Farming the Sun and the Crops at Once:
A Cost Benefit-Analysis of Implementing an Agrivoltaic System in China

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ABSTRACT

An Agrivoltaic system advocates growing crops underneath solar panels to ensure agricultural productions and solar energy generations at once. This system can potentially solve land use conflicts and promote sustainable farming in China. Multiple field studies have been conducted to understand performances of the Agrivoltaic system across the globe. Yet, literatures have neither discussed how the system performances would vary due to geographic heterogeneities on a larger scale nor understood how farmers would respond to these variations in terms of making adoption decisions. In this study, I investigate whether Chinese farmers are willing to adopt the Agrivoltaic system in their farmlands given their residential regions and corresponding regional solar policies. I found that six provinces (Shandong Province, Shanxi Province, Liaoning Province, Jilin Province, Inner Mongolia region, and Tibet region) have natural advantages for the system. Through cost-benefit analysis, I also found that 99% of the counties in China would economically benefit from adopting the system given current sets of solar subsidies while 93% of the counties would profit even if the subsidy drops 20% in the next 25 years. The northeast three provinces, the Jilin province in particular, have the highest economic potential for the Agrivoltaic system. Meanwhile, this study also indicates the implementation of the system can help address climate change by increasing renewable energy shares in the electricity market.

KEYWORDS

On-farm solar, photovoltaic, sustainable farming, geographic heterogeneities, decision making

INTRODUCTION

Greenhouse gas (GHG) emission from human activities are one of most significant drivers of climate change, and have been since the 1950s (Intergovernmental Panel on Climate Change, 2013). Carbon dioxide(CO_2) emissions, from traditional fossil fuel usage and industrial operations, contributes to 65% of global GHG emissions (Intergovernmental Panel on Climate Change, 2014). China, the largest emitter of CO_2, is facing challenges from climate change, such as air pollution, water pollution, extreme weather events, and changing patterns of infectious diseases (Kan, Chen, & Tong, 2012). These ecological changes, especially air pollution, have led to severe consequences in human morbidity and mortality rates (Zhang et al., 2010). Meanwhile, climate change also threatens Chinese economic development by reducing agricultural productivity and yields (Ju, van der Velde, Lin, Xiong, & Li, 2013). Climate change is predicted to have profound negative impacts on the quality of life for future generations (Manandhar, Pandey, Kazama, & Kazama, 2014). Through emissions, fossil fuel usage is catalyzing dangerous climate scenarios and causing irreversible damages to ecosystems and society in China and around the world. Therefore, it is important and policy-relevant for China to increase its share of clean energy and reduce GHG emissions.

Solar energy is one promising way to increase the renewable energy share in China, but its wide-scale adoptions can lead to land-use conflicts. Solar power is a clean and green energy source because it utilizes solar radiation to generate energy without creating emissions (Bazilian et al., 2013). To fulfill its emissions reduction pledges and targets from the Paris Agreement, China has been developing its solar energy industry and expanding its solar products manufacturing rapidly since 2004. After that, the global financial crises in 2008 and a series of anti-dumping plus countervailing duties by the western market in 2012 further stimulated the Chinese domestic market (Zou et al., 2017). The Chinese government established incentives to vitalize domestic markets and to implement large-scale photovoltaic (PV) on domestic lands ("13th FYP development plan for renewable energy," 2016). Large-scale deployment of PV, especially ground-mounted PV, creates great demands for land and thus competes with the agricultural sector for lands (Chen, Wu, Gao, & Ma, 2018). A land-conflict problem is unavoidable in China if the country wants to both expand solar deployments and ensure food security for its large population.

To resolve this potential land conflict, scientists have proposed the Agrivoltaic system, which enable the dual-use of land between solar plants and farming (Dupraz et al., 2011). Under the Agrivoltaic system, farmers implement photovoltaic panels on their farm lands to generate electricity while growing agricultural products underneath the solar panels at the same time. The Agrivoltaic system has been proven to be land efficient or economically feasible in several in-field case studies at a regional scale. In an Agrivoltaic system testing experiment, Dupraz et al. show that the overall land productivity can be 60-70% higher than normal durum wheat farm in Montpellier, France (Dupraz et al., 2011). Ravi et al. also indicate that while collocating solar and aloe under the system, plantation areas of high-value crops and land efficiency are increased in Rajasthan, India (Ravi et al., 2016). In terms of economic feasibility, Dinesh et al. show that an Agrivoltaic lettuce farm in Kansas City, United States can create over 30% increase in economic value (Dinesh & Pearce, 2016). Meanwhile, Malu et al. further confirm that the economic value of grape farms with the system increase about 15% compared to conventional farms in Nashik district, India (Malu, Sharma, & Pearce, 2017). Sekiyama and Nagashima prove that corn productions under the Agrivoltaic system would be no less than 96.9% that of corn plants grown without the system in Japan. Under optimal scenario, production can exceed traditional farming by 4.9% if PV arrays are spaced enough (Sekiyama & Nagashima, 2019). In terms of discussing the potential of the Agrivoltaic system in China, Chen et al. show positive economic outcomes while studying the system in the Xinjiang province with a focus on grapes (Chen et al., 2018). Two other articles discuss the overall potential of integrating photovoltaic in agricultural lands in China, but they focus on the context of greenhouses agriculture and rooftop photovoltaic (Li, Wang, Miao, & Ye, 2017; Xue, 2017). At this current stage, we lack knowledge of the potential and the economic feasibility of implementing the Agrivoltaic system across China, including how geographic heterogeneities due to the environment, electricity markets, and regional policy might influence farmers' incentives to adopt on-farm solar.

In this study, I address the feasibility of the Agrivoltaic system in China through the lens of farmers' decisions. Will Chinese farmers choose to adopt this system in their farmlands given their residential regions and the current set of solar policies? This study addresses three sub-questions. First, in which regions would farmers have a natural advantage to adopt the system given environmental variations across geography? Second, through cost-benefit analyses, what are the economic outcomes of the Agrivoltaic implementations at the county-level given different solar policies and electricity markets across space? 3. Finally, would the widespread adoptions of the Agrivoltaic system help address GHG emission effectively? Overall, this study provides insights into the potential of on-farm solar panels in the Chinese context. I hypothesize that farmers from the northwest region may have higher incentives to adopt due to the natural advantage of solar resources (Huang, Wang, Yang, & Li, 2018). I also anticipate farmers who live in regions with the strongest regional governmental support such as greater subsidies will have greater incentives to adopt. To answer these questions, I use solar system data, agricultural data, land type data, climate data, and some information on Chinese solar policy in this research study.

BACKGROUND

China solar energy framework

As one of the largest GHGs and CO_2 emitter in the world, China ratified the Paris Agreement with unconditional climate pledges along with several domestic solar policies. China's pledges aim to reduce CO_2 emissions per unit of Gross Domestic Product by 60% - 65% from the 2005 level by 2030. In the pledge, China emphasized a plan to increase the share of non-fossil energy in its energy mix to around 20% by 2030 (Watson et al., 2019).

To cope with its emission target, China has established ambitious renewable energy development targets as part of its strategies. The 12th Five Year Plan for 2011 – 2015 set targets on adding 160 GW installed capacity of renewable energy technologies. Solar energy was the third-largest contributor to reach this goal ("12th FYP development plan for renewable energy," 2012). Right after that, the central government set targets on raising renewable energy share to 15% of the total energy mix in its 13th Five-Year plan for 2016-2020. This latest five year plan focuses on solar power industry upgrading, application expanding, and cost reducing ("13th FYP development plan for renewable energy," 2016). Most recently, the country published its national renewable portfolio standard to further strengthen the Chinese goal towards 20% non-fossil fuel consumption by 2030. The portfolio sets minimum levels for renewable energy consumption for each province and encourages companies to adopt renewable energy sources voluntarily (Sharma, 2019). This new portfolio and the solar energy framework in China for the past decade indicate a growing trend of solar energy at both the national and regional levels.

China solar industry development

China is a major PV manufacturer in the world, which can be attributed to domestic renewable energy policies and international solar market dynamics in recent years. Alongside with its renewable energy framework, China has established a series of supports to promote its solar industry. In 2009, the central government launched the Building Integrated Photovoltaics (BIPV) subsidy program to support PV construction materials, components, rooftop projects, and wall projects (Jian, 2009). Then the government launched the Golden Sun Demonstration Project to subsidize raw material production and accessory production (Jian, 2009). These two projects were a turning point for large-scale production of PV in China. Most recently, the Technology Top Runner Program was released in 2015. This program offers Chinese PV industry players economic incentives to invest in higher-efficiency solar production technologies (Wen, Li, Gu, & Gao, 2017). Government supports and incentives accelerate the solar industry towards a larger scale.

In addition to domestic dynamics, foreign policies play important roles in incentivizing domestic deployments of PV. In 2012, severe anti-dumping and countervailing duties were charged by the United States and the European Union, which hindered the export portions of China's PV industry. To rebalance the supply and demand of PV, the Chinese government and enterprises reconfigured the solar market. Upgrading the domestic market in terms of increasing local demands and implementing large-scale PV power plants on domestic lands became a necessarily long-term task. As part of the large-scale PV applications, ground-mount or stilts-mount PV are the two major forms of deployments (Chen, Wu, Gao, & Ma, 2018). In this case, implementing larger scale of ground-mount PV or stilts-mount PV is a potential trend to balance solar productions and demands in China.

Chinese food security and land conflict problems

While large-scale deployments of the PV system yield high demands on land, a competition between the growing solar industry and the critical food sector is unavoidable. With a population of 1.39 billion people and only 7% of the arable land in the world, China faces enormous challenges in feeding its people. Because of that, food security always receives the highest attention of the central government in China (Fu, 2019). The Chinese government has continued efforts to buy or to lease agricultural lands in developing countries to grow foods. However, this is not a sustainable solution because other developing countries have growing demands on food and lands as well. The Chinese government focuses on agriculture reform which includes controlling the market, improving farming technology, importing, and curbing land loss (Niu, O'Brien, Chen, Nhamire, & Larson, 2017). Securing food supply highly relies on securing agricultural lands. It is clear that major usage of national lands needs to be reserved for the agricultural sector and the developments of ground-mount PV and stilts-mount need to be integrated into the land system without threating food productions.

The agrivoltaic system

The Agrivoltaic system which also refers to the Agrophotovoltaic system is a dual-use of lands for photovoltaic and agricultural productions (see Figure 1).

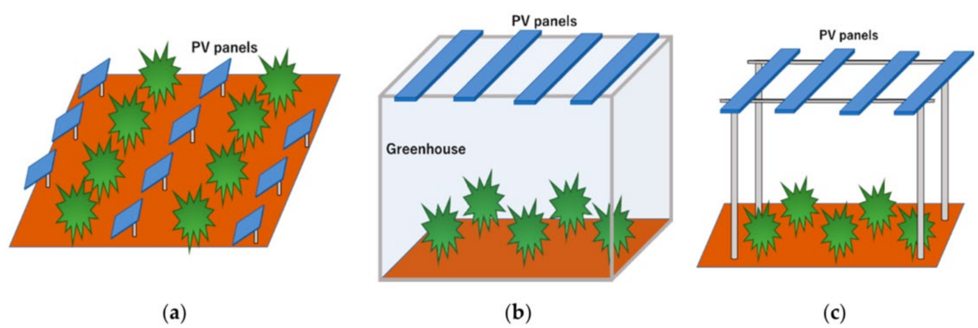

Figure 1. Three different types of agrivoltaic system. (a) using the space between photovoltaic(PV) panels for crops, (b) a PV greenhouse, and (c) a stilt-mounted system. Source:(Sekiyama & Nagashima, 2019)

This system has been proposed by scientists to integrate photovoltaic into agricultural systems and has been proven land-efficient as described in the introduction section. In this section, I will provide a summary of current pieces of literature from the perspective of the environmental effects of the system.

The Agrivoltaic system is considered to be environmentally friendly due to its ability to reduce irrigations, to alleviate water evaporation from the soil, and to maintain temperature for crop growth. The technique of dual-use of lands was proposed by Goetzberger et al. in 1981

(Goetzberger & Zastrow, 2007). Based on the Agrivoltaic model, Marrou et al. found that shading due to PV panels can save irrigation water by 14% - 29% depending on the level of shading and of soil covering (Marrou, Dufour, & Wery, 2013). Elamri et al. investigated the impact of rain distribution, water conservation, land use efficiency, and optimization of shading. They found that farms can reduce irrigation amounts by 20% if tolerating a 10% decrease in lettuces yield (Elamri, Cheviron, Lopez, Dejean, & Belaud, 2018). Research on water, soil, and land efficiency also provide some insights into location selection for the Agrivoltaic system. This co-productive system can be a future agricultural style in regions with a dense population and limited land resources (Dinesh & Pearce, 2016). It is also very promising to implement the system in semi-arid and arid regions due to any biological benefits brought by shading effects (Ravi et al., 2016).

The Agrivoltaic system seems to be a promising framework for sustainable agriculture. However, current understandings on the system are still limited. There is plenty of scopes for further research: (1) investigate how the system performs under different climate conditions and for different types of crops and lands; (2) optimize components of the system such as PV intervals, tile angles and so on; and (3) analyze the systems at regional and national levels in terms of its social benefits and social costs. Comprehensive applications and challenges on the Agrivoltaic system can be referred to a literature review by Weselek et al. (Weselek et al., 2019).

METHODS

Data collection

The main goal of this study is to understand how spatial heterogeneity, such as the environment, electricity markets, and regional policy would influence farmers' decisions to implement the Agrivoltaic farming system. In this study, data were collected separately to answer three sub-questions, which collectively informed the central research question.

In order to understand whether farmers from certain regions will have higher incentives to adopt the Agrivoltaic system compared to other farmers due to natural advantages, I collected data to reflect geographic information. First, I gathered land type data from the European Space Agency GlobCover Portal. The global land cover map used in this project was the GlobCover 2009 data. This data classifies global land cover into 22 types which are consistent with the United Nations

Land Cover Classification System (ESA, 2010). This data map was produced from an automated classification of MERIS time series with a resolution of 300 m and a projection of WGS84 ellipsoid. Using this data set, I excluded unsuitable land for solar plants such as water bodies, forests, high grasslands, etc. Then, I collected protected land data from Resource and Environment Data Cloud Platform (CAS, 2014-2017). This data maps out six types of ecological reserves in mainland China. The government protects these regions to preserve biological diversity and no other infrastructure can be built in these regions. I collected Global Horizontal Irradiance(GHI) data from World Bank Global Solar Atlas 2.0 which reflect solar radiation for each geographic coordinate (The World Bank, 2019). Then I also collected agricultural yield data from MapSPAM. These data reflect yield potential, production potential, physical area, and harvest area for each geographic coordinate point for 42 crops across the globe (International Food Policy Research Institute, 2019).

To understand the economic feasibility of the Agrivoltaic implementations across the county given different solar policies and electricity market across space, I conducted a spatial cost-benefit analysis. The costs and the benefits are quantified in monetary terms for the Agrivoltaic system in Chinese farmlands and the data are collected separately for the solar component and the crop component of the system. Associated benefits for the solar component involved electricity sale revenue and the PV electricity subsidy. These two parameters vary spatially. Associated costs for the solar component involved upfront cost, installation cost, maintenance cost, and operational cost. In this study, these four parameters are set at a fixed level across geography. Associated data for the crop component involved agricultural production prices and crop yield levels. Yields vary spatially while agricultural production prices are constant across the country. Two main sources for these data are data from public data sources and estimates from previous literature. To calculate the solar electricity sale revenue, I collected PV electricity production potential data from World Bank Global Solar Atlas 2.0 and standard electricity prices from price reports. The Global Solar Atlas 2.0 obtains its solar data from Solargis. This dataset reveals electricity potential(kWh) for 1000 kWp installed capacity ground-mount system. For each geographic coordinate, the optimum tilt of PV panels and the optimum azimuth of PV panels are calculated and set as default (The World Bank, 2019). PV electricity feed-in-tariff rates were collected from the latest documents regarding solar electricity pricing from the Chinese National Development and Reform Commission (NDRC). NDRC sets series standard for PV electricity subsidy levels corresponding to different installations of solar stations, different electricity producers, and different regions

(NDRC, 2019). The initial investments including upfront costs and installation costs which were estimated and calculated based on the initial investments from the 8 largest solar farm projects in China in 2018 (see Appendix A for information). Maintenance and operation costs with a lower bound of $10 per kW and a upper bound of $45 per kW were estimated from a budget report by Electric Power Research Institute (EPRI, 2015). I used these estimates to calculate costs for building on-farm solar stations. To access information on the crop component, I collected annual agricultural production prices from the Food and Agricultural Organization(FAO) of the United Nation and calculated the mean value of available crop prices between 2011 and 2019 (FAO, 2019). At the same time, I collected agricultural yield data from MapSPAM which was mentioned above (International Food Policy Research Institute, 2019). In answering this sub-question, I conducted my analysis focusing on 19 types of crop because only these crops have full data from both FAO and MapSPAM.

Aiming to understand how the adoption of the Agrivoltaic system would reduce GHG emission, I gained access to the greenhouse gas equivalencies calculator developed by United States Environmental Protection Agency. At the same time, I gathered an estimation on China's cost of carbon from literature. I used these data to calculate how much social costs the Agrivoltaic system would save in terms of emissions.

Data analysis

The process to identify regions with greater natural advantages for Argivoltaic implementations were based on four criteria: land type, crop yield, diffuse horizontal irradiance (DHI), and potential solar production. Lands that cannot build solar plants or cannot grow crops were first excluded using ArcGIS. Then, I used natural breaks classification to rank provinces based on the four criteria and assigned scores accordingly in R. All GIS data collected for addressing this sub-question were set to a same coordinate reference system – WGS84 and were clipped based on China's administrative map. In ArcGIS, the protected land layer was overlaid with the administrative map to first exclude restricted areas. Then, GlobCover layer was overlaid with the remaining administrative map for further analysis. In this study, land areas with value of 11(irrigated croplands), 14(rainfed croplands), 20(mosaic cropland 50-70%/ vegetation 20-50%), 30(cropland), and 140(closed to open herbaceous vegetation) were treated as potential suitable lands because this research aims to implement solar plants on top of agricultural plants. I calculated the percentage of lands that are potentially suitable for the system in each province. Then, I assigned scores to each province based on the percentage of the suitable lands. Provinces were classified into 7 classes following natural break classification. A province that was classified into the group with the lowest percentage share of suitable lands received a score of 1 and a province that was classified into the group with highest percentage share of suitable lands received a score of 7. At the same time, 19 types of crop data from MapSPAM were analyzed. I first conducted similar classification for each province: province with lower yield potential received a score of 1 while province with higher yield potential received a score of 7. In addition, I calculated the mean value of solar GHI for each province and classified the data into 7 classes. Regions with higher level of solar radiations received a higher score. Lastly, I calculated the mean value of predicted production for each province and again assigned all provinces into 7 classes using the similar approach as above. To determine the level of provinces' natural advantages for implementing the system, I summed the scores for each province by scale as below.

$$Final\ Scores = Suitable\ Land\ Score \times 0.2 + \frac{\sum_{i=1}^{i=19} Crop\ Potential\ Score_i}{19} \times 0.3 + GHI\ Score \times 0.3 + PV\ Production\ Score \times 0.2$$

To evaluate the economic profitability of implementing the Agrivoltaic system in different regions, I conducted cost-benefit analyses by building net present value models. I estimated the change in benefits and costs for farmland with the Agrivoltaic system relative to traditional farmland that do not adopt the system. In a traditional farm, there would be no additional benefits and costs from the photovoltaic system nor changes in crop yields. Therefore, I can estimate the changes between Agrivoltaic farms and traditional farms by calculating the monetary changes in these components directly. In this study, I compared two Agrivoltaic scenarios to the traditional scenario separately. In the baseline Agrivoltaic scenario, I used electricity prices and solar subsidy level in 2019 to perform the calculation. In the alternative Agrivoltaic scenario, I assumed a 20% reduction in solar subsidy compared to the 2019 standard because there is a falling trend of financial supports on solar projects from the government. Specifically, the NPV was calculated with the following formula:

$$NPV = \sum_{t=0}^{t=T} \frac{Benefits_t}{(1+r)^t} - \sum_{t=0}^{t=T} \frac{Costs_t}{(1+r)^t}$$

where benefits and costs for each time period t $\in [0,24]$ were discounted to the present at a rate of 3%. In this study, a 25-years windowd for the Agrivoltaic systems was considered because a solar panel can usually last for 25 years. The 3% discount rate is the farm loan rate (Kauffman and Kreitman, 2018) minus the rate of inflation. Throughout the calculation process, I used a currency exchange of 0.14 to convert Chinese yuan to U.S. dollars for some data. In the cost-benefit analyses, I broke down the analyses for the Agrivoltaic scenarios into two components: the solar component and the crop component. For the solar component, I assumed a 1000 kWp solar farm would be built in each county which would acquire 39 Chinese mu of land according to industry estimation in China (Tonking New Energy, 2019). The annual benefits of the solar component were calculated with the following formula:

$$\begin{aligned} &Annual\ Solar\ Revenue \\ &\quad = Solar\ Farm\ Peak\ Capacity\ (kWp) \\ &\quad \times Annual\ Average\ Electricity\ Production\ Capacity({}^{kWh}/_{kWp}) \\ &\quad \times \big(Regional\ Standard\ Electricity\ Price\ (RMB\ yuan)) \\ &\quad + Regional\ Solar\ Feed\ in\ Tariff\ (RMB\ yuan)\big) \times 0.14 \end{aligned}$$

where solar farm peak capacity was set as 1000 kWp and the annual average electricity production was the county-level mean value of solar electricity generation potentials. The annual costs of the solar component were calculated with the following formula:

$$\begin{aligned} &Annual\ Solar\ Cost \\ &\quad = Solar\ Farm\ Peak\ Capacity\ (kWp) \\ &\quad \times \big(Initial\ upfront\ and\ installation\ cost\ (RMB\ yuan) \times 0.14 \\ &\quad + Maintance\ \&\ Operational\ cost\ (\$)\big) \end{aligned}$$

where the costs were estimated from literatures and industrial reports as described in the data collection section. For the crop component, I conducted calculations focusing on completed crops which assumed all irrigation technologies would be implemented. Given the lack of research on how crop yields would change underneath the solar panels compared to traditional farming, I treated crop yield as a dynamic variation in the cost-benefit analyses. That is, I did not assume a certain amount of increase or decrease in crop yield due to the introduction of on-farm solar, but rather calculated a crop tolerance index(CTI) for each county. The crop tolerance index reflects how large of a percentage reduction in crop yield could still maintain a positive economic return in that particular county. After all calculations were completed, I used ArcGIS to visualize and ranked the total profit and CTI using a natural break classification.

In terms of analyzing how the implementation of the Agrivoltaic system in the county-level may address climate change, I estimated potential CO_2 reduction from the energy transition using the greenhouse gas equivalencies calculator. By inputting total solar electricity production potentials, corresponding CO_2 reduction values were generated. To take this effort one step forward, I calculated the avoided social costs of carbon that corresponds to these amounts of CO_2 reduction.

RESULTS

Data summary

The GlobCover 2009 data from the European Space Agency GlobCover Portal classifies land into 22 types and 5 types of land are considered suitable for implementing the Agrivoltaic system in this research. Over 124 million raster cells cover the Chinese administrative map. 43.54% of these raster cells are classified as suitable lands. The protected land data from Resource and Environment Data Cloud Platform identifies 50 regions as ecological reserve that are excluded from any type of commercial activity. Among the 19 types of crops that are considered in this research, the accumulated crop yield potentials are relatively high in Hubei province, Jiangsu province, Zhejiang province, Jilin Province, and Chongqing City. From the GHI data, I observed that Tibet region, Qinghai Province, Ningxia Province, Gansu Province have mean GHI value greater than 1600 kWh/m^2. The Photovoltaic electricity production potential data reveals electricity potential(kWh) for 1000 kWp installed capacity ground mount system. The highest production value in China is 2318.97 kWh, which is located in southwest China (Tibet region) and Northwest China (Inner Mongolia region). The lowest value is 537.283 kWh, which is located around central China (Sichuan Province) (see Appendix B for all maps for data visualizations). Electricity prices are different on the province level. Solar feed-in-tariff are differential on resource region types and solar station types (see Appendix C for information on solar electricity prices). Counties across the nation are classified into three resource regions by the central government, corresponding to three tiers of pricings. Pricing tiers are further classified by the types of solar stations. Solar stations under the poverty alleviation program typically receive a higher price compared to regular stations. However, regardless of resource region types and station types, each kWh of electricity generated will receive extra payment through the solar feed-in-tariff.

Annual crop data from the MapSPAM contains crop yields data for major food crops in China. In general, crop productions are concentrated in the drainage areas of the Yangtze River (Shanghai Shi, Zhejiang Province, Anhui Province, Hubei Province, Sichuan Province), the estuary of the Yellow River Basin Basin (Shandong Province, Hebei Province, Henan Province), and in the area of northeast three provinces (Heilongjiang Province, Jilin Province, and Liaoning Province). For example, rice production is concentrated near the Yangtze River with a highest yield of 62751 kg/ha and wheat production is concentrated around the Yellow River Basin with the highest yield of 23249 kg/ha.

Data analysis

After conducting geospatial analysis on ArcGIS, I estimated geographic locations which may have natural advantages for the Agrivoltaic system based on the four criteria. First, provinces were classified into 7 classes based on the percentage share of suitable land within each province. The natural jenks were 0%, 12.27%, 59.64%, 71.31%, 79.16%, 85.94%, 94.67%, and 100%. There were 5 regions which fell within the 94.67%-100% class and received a score of 7 in the calculation. Secondly, provinces were classified into 7 classes based on their crop yield potentials and received aggregated scores. Hubei province, Jiangsu province, Zhejiang province, Jilin Province, and Chongqing City received scores higher than 80 points. Thirdly, provinces were classified into another 7 classes based on the mean potential solar production. The natural breaks were 872.32, 978.56, 1125.44, 1261.11, 1430.65, 1593.59, 1711.54, and 1850.33(units in kWh). There were 7 provinces that fell into the highest score range in the calculation. Fourthly, I classified provinces into 7 classes based on the level of GHI and 4 provinces received points higher than 6. Based on these four criteria, geographic locations with the greatest natural advantage are Shandong Province, Shanxi Province, Liaoning Province, Jilin Province, Inner Mongolia Region, and Tibet Region. These Provinces received scores higher than 4.5 in the calculation (see Appendix D for detailed scores).

Net present value models were built to conduct the cost and benefit analysis for implementing the Agrivoltaic system. County-level total profits were calculated and then were classified into 5 classes for visualization purposes. Due to geographic differences, crop yield potentials for 19 types of selected crops, PV electricity generation capacity, and electricity prices varied across counties. Thus, I observed wide variations within solar electricity revenue and crop revenue. However, a consistent solar electricity costs were calculated. A standard installation cost of a 1000 kWp solar farm was around $1,223,847.403 given a currency exchange rate of 0.14. A price ceiling for maintenance and operational was around $8,96,126.6521 given a discount rate of 0.3 and a time span of 25 years. Counties were classified into 5 classes following natural break classification based on total profits (level 5 has the highest profitability while level 1 has the lowest profitability). In general, counties located in East China tended to have a higher profitability than counties located in West China. Under the baseline scenario, only 4 counties were in the level 5 and all of them were located in Jilin Province (Figure 2). There were 30 counties from 12 provinces fell into level 4. The northeast three provinces (Heilongjiang Province, Jilin Province, and Liaoning Province), Shandong province and Hubei Province were the hotspot provinces for this class. Under the reduced feed-in-tariff alternative scenario, counties which fell into the level 5 and the level 4 were the same as the base scenario (Figure 3). Other than that, 6 counties located in the Great Northwest region downgraded from level 2 to level 1. However, a county in Hunan Province upgraded from level 1 to level 2 and 1 county in Shanxi Province upgraded from level 2 to level 3.

Other than the total profits, the crop tolerance indexes (CTI) were calculated and visualized as well. Crop tolerance indexes (CTI) under the Agrivoltaic system for both scenarios were first classified into three classes: greater than 1, smaller than 1 but larger than 0, and smaller than 0. In this study, a CTI greater than 1 means that profits of the crop component would be less than profits of the solar component initially. A number smaller than 0 means the solar component would not make any profit initially. If the CTI falls between 0 and 1, a smaller CTI means a higher level of tolerance in profits if crop yields decrease underneath solar panels. For counties which had CTIs between 0 and 1, I reclassified them into 5 classes using the natural jenks method (level 1 was the highest tolerant level while level 5 was the lowest tolerant level). For the baseline scenario, 66 counties had CTI greater than 1 and majority of these counties were located in the Greater Northwest region and Inner Mongolia region. Only 3 counties located in Sichuan Province had CTI lower than 0. Then, counties with CTI between 0 and 1 were reclassified into 5 classes. 32 counties were in level 1 and most of them were centered around Sichuan Province, Guizhou Province, Chongqing City, Anhui Province, Hubei Province, and Jilin Province (Figure 4). For the alternative scenario, 37 counties had CTI greater than 1 and the geographic pattern was similar to the baseline scenario. 22 counties had CTI smaller than 0 and they were located in Sichuan Province, Guizhou Province, and Chongqing City. For those counties with CTI between 0 and 1, 54 counties were in level 1 and they were located in Anhui Province, Hubei Province, Hunan Province, Shaanxi Province, Sichuan Province, Yunnan Province, and Jilin Province (Figure 5) (see Appendix E for detailed calculation) .

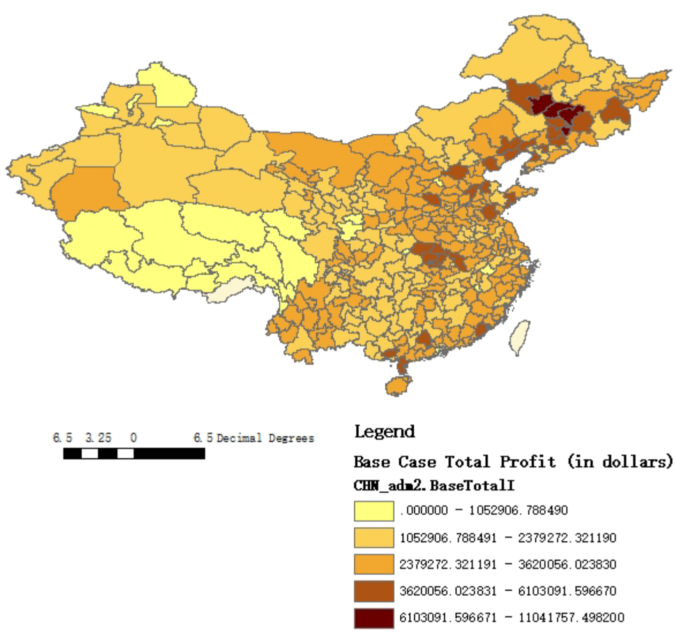

Figure 2. Total profit for the baseline Agrivoltaic scenario. County were classified into 5 classes following natural break classification based on total profits (level 5 has the highest profitability while level 1 has the lowest).

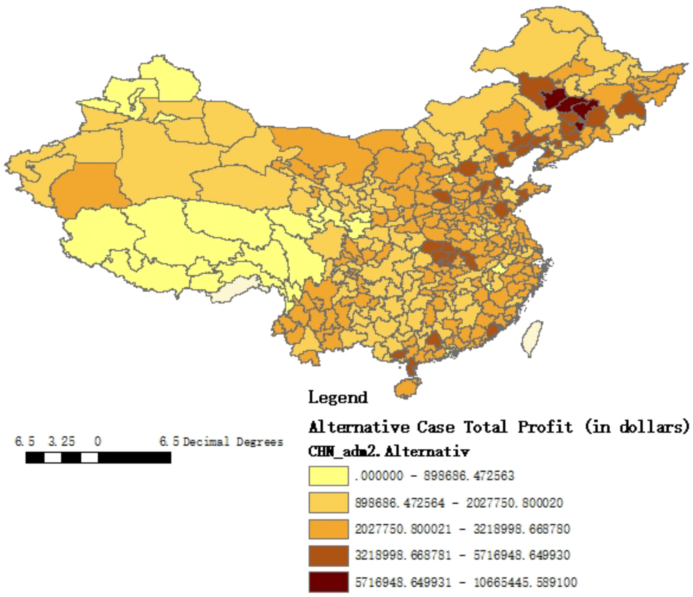

Figure 3. Total profit for the alternative Agrivoltaic scenario. Counties were classified into 5 classes following natural break classification based on total profits (level 5 has the highest profitability while level 1 has the lowest).

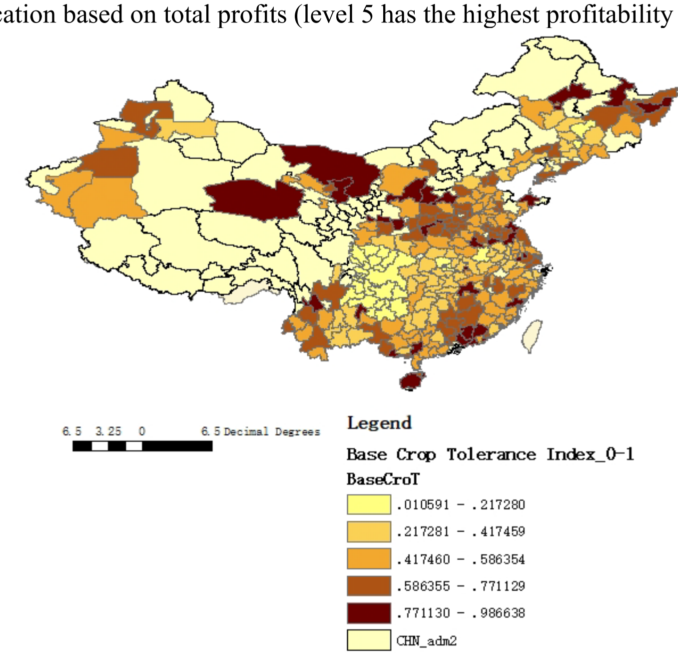

Figure 4. Crop tolerance index for the baseline Agrivoltaic scenario. County has CTI between 0 – 1 were classified into 5 classes following natural break classification. (level 1 has the highest tolerance while level 5 has the lowest).

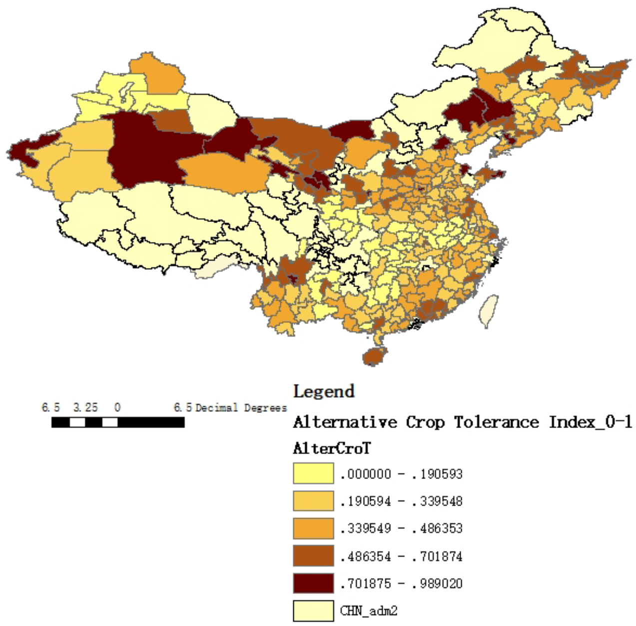

Figure 5. Crop tolerance index for the alternative Agrivoltaic scenario. County has CTI between 0 – 1 were classified into 5 classes following natural break classification. (level 1 has the highest tolerance while level 5 has the lowest tolerance).

Based on the baseline model in China, if each county built a 1000 kWp Agrivoltaic farm, the entire system would generate 430,371,146.9 kWh of soalr electricity. After using the greenhouse gas equivalencies calculator developed by the EPA, this amount of clean electricity would avoid 304290 metric tons of CO_2 emissions from dirty energy sources. The China's social cost of carbon is $24 per metric tons (Ricke, Drouet, Caldeira, & Tavoni, 2018). In this case, the hypothetical Agrivoltaic adoption in this setting could avoid $7,302,960 of social damage from GHG emissions.

DISCUSSION

Due to lack of empirical modeling, the overall compatibility and profitability of the Agrivoltaic system across China were unknown. To fill the knowledge gap, this research modeled hypothetical implementations of the Agrivoltaic system in China and provided insights from the perspectives of natural environmental advantage, economic feasibility, and carbon emission reduction.

This study investigated the natural advantage for implementing the system and suggested that six provinces(Shandong Province, Shanxi Province, Liaoning Province, Jilin Province, Inner Mongolia Region, and Tibet Region) would have natural advantages for implementing the Agrivoltaic system based on the criteria of land type, crop yield, DHI, and potential solar production. This result was consistent with geographic characteristics. Shandong Province lies on the north China Plain and the edge of the estuary of the Yellow River which features soil and water resources for crop cultivation and provides moderately ample sunlight resources. Liaoning Province and Jilin Province located in Northeast China where has highly fertile black soil. Whereas Inner Mongolia region, Tibet region, and Shanxi Province tend to have greater sunlight because of higher altitudes, thinner air, a lower density of cloud covers, and higher atmospheric transparency compared to other provinces in China.

This study also investigated the economic profitability for implementing the Agrivoltaic system across regions by assuming each county would build a solar farm with a 1000 kWp capacity. The baseline model indicated that 99% of the pure Agrivoltaic system would yield a positive change in profits and would bring excess net revenue to farmers. Only three counties in Sichuan Province have negative returns for investing in the solar system. In this case, farmers in these three counties may be better off owning a traditional farm rather than an Agrivoltaic farm. The alternative model indicated that around 93% of the Agrivoltaic system would still bring excess net revenue to farmers despite experiencing a reduction in feed-in-tariff except for Sichuan Province, Guizhou Province, and Chongqing City. These regions lack solar resources inherently and thus would lose money from solar investments. While accessing the crop tolerance index, farmers whose residential regions receive a score greater than 1 should not choose to adopt the system because revenue from the solar component may not offset costs from crop yield reduction. Farmers whose residential regions receive a score smaller than 0 should not adopt either because the solar system would not make any profit initially. In these two cases, farmers would be better off using traditional farming rather than the Agrivoltaic farming. After analyzing both the total profit and the crop tolerance index, this study found that counties in the Northeast three provinces have a relatively higher potentials to adopt the system. This study also identified several regions that have distinct performances compared to other counties nearby. For example, Shihezi county was the only county in Xinjiang province which would not bring excess revenue. Although Shihezi county may have the same levels of solar potential compared to other counties across the country, the standard electricity price is low in Xinjiang Province, and the feed-in-tariff price is low in the county. These two elements, coupled with the small solar potential in Shihezi county compared to other counties in Xinjiang province, made this particular county less attractive for the Agrivoltaic system. This observation was mostly consistent with one previous modeling in Xinjiang Province, which indicated a positive economic output except for the exception in Shihezi County (Chen et al., 2018). Overall, this study indicated that both the baseline scenario and the alternative scenario suggested a high probability of gaining extra revenue from the Agrivoltaic system. This result was consistent with arguments from previous literature, saying that the implementations of the Agrivoltaic system enhance the profitability of farming (Dinesh & Pearce, 2016; Malu et al., 2017; Weselek et al., 2019).

This research assessed the main criteria that may influence Chinese farmers' incentives to adopt the Agrivoltic system and provided insights for policy. If farmers are going to make rational decisions, they would choose the system if the system brings them additional profit, if their farmlands can tolerate crop yield variation under the solar panels, and if the profitability does not change significantly when the solar feed-in-tariff decrease. According to the model, Jilin province best fits these criteria and has the highest potential with the Agrivoltaic system. Thus, local farmers should be willing to take advantage and adopt the system. At the same time, to advocate for the new farming system, local governments may want to initiate programs to support farmers by taking their first steps toward transforming their farming systems. For example, local government can initiate financial support programs to help farmers cover the upfront costs. At the same time, technical support programs or information campaigns may be helpful to encourage adoption. For other regions that also meet these criteria, farmers still have the incentive to adopt, but it is weaker than in Jilin province. In this case, the government could potentially change the decreasing trend of solar feed-in-tariff to incentivize farmers. But, even if the government does not take such action, farmers may recognize the decreasing costs of solar systems across the country and the potential profitability they may gain from this. For regions that do not bring excess revenue, such as Sichuan Province, Guizhou Province, and Chongqing City, farmers should be conscientious before making investment decisions. For regions that may have low tolerance in crop variation, such as some parts in Xinjiang Province and Inner Mongolia region, local level supervisions are needed before taking any actions. This research also showed a possible scenario for electricity usage in farm lands. With the Agrivoltaic system, farmers may be less dependent on centralized electrical power system because they now have electricity sources in their farms. In this case, the renewable energy share may increase in the energy mix for the agriculture sector. From the presentative of emission reduction, the Chinese government may be encouraged by this possibility and seek to promote the Agrivoltaic system as an approach to meet China's climate pledge.

Limitations and future directions

There were certain limitations associated with this research due to restrictions from getting regional level data. I used county-level crop yield data, solar production data, and electricity price data in the analysis but only had country-level crop price data and country-level solar system cost data. Because of such heterogeneous scales of data, I set uniform assumptions across the country in the model, which led to a less comprehensive analysis in capturing variations across the country. Meanwhile, this cost-benefit model involved two components: the crop component and the solar component. Due to absences of literature on understanding agronomy underneath solar panels and a lack of series of soil data, microbial data, and nitration data, I was not able to access the changes of crop yield under the Agrivoltaic system. Although I estimated crop yield tolerance levels based on the existing data, with a hope to anticipate crop variations, this may not reflect the actual crop performances. Furthermore, Chinese solar policies changes frequently on a regional basis. In this research, I used a fixed rate to describe the changing of the policy, which may not fully match with reality.

Given these limitations and with a hope to move the research forward, I would suggest more work to be done to increase the accuracy of the crop component of the Agrivoltaic system in the analysis and to capture regional, county-level variations more preciously. First of all, future research can implement crop models and climate models into the cost-benefit analysis to better understand how crop yield varies along with geographic characteristics. More research on agronomy should be conducted to fully understand how irrigation, nutrition, and returns of different crops would change underneath the solar panels. Secondly, I suggest conducting case studies on the local level to confirm the result of this study. A modeling focus on a particular county or a specific province should help capture regional variations and provide detailed information on how to put the Agrivoltaic system into practice. Lastly, I suggest developing a model to consider crop prices, electricity price, and solar feed-in-tariff as dynamic variables instead of fixed-rate numbers.

Although more research on the topic needs to be conducted, my study provided a blueprint for understanding the potential of the Agrivoltaic system in Chinese farmlands. My research identified regions that have both natural advantages and economic advantages for farmers to implement the system as well as demonstrated possible fluctuations in the suitable areas if the Chinese solar policy remains on its current trend. This study also estimated a large social benefit from carbon emissions reduction associated with the adoption of on-farm solar. As a result, this paper provides promising direction for carbon policy.

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APPENDIX A: Initial investments for on-farm solar system in China in 2018

Initial Investment for on-farm solar project in China (2018)			
Project	Capacity (MW)	Initial Investment(hundred million in yuan)	Initial Investment (dollars/kW)
Jiangshan Solar Valley	200	20	1400
Dangyang City Agri-Solar Project	80	10.5	1837.5
Lingwu Photovoltaic Project	228	13.65	838.1578947
Houtonshan Valley Solar-Agri Project	40	3.06	1071
Gurong Valley Solar-Agri Project	40	3.8	1330
Shenhe Valley Solar-Agri Poverty Alleviation Project	5.33	0.48	1260.787992
Qingtian Solar-Agri Project	30	2.3	1073.333333
Guiping Solar-Agri Electricity Generation Project	40	2.8	980
		Average Initial Investment (dollars/kW)	1223.847403

Table A1. Initial investments for on-farm solar system in China in 2018. I calculated an average initial investment for on-farm solar system in China based on 8 largest on-farm solar projects in China back in 2018. In the calculation, I assumed a 1:0.14 currency exchange rate between yuan and dollar. Information on these projects were gathered from news and project reports.

APPENDIX B: Criteria for accessing natural advantages

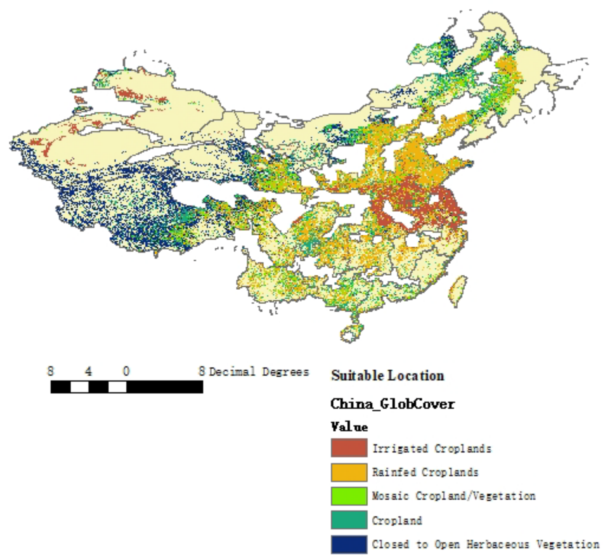

Figure B1. Regions with suitable land type for the Agrivoltaic System. Map visualizing global land cover map from the GlobCover 2009 data. Land areas with value of 11(irrigated croplands), 14(rainfed croplands), 20(mosaic cropland 50-70%/ vegetation 20-50%), 30(cropland), and 140(closed to open herbaceous vegetation) in the raster data were regarded as potential suitable. Natural reserve regions were excluded from this map.

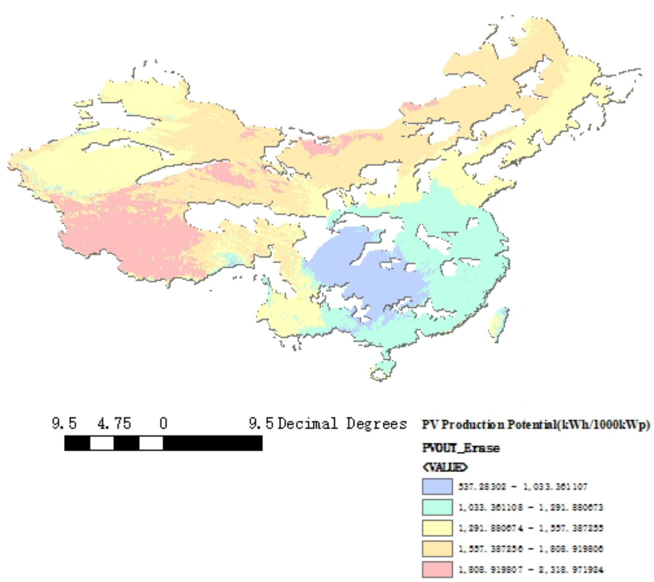

Figure B2. Solar energy production potential map. Map visualizing potential amount of electricity that can be generated from solar system in different regions. Solar production potentials values were classified into 5 classes following natural jenks. Natural reserve regions were excluded from this map.

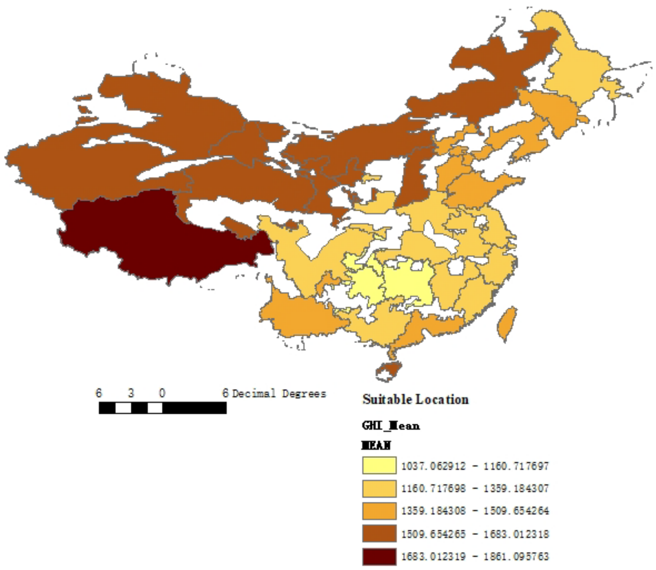

Figure B3. DHI level map. Map visualizing direct horizontal irradiance level in China. DHI potentials were classified into 5 classes following natural jenks. Natural reserve regions were excluded from this map.

APPENDIX C: Information on solar electricity prices

ID	Province	Basic Electricity Price (yuan)	ID	Province	Basic Electricity Price (yuan)
1	Anhui	0.3693	16	Jiangxi	0.4143
2	Beijing	0.3698	17	Jilin	0.3731
3	Chongqing	0.3964	18	Liaoning	0.3749
4	Fujian	0.3932	19	nner Mongoli	0.2932
5	Gansu	0.2978	20	ingxia	0.2595
6	Guangdong	0.453	21	Qinghai	0.2277
7	Guangxi	0.4207	22	Shaanxi	0.3545
8	Guizhou	0.3515	23	Shandong	0.3949
9	Hainan	0.4298	24	Shanghai	0.4155
10	Hebei	0.3682	25	Shanxi	0.382
11	Heilongjiang	0.3723	26	Sichuan	0.4012
12	Henan	0.3779	27	Tianjin	0.3655
13	Hubei	0.4161	28	injiang Uygu	0.25
14	Hunan	0.45	29	Tibet	NA
15	Jiangsu	0.391	30	Yunnan	0.3358
			31	Zhejiang	0.4153

Table C1. 2019 Province-level basic electricity price in yuan. This table only includes mainland China.

Resource Region	**Solar Station Standard Price**		**Distribute Solar Feed-in-tariff**		**Region**
	Regular Station	**Poverty Alleviation Station**	**Business**	**Resident**	
Type I	**0.40 yuan/kWh**	**0.65 yuan/kWh**	**0.1 yuan/kWh**	**0.18 yuan/kWh**	**Ningxia, Qinghai Haixi, Gansu Jiayuguan, Wuwei, Zhangye, Jiuquan, Dunhuang, Jinchang, Xinjiang Hami, Tacheng, Aletai, Kelamayi, Neimenggu Chuchifeng, Tongliao, Xinganmeng, Hulunbeier(outside)**
Type II	**0.45 yuan/kWh**	**0.75 yuan/kWh**			**Beijing, Tianjin, Heilongjiang, Jilin, Liaoning, Sichuan, Yunnan, Neimenggu Chifeng, Tongliao, Xinganmeng, Hulunbeier, Hebei Chengde, Zhangjiakou, Tangshang, Qinhuangdao, Shanxi Datong, Suzhou, Yizhou, Yangquan, Shanxi Yulin, Yanan, Qinghai, Gansu, Xinqiang(exclude region I)**
Type III	**0.50 yuan/kWh**	**0.85 yuan/kWh**			**Region other than Type I and Type II**

Table C2. 2019 Regional-level solar feed-in-tariff rates.

APPENDIX D: Scores on accessing natural advantages

	Province	suitland_percentage_class	GHI_class	pv_production_class	BANA	BARL	BEAN	CASS	CHIC	COCO	COTT	GROU	LENT	MAIZ	POTA	RAPE	RICE	SOYB	SUNF	SWPO	TEAS	TOBA	WHE/	Crop Sum	FinalScore
1	Shanghai	3	3	3	1	5	7	2	1	1	4	2	7	3	1	6	6	6	1	3	1	1	5	63	3.09473684210526
2	Yunnan	5	5	5	3	5	2	5	5	1	1	2	3	4	4	4	3	3	5	4	4	7	2	67	4.5578947368421
3	Inner Mongolia	4	6	7	1	3	2	4	3	1	1	2	2	3	5	2	1	2	5	4	1	1	2	45	4.71052631578947
4	Beijing	4	4	5	1	1	2	2	1	1	5	3	2	5	1	1	2	4	4	2	1	1	5	44	3.69473684210526
5	Taiwan	7	5	4	3	1	1	1	1	1	1	2	1	2	4	1	2	1	1	2	4	2	1	32	4.20526315789474
6	Jilin	6	4	6	1	2	5	7	5	1	3	5	4	7	7	1	6	5	6	7	1	6	2	81	4.87894736842105
7	Sichuan	5	3	4	2	6	4	4	7	1	3	4	6	4	4	5	4	5	2	3	4	5	4	77	3.91578947368421
8	Tianjin	5	4	5	1	1	5	3	1	1	7	3	4	7	1	1	4	7	6	2	1	1	5	61	4.16315789473684
9	Ningxia	5	6	6	1	2	1	1	2	1	1	1	2	4	3	2	2	1	7	1	1	2	3	38	4.6
10	Anhui	6	3	3	2	6	1	3	5	1	5	6	3	4	2	5	5	5	1	3	3	3	6	69	3.78947368421053
11	Shandong	7	4	5	1	1	6	3	1	1	5	7	3	6	5	7	3	7	1	4	3	3	7	74	4.76842105263158
12	Shanxi	7	5	6	1	1	3	4	4	1	2	2	3	5	4	2	1	3	5	5	1	2	3	52	4.92105263157895
13	Guangdong	5	3	3	6	1	3	1	1	1	1	5	2	4	4	1	4	5	1	2	7	4	1	54	3.35263157894737
14	Guangxi	6	2	2	5	1	3	1	2	1	3	3	3	3	3	2	5	4	1	1	6	3	1	51	3.00526315789474
15	Xinjiang	3	5	6	1	4	3	1	2	1	5	2	2	6	2	2	2	2	6	1	1	1	5	49	4.07368421052632
16	Jiangsu	6	3	3	1	7	6	3	5	1	6	5	5	6	1	6	7	7	2	3	2	1	6	80	3.96315789473684
17	Jiangxi	3	3	2	1	1	3	2	3	1	4	5	4	2	4	3	6	4	1	2	3	3	1	53	2.73684210526316
18	Hebei	3	4	5	1	1	4	4	2	1	5	6	3	6	6	2	1	6	3	4	1	1	5	62	3.77894736842105
19	Henan	5	3	3	1	5	1	3	4	1	5	7	5	6	1	6	2	6	2	3	2	6	7	73	3.65263157894737
20	Zhejiang	7	3	3	1	7	6	4	6	1	6	4	6	4	5	5	5	7	1	3	6	2	4	83	4.21052631578947
21	Hainan	6	5	4	7	1	7	1	1	1	1	5	4	5	2	1	3	7	1	2	1	1	1	52	4.32105263157895
22	Hubei	4	2	2	1	7	6	6	4	1	5	6	6	5	6	6	5	7	2	5	5	3	4	90	3.22105263157895
23	Hunan	5	2	2	1	2	4	3	3	1	4	3	4	4	4	4	4	6	1	2	5	5	2	62	2.97894736842105
24	Gansu	2	6	6	1	4	5	1	4	1	2	1	4	4	4	5	1	2	6	1	1	1	4	52	4.22105263157895
25	Fujian	7	3	3	4	1	5	3	2	1	1	4	4	3	5	2	3	6	1	3	7	7	1	63	3.89473684210526
26	Tibet	6	7	7	2	1	7	1	1	1	1	1	4	1	2	3	1	2	1	1	1	1	2	34	5.23684210526316
27	Guizhou	3	1	1	2	2	4	5	4	1	2	3	4	5	4	4	5	3	4	5	4	6	3	70	2.20526315789474
28	Liaoning	6	4	6	1	1	6	6	2	1	2	5	3	6	6	2	3	5	3	6	1	6	2	67	4.65789473684211
29	Chongqing	3	1	1	3	4	5	5	7	1	1	4	5	5	4	5	4	5	2	3	6	7	3	79	2.34736842105263
30	Shannxi	7	3	4	1	3	3	4	3	1	2	1	4	3	3	3	2	3	3	4	2	4	3	52	3.92105263157895
31	Qinghai	2	6	7	1	7	3	1	5	1	1	1	6	1	5	4	1	1	1	1	1	2	4	47	4.34210526315789
32	Hongkong	1	4	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
33	Heilongjiang	3	3	6	1	1	4	4	2	1	1	2	3	6	5	2	4	5	6	2	2	3	2	56	3.58421052631579

Table D1. Scores to identify regions with natural advantages based on four criteria.

APPENDIX E: Cost-benefit analysis calculation

https://drive.google.com/a/berkeley.edu/file/d/1oa9L_MoRoTGKvW-GedIrBgs4QodMyuui/view?usp=sharing

Table E1. Details calculation for the cost-benefit analysis.