease payments from solar developers, resulting in farmer net returns for Reference AV being the lowest, at $1,400 Mil. Ha. Farmers would, therefore, receive positive net returns under any solar system setup and would be best off leasing their land to a Utility-scale PV. Generally, solar development is spatially located near gridlines because transmission costs are lowest near gridlines. However, when considering only marginal land for solar development, the adoption of solar systems is spread further away from transmission lines, resulting in higher costs. When excluding lands cultivating corn for Reference AV agrivoltaic systems, the location of solar development changes drastically as such crops are mostly in the southern regions. In this case, some areas may not be able to meet solar targets through agrivoltaic systems, whereas others will see higher adoption costs.

1.4 Discussion and Conclusion

We provide a comprehensive economic analysis of the potential of U.S. agriculture to meet solar development targets using utility-scale PV and agrivoltaic solar systems, and the impact such adoption will have on crop production and farmer profitability. We show that even to meet the high 1.6TWac capacity generation using only cropland, only a fraction of ag land is needed under utility solar. This is corroborated by previous literature (Korfiati et al., 2016; Lopez, Roberts, Heimiller, Blair, & Porro, 2012)(Lopez et al., 2012), which shows that the potential of the US is many terawatts higher than current and future solar requirements. We show that utility solar has the smallest footprint in terms of developed land compared to other solar system setups so developers adopt in each balancing authority can site utility solar where site and transmission LCOE is lowest.

When considering marginal land only, the location of solar development is more spread out and further away from transmission lines, raising costs. Additionally, some balancing authorities may not have enough marginal agricultural land to provide solar development sites. However, targets can be reached by developing only marginal agricultural land within each or neighboring balancing authority. However, such adoption leads to more spread-out adoption and marginally higher costs.

In considering agrivoltaics, the Ag/PV split is cheaper than traditional agrivoltaics as it does not have a higher CAPEX and maintains farmland around solar developments. However, Solar/Farm split developments may be spread out and not near the cheapest locations. Traditional agrivoltaics lead to higher costs for developers and the lowest net addition to farmers. Utility and AV Optimistic do not need much land, so developers adopt in each eGRID where site LCOE is lowest.

When considering soybean-only lands, the location of solar development changes drastically as soybean-only (and soybean wheat, etc.) crops are mostly in the southern regions. In this case, many balancing authorities may not achieve their targets.

Overall, our work shows that farmers and solar developers would have higher Further, we show that Utility PV will have a lower impact on aggregate cropland usage and overall crop production than agrivoltaic systems. Returns under traditional Utility-scale PV solar systems when compared to agrivoltaic systems. We also show that solar development on marginal agricultural land is a viable option for solar developers, which may have a more negligible impact than siting utility solar on permanent cropland. However, not every balancing authority may have enough marginal cropland available.

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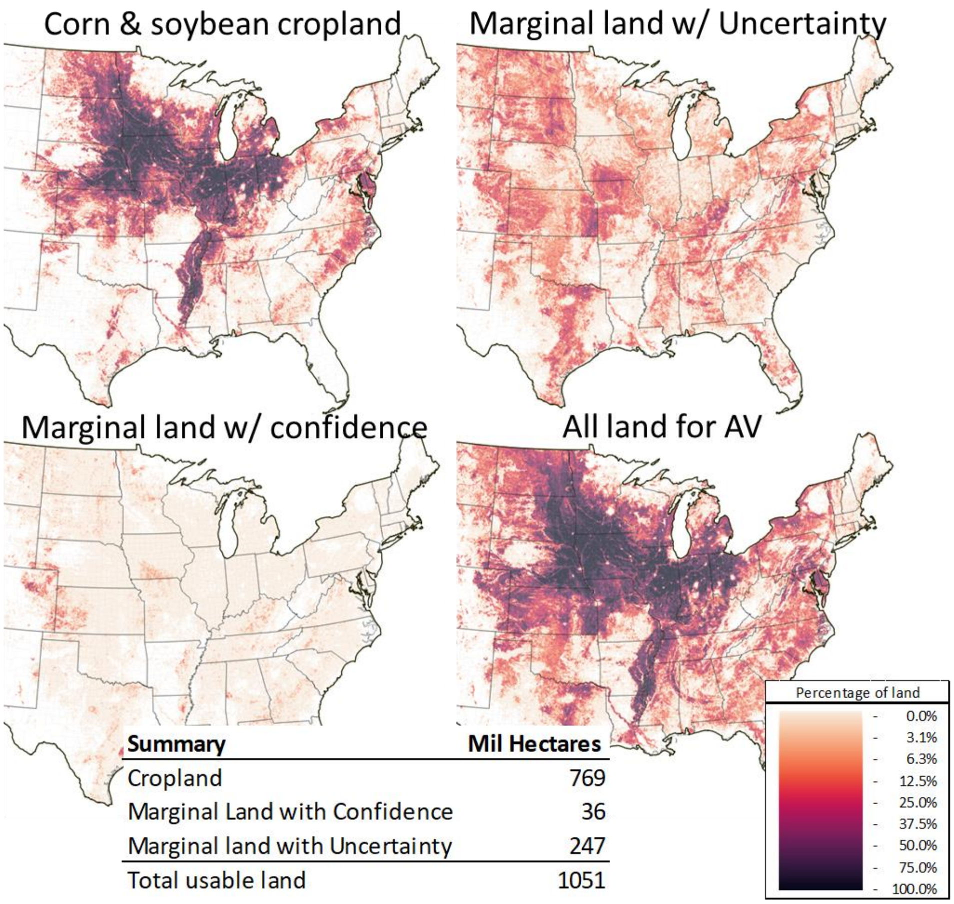
Figures

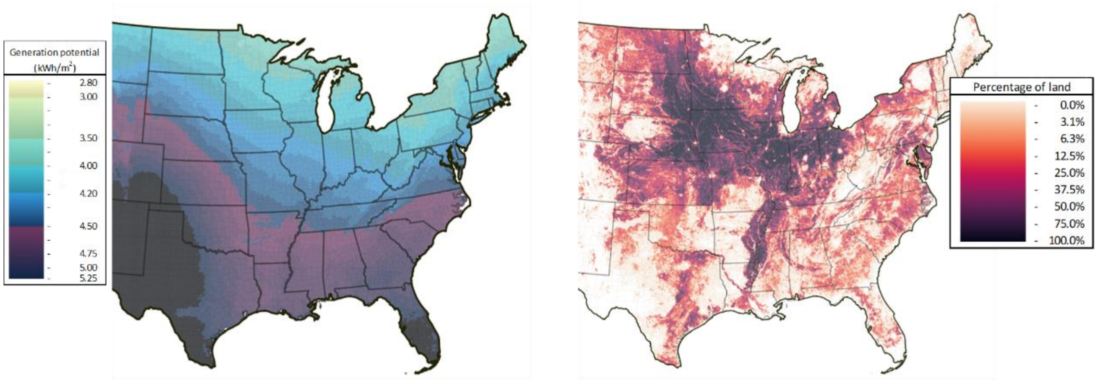
Fig. 1 Agricultural land availability suitable for solar development



Summary	Mil Hectares
Cropland	769
Marginal Land with Confidence	36
Marginal land with Uncertainty	247
Total usable land	1051

Source: computed by authors based on CDL and Jiang et al data. Agricultural land included are corn and soybean cropland that are either permanent cropland (“Corn & soybean cropland) and idle marginal lands (land determined to be either certain or uncertain marginal land) that are suitable for solar siting (with a slope under 10 degrees). Graph shows the percentage of total land that is agriculture land suitable for solar siting.

Fig. 2 Solar generation potential across the rainfed US

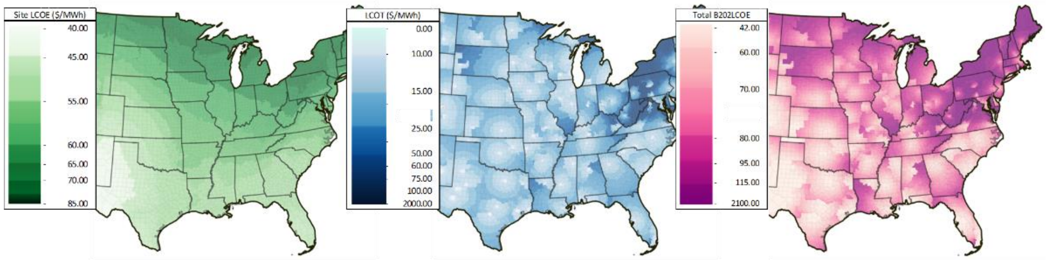


Solar generation potential (kWh/m2)

Cropland and marginal land availability (%/Acre)

Source: computed by authors based on NREL data. Right graph is from Figure 1 showing the percentage of total land that is agriculture land suitable for solar siting

Fig. 3 Spatial distribution of Site-LCOE, LOCT, and Total LCOE for utility solar



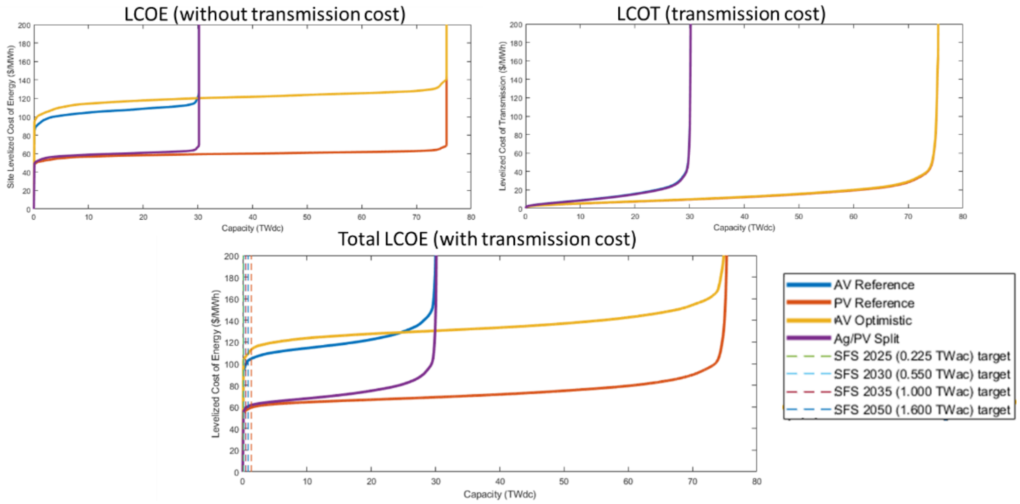
Site LCOE ($/MWh)

LCOT (Transmission) ($/MWh)

Total LCOE ($/MWh)

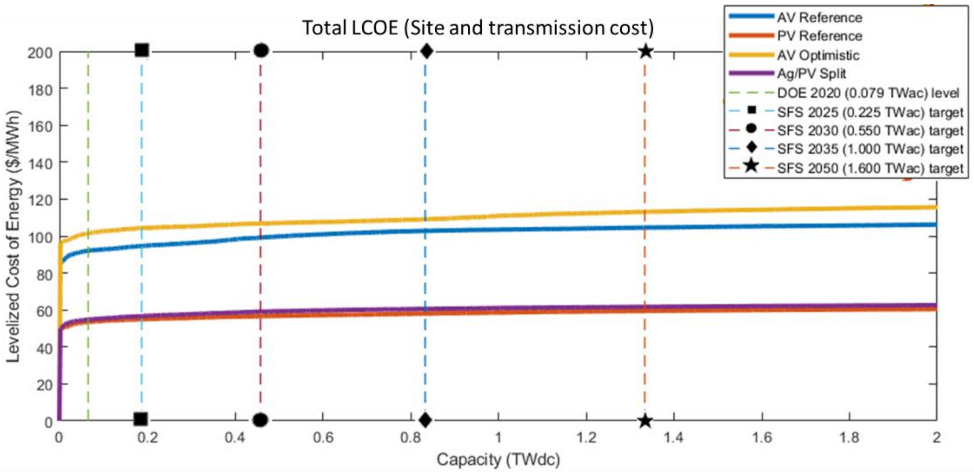
We show the breakdown of levelized cost of energy for utility solar. In the left (green), we show that the LCOE cost is highest in the northeast due to lower solar generation potential. The the center we show that the LCOT cost (blue graph) is lowest nearest to transmission to lines and significantly higher further from transmission lines. On the right, we show that mixture of the LCOE and LCOT (magenta graph).

Fig. 4 Supply curves of solar electricity based on Site-LCOE, LOCT, and Total LCOE without regional constraints



We show a breakdown of the supply curves based on LCOE. We show that the distribution of LCOE and LCOT differs by solar system setup. Overall, AV setups cost more for generation and transmission, have lower cumulative capacity, and cost more per M.W than utility solar (PV Reference). Additionally we note that in order to meet Solar Futures Study targets, a fraction of overall agriculture land is required.

Fig. 5 Supply curves of solar electricity overlayed with SFS targets without regional constraints



Solar Futures Study targets for 2025, 2030, 2035, and 2050 can potentially be met at the lowest cost by PV and the highest cost by AV Optimistic

Fig. 6 Percentage and acreage of agricultural land required to meet solar futures target

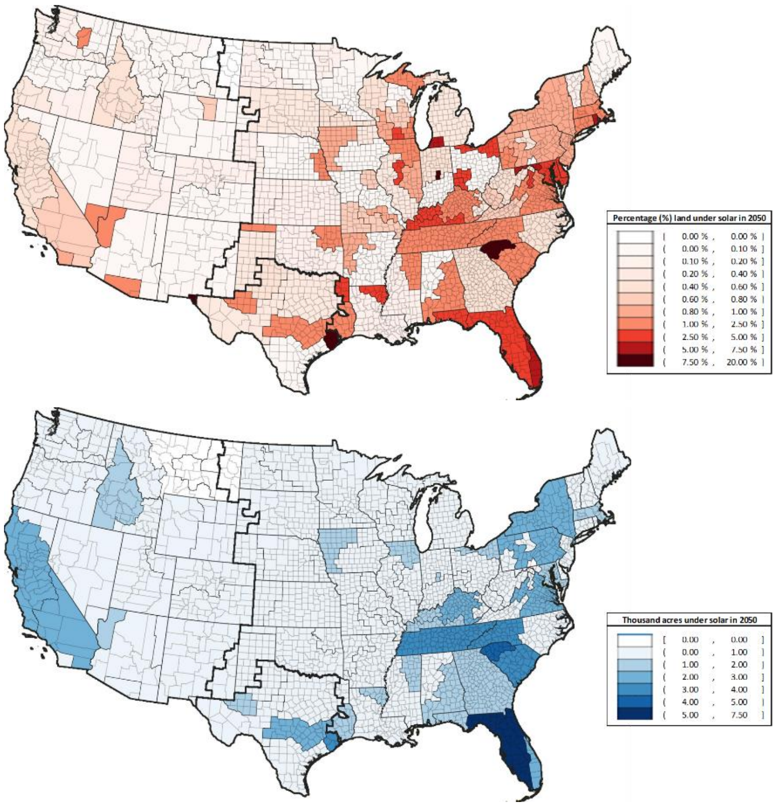


Fig. 7 Land usage and cropland converted under P.V. and A.V. adoption.

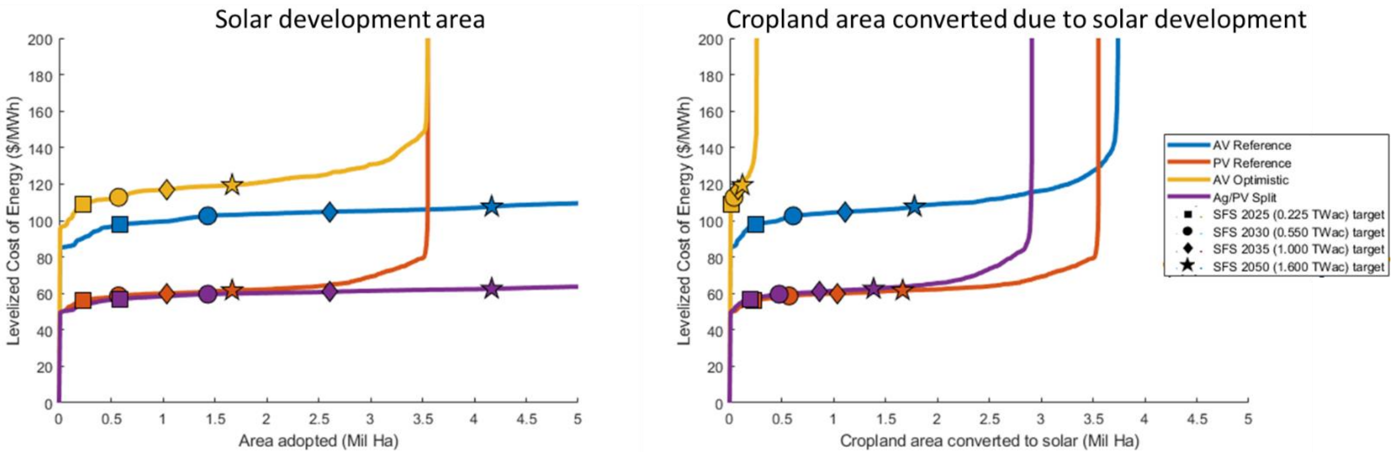


Fig. 8 Cropland returns forgone by conversion of land to solar

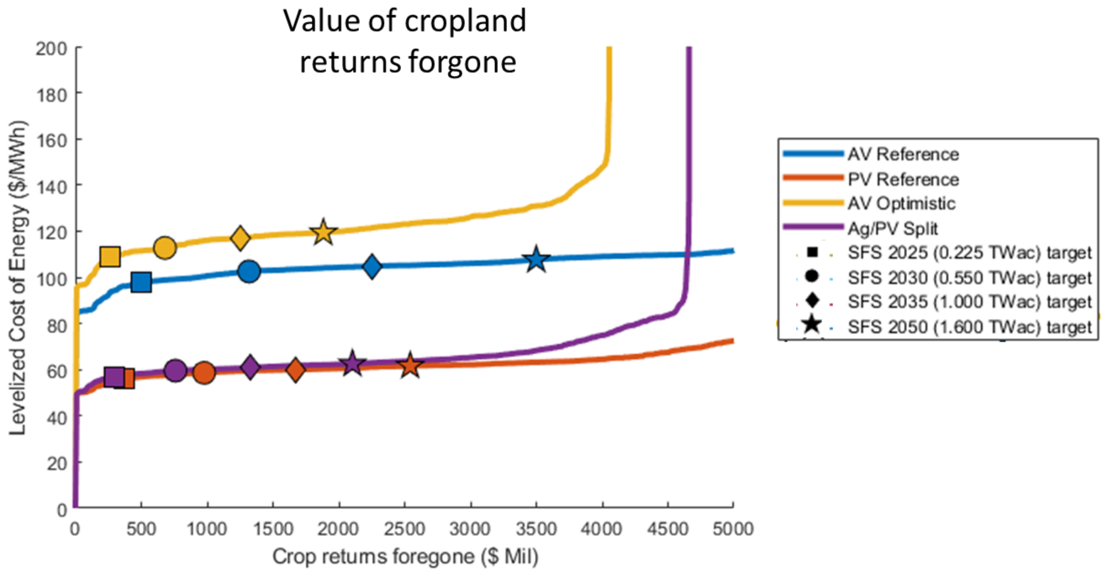


Fig. 9 Farmer returns under P.V. and A.V. adoption to reach each solar target.

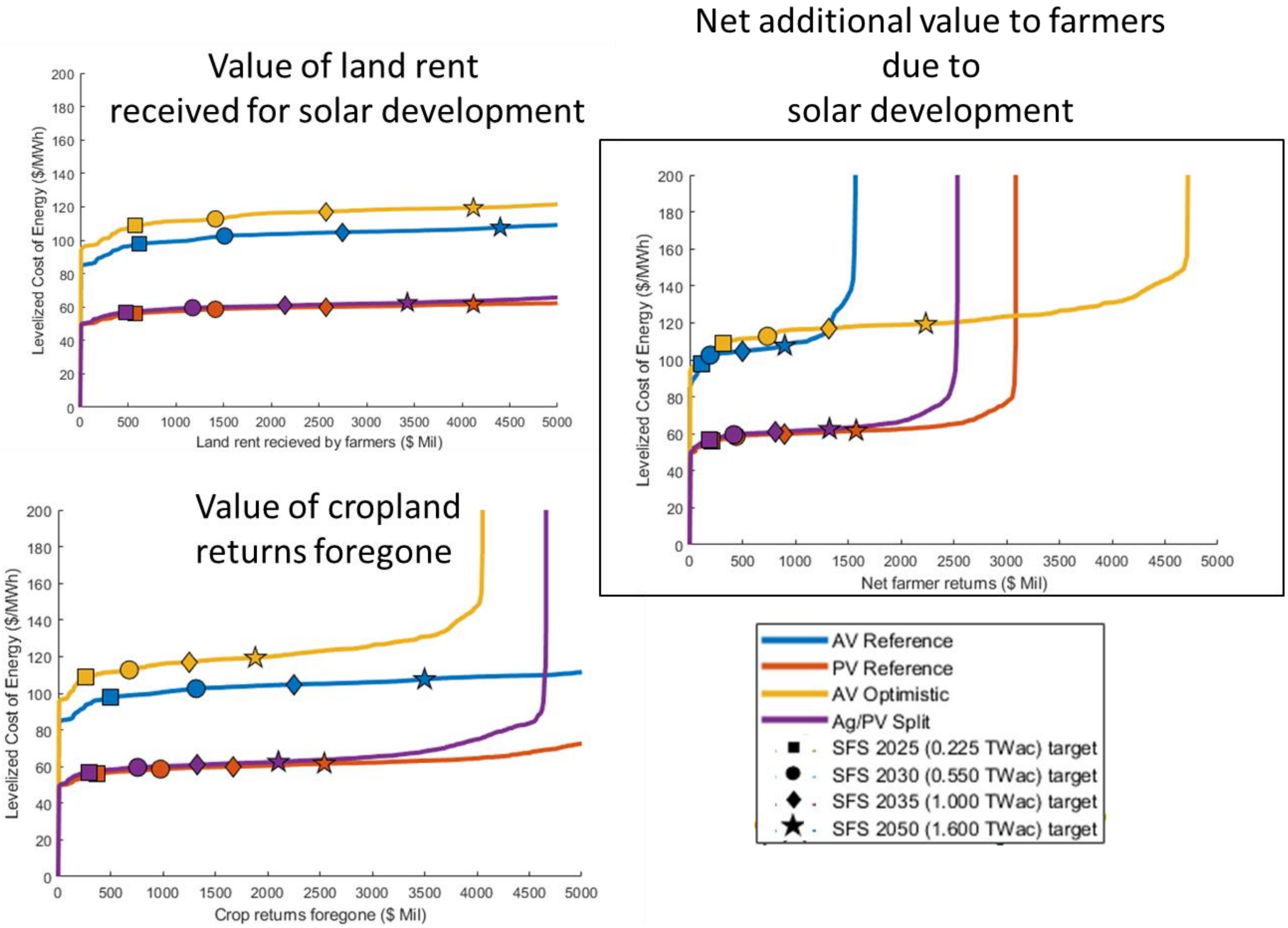


Fig. 10 Lowest cost areas used to meet solar targets using utility solar on all cropland and marginal cropland only.

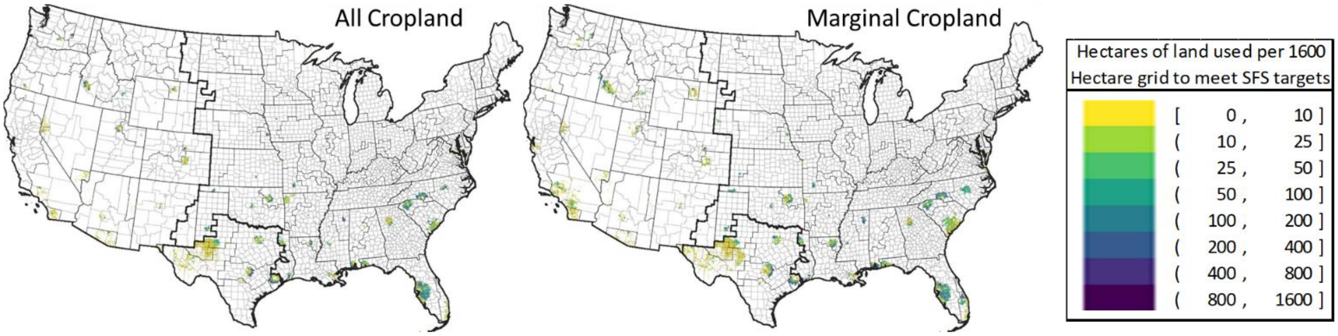


Fig. 11. Solar system configuration used to meet 2050 SFS targets on all cropland.

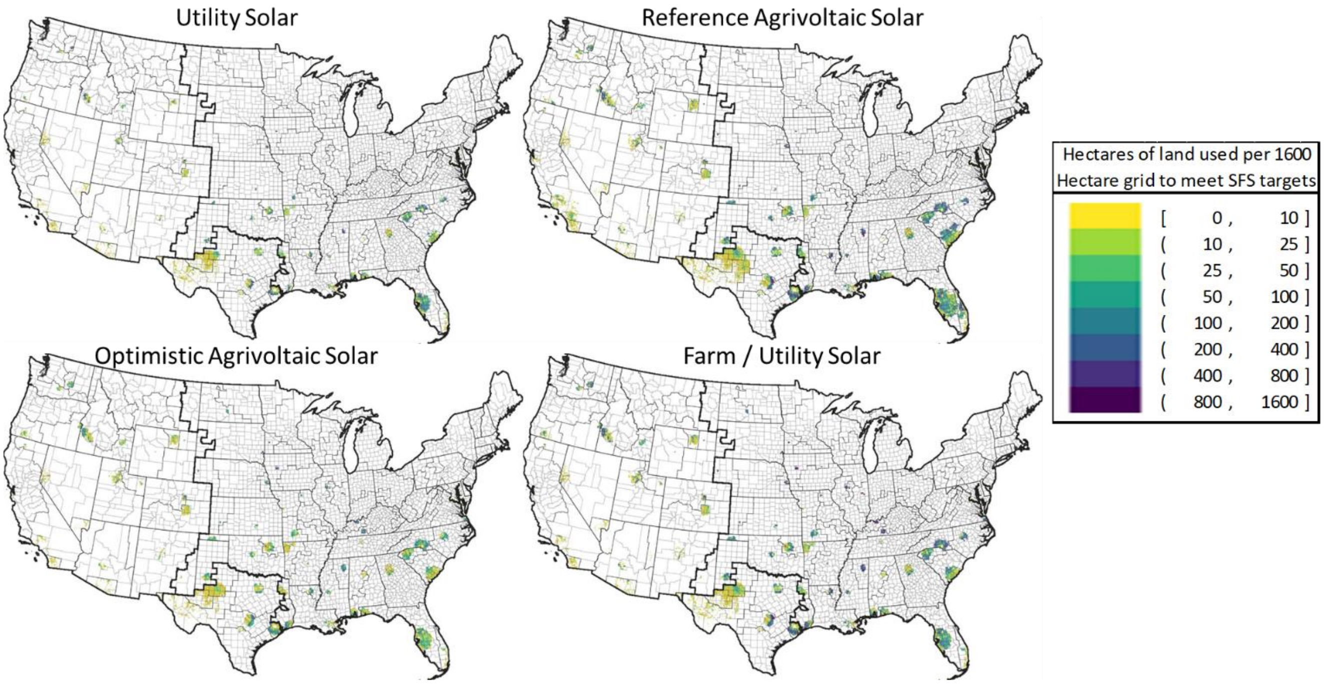


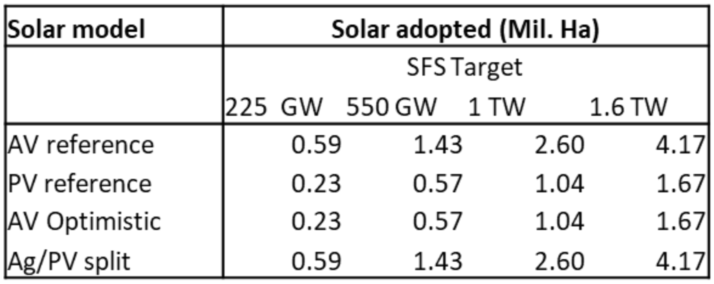
Table 1. Solar system setup

Scenario	Solar system reference	Panel spacing (ft.)	Height (ft.)	Cropped area (acres)	PV capacity (MW)	CAPEX ($/W)	Lease Payment ($/field/year)
1	Utility PV	18	4	0	25.90	1.15	80,000
2	Reference AV	43.5	8	45.82	10.36	2.66	
3	Dense AV	23.5	8	28.91	19.61	2.66	
4	Optimistic AV	18	12	74.5	25.90	3.06	
5	Ag/PV split	18	4	53.37	10.36	1.15	

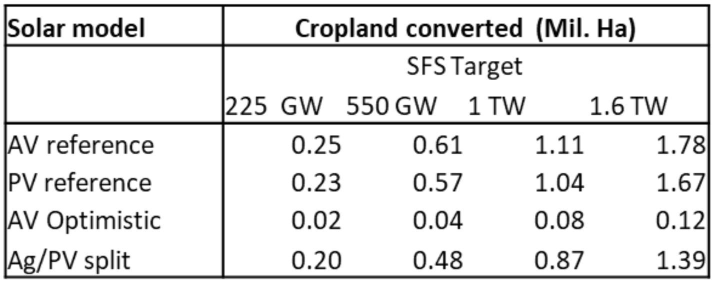
Scenario description:

1. Utility PV = Utility-scale PV. 2. Reference AV. 3. Dense AV = Reference AV with a higher density of panels on the field through less spacing between panels. 4. Optimistic AV = Utility-scale power generating with farming under panels, crops on almost all available land, night farming/stowing panels, and automated equipment. 5. Ag/PV Split =Field split between crops and utility PV, with the same power generating potential as Reference AV.

Table. 2 Land used to reach SFS targets under each solar configuration (paired with Fig 5)



Solar model	Solar adopted (Mil. Ha)			
	SFS Target			
	225 GW	550 GW	1 TW	1.6 TW
AV reference	0.59	1.43	2.60	4.17
PV reference	0.23	0.57	1.04	1.67
AV Optimistic	0.23	0.57	1.04	1.67
Ag/PV split	0.59	1.43	2.60	4.17

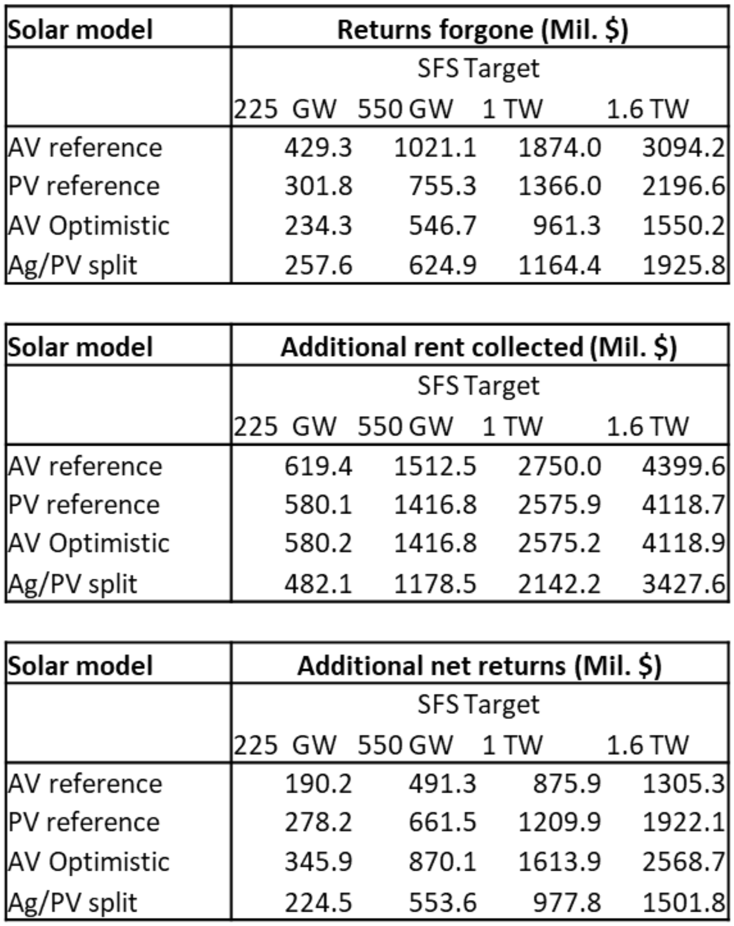


Solar model	Cropland converted (Mil. Ha)			
	SFS Target			
	225 GW	550 GW	1 TW	1.6 TW
AV reference	0.25	0.61	1.11	1.78
PV reference	0.23	0.57	1.04	1.67
AV Optimistic	0.02	0.04	0.08	0.12
Ag/PV split	0.20	0.48	0.87	1.39

Table. 3 Foregone returns to reach SFS targets under each solar configuration (paired with Fig 6)

Solar model	**Returns forgone (Mil. $)**			
	SFS Target			
	225 GW	550 GW	1 TW	1.6 TW
AV reference	429.3	1021.1	1874.0	3094.2
PV reference	301.8	755.3	1366.0	2196.6
AV Optimistic	234.3	546.7	961.3	1550.2
Ag/PV split	257.6	624.9	1164.4	1925.8

Table. 4 Farmer returns breakdown (foregone returns, additional rent, and net returns) under P.V. and A.V. adoption (paired with Fig 7)



Solar model	Returns forgone (Mil. $)			
	SFS Target			
	225 GW	550 GW	1 TW	1.6 TW
AV reference	429.3	1021.1	1874.0	3094.2
PV reference	301.8	755.3	1366.0	2196.6
AV Optimistic	234.3	546.7	961.3	1550.2
Ag/PV split	257.6	624.9	1164.4	1925.8

Solar model	Additional rent collected (Mil. $)			
	SFS Target			
	225 GW	550 GW	1 TW	1.6 TW
AV reference	619.4	1512.5	2750.0	4399.6
PV reference	580.1	1416.8	2575.9	4118.7
AV Optimistic	580.2	1416.8	2575.2	4118.9
Ag/PV split	482.1	1178.5	2142.2	3427.6

Solar model	Additional net returns (Mil. $)			
	SFS Target			
	225 GW	550 GW	1 TW	1.6 TW
AV reference	190.2	491.3	875.9	1305.3
PV reference	278.2	661.5	1209.9	1922.1
AV Optimistic	345.9	870.1	1613.9	2568.7
Ag/PV split	224.5	553.6	977.8	1501.8