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Do agrivoltaics improve public support for solar? A survey on perceptions, preferences, and priorities

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Abstract

Agrivoltaic systems integrate agricultural production with solar photovoltaic electricity generation. Given the proven technical, economic, and environmental co-benefits provided by agrivoltaic systems, increased proliferation is anticipated, which necessitates accounting for the nuances of community resistance to solar development on farmland and identifying pathways for mitigation. Minimizing siting conflict and addressing agricultural communities' concerns will be key in continued deployment of agrivoltaics, as localized acceptance of solar is a critical determinant of project success. This survey study assessed if public support for solar development increases when energy and agricultural production are combined in an agrivoltaic system. Results show that 81.8% of respondents would be more likely to support solar development in their community if it integrated agricultural production. This increase in support for solar given the agrivoltaic approach highlights a development strategy that can improve local social acceptance and the deployment rate of solar. Survey respondents prefer agrivoltaic projects that a) are designed to provide economic opportunities for farmers and the local community b) are not located on public property c) do not threaten local interests and d) ensure fair distribution of economic benefits. Proactively identifying what the public perceives as opportunities and concerns related to agrivoltaic development can help improve the design, business model, and siting of systems in the U.S.

Keywords: Agrivoltaics, Solar development, Social acceptance, Public opinion, Land use, Energy siting

1 Introduction

Conventional fossil-fuel based energy production and agricultural land use are the leading sources of anthropogenic greenhouse gas (GHG) emissions [23]. Solar photovoltaic (PV) energy is renewable, generates low emissions relative to fossil-fuel sources [58], and is the cheapest source of electricity in the world [53]; the increased deployment of PV systems will be instrumental in mitigating GHG emissions and the associated climate change impacts. Yet spatial constraints in large-scale solar PV development are eminent, as taking advantage of high solar resource availability implies continued open space development and competition for land that receives abundant solar insolation, specifically agricultural land [1, 31]. The potential to deploy solar PV could be cut in half in areas where land is favored for agriculture rather than energy production [31], indicating that strategies for ameliorating conflicting land use trade-offs are requisite to enable continued large-scale PV development [91]. Additionally, instances of land use conflict related to solar energy development can give rise to community resistance [20]; among the nuanced reasons for this localized opposition, land type and land use have been identified as critical for shaping public acceptability of solar development [18, 92]. These coupled challenges signify that both land constraints for renewable energy [16] and associated public perceptions will have implications on

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large-scale PV deployment, which emphasizes the need for enhanced development strategies that optimize land use and invoke community acceptance.

Siting solar PV systems to be compatible with multiple uses is becoming an increasingly effective approach to address land constraints, and recent survey research has confirmed that mixed use solar projects, specifically on agricultural land, are among the most highly supported development types [92]. These mixed-use solar projects that combine PV electric generation and agricultural production are commonly known as agrivoltaic systems [3, 32, 33, 100]. Agrivoltaic systems leverage a single plot of land for dual purposes by integrating crop (e.g., [34]) or livestock production (e.g., [5, 6]) with solar PV energy generation [99]. They can simultaneously increase land use efficiency [33] and the economic value of farms [32, 38, 69], while providing rural employment opportunities [61, 86]. Agrivoltaic applications are wide ranging and vary across geographic context, having been originally deployed with plant-based agriculture such as wheat [33], corn and maize [4, 93], *aloe vera* [88], grapes [67], and lettuce [68]. Researchers studying the effects of co-locating crops with solar PV have discovered valuable auxiliary benefits to plants such as reduced temperature fluctuations [14], greater soil moisture retention [45, 112], and increased resilience to drought stress [8]. Further, integrating animal husbandry on a solar PV array as a sustainable (environmentally and economically) form of vegetative maintenance has gained popularity [66, 73, 77], and has been empirically determined to reduce greenhouse gas emissions and demand less fossil energy than conventional separate production [79]. A study by Proctor et al. [86] found that only 0.94% of U.S. farmland would be needed to satisfy 20% of 2019 electricity generation using agrivoltaic systems. Additionally, research shows that converting only 1% of cropland to agrivoltaics could satisfy global energy demand with PV production [1]. Agrivoltaic systems may minimize land use trade-offs and consequently soften community resistance to solar infrastructure encroaching on arable land [80]. Although agrivoltaics have been demonstrated as a viable alternative to conventional ground-mounted solar development practice [111], diffusion of the innovation may be suppressed by community opposition towards local energy development proposals, as previous research on renewable energy technology suggests [11, 12, 15, 35, 62, 104]. Given the proven economic, technical, and environmental co-benefits provided by agrivoltaic systems, increased proliferation is anticipated, which necessitates connecting this technology with the interests of agricultural communities and designing locally appropriate systems that minimize land use conflict [80, 81]. Identifying the factors of agrivoltaic development that can minimize siting conflict and address agricultural communities' concerns will therefore be critical in promoting the acceptance of this technology.

This research aims to measure if public support for solar development increases when energy and agricultural production are combined in an agrivoltaic system. By use of survey methodology, the objective is to answer our guiding research question: *Is public support for agrivoltaics higher than public support for conventional solar*? *What development and planning factors influence support for or opposition to agrivoltaics?*

This research provides a novel exploration of public perceptions about integrating solar PV with agricultural production in an agrivoltaic system – which is a cornerstone of the success of this technology but has yet to be considered empirically. The survey instrument uses rabbit-based agrivoltaics as an example to help respondents conceptualize a livestock-based project when considering agrivoltaic development in their community. The findings are discussed in the context of ongoing social science research concerned with resistance to energy development with the aim of providing insight applicable for solar developers, policy makers, and land use planners, as identified public preferences and concerns can inform enhanced development practices and facilitate increased deployment of agrivoltaic systems in the U.S.

2 Literature survey

Given that agrivoltaics is a relatively nascent form of solar development, even in areas with a mature PV industry and substantial agricultural production having little agrivoltaics [83], there is a dearth of social science research dedicated to investigating the social acceptability and perceptions of the technology. Existing research concerned with the social dimensions of agrivoltaic development suggests that community acceptance, farmer adoption, and local regulatory environments will play a crucial role in the broader realization of these systems [57, 63, 78, 80, 81]. Based on previous theoretical and empirical studies related to social acceptance of renewable energy (RE) (e.g., [7, 9, 36, 95, 104, 108]), it is anticipated that successful deployment of agrivoltaics will necessitate sensitivity to and accommodation of public perceptions, especially rural perceptions, related to solar infrastructure on farmland. While majority of research related to social acceptance of RE is focused on wind (e.g., [13, 39–41, 44, 74, 116]) and less so on solar [18–20, 92, 96], the general concepts and factors identified as influential of support can be applied to develop a framework for understanding factors that may play a role in shaping public perceptions about agrivoltaic systems.

Previous research that investigates social perceptions about RE development confirm widespread public support [11, 12, 114], with solar energy being the most positively regarded type [43]. Despite this high, general support for RE, many development efforts are challenged by localized opposition when it comes to the proposal of a specific facility in a community (e.g., [29, 97, 105]). Some scholarship dismisses explanations of this localized opposition as "NIMBY" syndrome, as this theory is empirically inconsistent and oversimplified [24, 26, 113]. More recent literature characterizes localized opposition to RE development as a nuanced and complex social response, demonstrating that variation in support and opposition towards a specific project is influenced by a broad range of demographic (e.g., [40, 43]), contextual (e.g., [110, 113]), and socio-psychological factors (e.g., [15, 39, 70]), rather than mere proximity as the NIMBY theory suggests.

Research focused on identifying factors that shape public support or opposition towards RE development in general provide broad insight into the factors that have a statistically significant influence on social acceptance. Contextual factors related to proximity and visual impact have been demonstrated to be important predictors of support or opposition to a development; proximity has been demonstrated to have a strong but variable influence on public attitudes [104, 109] and public survey research has found greater acceptance for developments that are out of sight [56]. Larson & Krannich [62] detail alternative predictors of attitudes towards RE development, identifying individual beliefs about opportunities and threats related to context-specific proposals as having implications on support for a local project [42]. Other researchers demonstrate social acceptance of RE is a function of community perceptions related to procedural justice, public participation, and fairness in the planning process [2, 44, 55, 70]. Socio-economic opportunities and threats are also important factors that shape public perceptions about RE development [7]. Individual belief in potential economic opportunities, specifically in the context of rural economies, contribute to increased support for RE [65]. Public support for RE is also influenced by perceptions related to the distribution of economic benefits related to a project [114] (e.g., ownership of a solar site by a utility that manipulates rate structures to discourage distributed PV [84] may be blocked by local opposition [103]). Further, socio-psychological factors such as place identity and place attachment are central concepts related to public support and opposition to RE (e.g., [27]). Opposition to development is associated with one's positive identification with the land [28]; those who have a particular sense of identity connected to rural landscapes have proven to be more likely to oppose RE development [104]. Based on these studies, it is anticipated that public perceptions about visual impact, socio-economic opportunities and threats, and rural place attachment will prove consequential for local social acceptance of agrivoltaic development.

There is a scarcity of empirical research directly aimed at identifying factors that influence support or opposition to solar PV development in the U.S. (exceptions include [18–20, 92]). These studies have found rural residency [19, 20], land type [20, 92] and distribution of economic benefits [92] to have strong influence on public perceptions related to solar projects. A survey by Carlisle et al. [20] found that rural residents are more likely to oppose local solar development than urban residents, suggesting that rural communities perceive land use differently. Schelly et al. [92] found that solar developments that are co-located with other land uses and those that provide income opportunities to farmers receive highest levels of public support, representing key factors that may be important in shaping attitudes towards agrivoltaic development. The factors that influence support or opposition to solar PV development in the U.S. identified by these studies provide a foundation for exploring public perceptions about agrivoltaics – which has not been previously studied. To build upon this body of scholarship concerned with the social acceptance of solar and to fill an important research gap related to public perceptions about agrivoltaic systems, this study investigates if the agrivoltaic approach increases public support for a solar project.

3 Methodology

This study used survey methodology to analyze differences in public support between conventional solar and agrivoltaic development. In alignment with the purpose of this research, survey is the preferred method to test hypotheses about differences in support for solar development alternatives. Based on previous survey studies on public perceptions about solar development in general [18–20, 92], there was reason to anticipate that support for agrivoltaics will be influenced by residential characteristics (i.e., rural versus urban), type of land being developed, project proximity, and financial model. Because a survey by Carlisle et al. [20] found that rural residents are less supportive of solar in their community than those living in urban areas, it was reasonable to presume that agrivoltaic projects will be perceived differently by individuals of differing residential characteristic, specifically because these projects are integrated on agricultural land and therefore are more likely to impact rural communities, both in terms of economic opportunity [86], and land development [1]. Schelly et al. [92] found that mixed-use solar projects located on agricultural land are among the most highly supported development types, therefore it was expected that support for agrivoltaic projects will be higher than support for conventional solar. The survey method allowed us to test our expectations about differences in support for solar development alternatives and then logically generalize our findings beyond our two case study regions to communities with similar characteristics to help inform agrivoltaic development practice in the U.S.

3.1 Case study selection

This study was conducted in two separate counties of the central United States: Lubbock County, Texas and Houghton County, Michigan. The logic behind the purposive sampling of Lubbock and Houghton counties is three-fold: 1) these counties represent areas of potential for economic development from agriculture and renewable energy based on existing community interests; 2) to derive comparative insight into variation in public perspectives across regions of different climate and demographics; and 3) both locations are relevant to the broader case study project and provide sufficient access to data. Following case selection guidelines outlined by Yin [117], these counties were chosen to illuminate our research question about public support for alternative solar development types (which is best investigated by collecting evidence in communities of varying characteristics), and reflect our unit of analysis under study (communities), which is consistent with other survey studies on public attitudes towards energy development (e.g., [20]). Ultimately, case selection was based on an effort to make analytic generalizations [117] – the resulting data is positioned to speak to broader topics of public perceptions about alternative solar development types and land use, rather than reflect the distinct, contextualized experience of residents in Houghton and Lubbock counties.

The U.S. Census Bureau (2020) estimated Lubbock's population to be 308,392 and Houghton's to be 35,890 [21, 22]. Both counties are relatively rural with pockets of population centers; Lubbock County has a population density per square mile of 344.3 persons, whereas Houghton County has a population density per square mile of 35.6 [21, 22]. Because there is an 8-fold difference in population density between counties, it was hypothesized that public perceptions about land development may vary across these case studies. Further, these counties share similar sociodemographic characteristics in terms of age, education, and median household income (see Table 1), which permits consideration of factors beyond demographics as influential in shaping public perception towards local solar and agrivoltaic development. Despite these demographic similarities, these locations vary in terms of geography and climate. Located in the American Southwest, Lubbock has an annual high temperature of 74 °F and an annual average snowfall of 9 in [101]., compared to Houghton located in the northern-Midwest that experiences an annual high temperature of 49 °F and an annual average snowfall of 208 in [102]. Additionally, Lubbock County receives 4.3 kWh/m^2/day of solar irradiance whereas Houghton County receives only 4.0 kWh/m^2/day [75] and has some of the worst snow-related solar losses in the country [49]. Therefore, Lubbock County is a good alternative case to Houghton County because contrast in climate may play an impactful role in resident's perceptions about the efficacy of solar in their region and in the feasibility of agrivoltaic development in their communities.

3.2 Procedure

A mail survey with the option for online completion of an identical questionnaire was administered to both Lubbock County and Houghton County residents. The survey was launched in October 2020 and was closed in January 2021. A financial incentive of $2 was included with the mailed survey to stimulate a higher response rate. The survey participants were contacted in two waves; the first wave included a postcard with information to access the online survey, while the second wave included the full printed survey, the $2 incentive, and return postage. Online survey data were collected using Qualtrics software [87] and exported to IBM SPSS Statistics (version 26) [52], whereas mail survey data were manually input into a spreadsheet and exported to SPSS for statistical analysis. Digital landowner parcel maps from both counties were used as the sample frames from which a simple random sample of households was drawn and recruited as study participants with a sample size of approximately 1000 respondents per county. The motive behind this sampling strategy was to collect responses from individuals who reside in these counties as their primary residence in order to examine county resident perceptions towards solar and agrivoltaic development in their local community. The sample frame for Houghton County was acquired from the Houghton County Tax Equalization Department and this frame is composed of all property or parcel owners in the county as of the year 2010 [50]. The Houghton County frame was first manually cleaned using property ownership names to remove all non-household units (businesses, churches, trusts, etc.) prior to sampling. The sample frame for Lubbock County was obtained from the Texas Natural Resources Information System online database [98]. The information on this frame is from 2019 and was recorded at the county level using a standardized schema that classifies land parcel types based on State of Texas legal land use codes. This coding scheme was used to distinguish residential land parcels from commercial or industrial parcels to filter out non-household cases prior to sampling.

Utilizing these land use codes and manual identification of ownership attributes, entities that did not belong in the target population of county residents such as vacant lots, open-space agricultural land, commercial, industrial, and utility parcels were removed from the dataset in order to refine a sample frame representing real residential parcels in Houghton County and Lubbock County. A final query of both datasets was conducted to remove any duplicate addresses to ensure equal probabilities of selection among households.

3.3 Sample

Table 1 compares the county population characteristics of Lubbock and Houghton counties to the survey respondent characteristics of our sample on selected sociodemographic variables relevant to representing our target populations. Table 1 shows that differences between our sample and the target population exist with respect to age, education, and income. Survey respondents were older and more educated (as well as wealthier in Lubbock County) than the county as a whole. However, these differences are not problematic for our data analysis purposes because they are to be expected when considering that our goal was to represent landowners in both counties - who tend to be older, wealthier, and more educated than non-landowners, as is typically found in most landowner surveys (e.g., [94]). In that sense, the sample and respondents for this study are adequate to provide insight into landowner perceptions about solar development types in both Lubbock and Houghton counties.

A total of 176 survey responses were collected from a sample of 2012 households, which resulted in a cumulative response rate of 8.7%. Of the survey respondents, 60 (34%) were from Lubbock County, 91 (51%) from Houghton County, and 25 (14%) were unidentifiable by location. Response rate varied between the two counties: 60 of 1004 households completed the survey in Lubbock (5.9% response rate), and 91 of 1008 households completed the survey in Houghton (9% response rate). The effective sample size (176) resulted in a sampling error of 7% at the 95% confidence level. Sampling error in Lubbock County is 12% and 10% in Houghton County. The relatively small sample may limit the ability to detect "weak" statistically significant relationships in the data – results that have failed to achieve statistical significance may be a consequence of not having enough data (or statistical power) to detect relationships. However, this is only a concern for results that have failed to achieve statistical significance, given statistically significant relationships have been detected in the data collected from this sample (section 4.3). Response rate has informed the interpretation of results and suggests that there may be other solar development factors significant to respondents that cannot be observed in a sample of this size.

3.4 Survey design

Survey items were designed to identify factors of importance in local solar or agrivoltaic development and planning, and to observe if incorporating an agricultural function to a solar system increases public support for a project. The development and planning factors included in this study (independent variables) were based on analytic concepts in the literature and existing variables that have been found to influence public perceptions towards energy development, such as land type [92], residential characteristics [20], socio-economic opportunities and threats [7], distribution of project benefits [114], and place-attachment [27]. These factors were loosely organized into five categories: siting, distribution of benefits, economics, environment, and place-protective considerations. These categories of factors were used throughout the survey to 1) identify

Table 1 Comparing county population characteristics to survey respondent characteristics on selected sociodemographic variables

Demographic	Houghton, Michigan		Lubbock, Texas	
	U.S. Census Bureau	Survey respondents	U.S. Census Bureau	Survey respondents
Population by age range	20–29: 21%	20–29: 2%	20–29: 20%	20–29: 0%
	30–39: 9%	30–39: 3%	30–39: 13%	30–39: 10%
	40–49: 9%	40–49: 4%	40–49: 11%	40–49: 13%
	50–59: 11%	50–59: 14%	50–59: 10%	50–59: 21%
	60–69: 12%	60–69: 40%	60–69: 9%	60–69: 30%
	70+: 12%	70+: 32%	70+: 8%	70+: 23%
Percent of persons with Bachelor's degree or higher	33.6%	39.6%	32%	60%
Median household income	$44,839	$50,000–$99,000[a]	$53,425	$50,000–$99,000[a]
Population	35,890	91	309,382	60

[a] Most common total annual household income range

the benefits and concerns respondents perceive to be associated with solar and agrivoltaic development in their community; 2) measure the relative importance of factors with respect to support; and 3) compare development and planning factors that were perceived as important for solar versus agrivoltaic projects. Answer categories for questions about factors related to support for local solar and agrivoltaic projects were based on a five-category Likert scale from 1 (strongly oppose) to 5 (strongly support). Answer categories for questions about factors related to project planning were based on a four-category Likert scale from 0 (not at all important) to 3 (extremely important). These response items were intended to provide insight into the variations in preference among the different considerations involved in solar development, and more specifically, agrivoltaic projects. Beyond the independent variables measured as development and planning factors, other independent variables included were general sociodemographic characteristics such as age, gender, education, political affiliation, and median income household because previous survey research demonstrates correlation between these variables and public support for renewable energy. Devine-Wright [25] provides reference to several studies which have found that younger individuals, those with more education, democratic political ideology, and higher household income are more likely to support renewable energy. A complete survey protocol is provided in the Additional file 1.

The main dependent variable in this study is a measure of marginal increase in support for solar based on the agrivoltaic approach. Support for agrivoltaics relative to support for conventional solar was captured by questions related to various development and planning factors and a single question intended to measure direct increase in support for mixed-use projects. Nuances in support based on development and planning factors were captured through the five-category Likert-scale type questions described above (strongly oppose-strongly support) and direct increase in support was gauged by asking the following question, "Would you be more likely to support a solar project near you if it combined the production of both energy and food?" The answer categories range from less likely to support, do not support, to more likely to support, with an option to denote "it depends" and provide explanation. This measure allows us to observe marginal changes in support for local solar development based on an introduced agricultural function, rather than observe direct levels of absolute public support for agrivoltaics.

To investigate if support for conventional mid-to-large scale solar development versus agrivoltaic development differ, a project scenario was presented with an identical series of factors and a corresponding 5-category Likert scale from 1 (strongly oppose) to 5 (strongly support). The scenario provided information to respondents about conventional solar development in terms of land use, spatial requirements, and electricity output, and then described the distinction between a traditional solar project and an agrivoltaic project (i.e., integration of agricultural production). Participants were asked to indicate which of the development factors (independent variables described above) listed would shape their support or opposition for the two solar system scenarios in their local community. This measure was intended to provide insight into differences in attitudes towards each system based on the introduced agricultural function and measure marginal increase in support for solar given the agrivoltaic approach.

3.5 Analysis

Among survey respondents, some withheld indication of their county of residence. This missing value error resulted in three separate groups of data. ANOVA tests were used to compare differences across county groupings (Lubbock, Houghton, unidentified) related to support for local solar and agrivoltaic projects, development and planning factors of importance, and reasons to support or be concerned about agrivoltaic systems. Differences across county groupings with respect to support and factors of importance were negligible and failed to demonstrate statistical significance. Responses across county groupings were nearly identical to each other on all tested variables. Additionally, participants were prompted to categorize the area in which they live as urban, suburban, rural, or other. This variable was recoded as a binary (0 = urban and suburban residents, 1 = rural residents) prior to analysis to explore differences in attitudes towards local solar and agrivoltaic development between respondents of varying residential characteristics. Contrary to expected differences in rural versus urban perceptions about solar [20], this study found no statistically significant distinctions between the groups. Based on the lack of statistically significant differences between counties in terms of support, factors of importance, and resident types, all data was aggregated for analysis.

4 Results

Results indicate that an overwhelming majority of respondents (71.8%) generally support solar development in their community (7% margin of error). Further, 81.8% of respondents declared they would be *more likely* to support solar development in their community if it combined the production of both energy and agriculture, which indicates a marginal increase in support for solar given the agrivoltaic approach. The key development and planning factors identified as most important to respondents in terms of support for agrivoltaic systems include income opportunities for farmers (89%) and local economies (88%). The key factors identified as most important to respondents in terms of opposition to agrivoltaics include siting considerations related to visibility (32%) and land type (preference for siting on agricultural land (68%) or private property (60%) versus public property (54%)), and distribution of project benefits (25%), which are equivalent to the most important factors related to solar development in general. Multivariate logistic regression results indicate that preference for project siting on existing agricultural land ($p < .05$), project construction by a local company ($p < .1$), opposition to siting on public property ($p < .05$) or opposition to local development in general ($p < .01$) have a statistically significant influence on support levels for agrivoltaics relative to conventional solar. Survey respondents prefer agrivoltaic projects that a) are designed to provide economic opportunities for farmers and the local community b) are located on private property or existing agricultural land c) do not threaten local interests and d) ensure fair distribution of economic benefits. These findings are statistically relevant to the participating counties and can inform approaches to solar development that include community priorities to generate multiple co-benefits and promote acceptance.

4.1 Comparing key factors that influence support

The survey first prompted participants to indicate which of the listed factors would shape their support or opposition for mid-to large-scale solar and agrivoltaic development in their community. Comparison of the frequency distributions presented in Figs. 1 and 2 illustrate that there are no notable differences in the factors that influence support for solar versus support for agrivoltaics. Across the two scenarios, the same factors remain important to respondents when conceptualizing their support for alternative solar development types in their community. For example, the percent of respondents (89%) indicating support or strong support for projects that provide additional income to farmers remains constant across the two development types. Factors related to local economic and environmental benefits, and project siting on public property remain equally important between development types, only varying by up to 3%. The key factors found to be most important for shaping support for both solar and agrivoltaics are related to economics. Benefits to local farmers by providing additional income (89%) and benefits to the local economy (91% solar; 88% agrivoltaic) were identified by respondents as the most important development factors, as indicated by the highest reported levels of support and strong support for these factors.

When comparing factors that influence opposition to conventional solar (Fig. 1) and agrivoltaics (Fig. 2), the same factors were found to be important across both scenarios. The key factors that influence opposition are

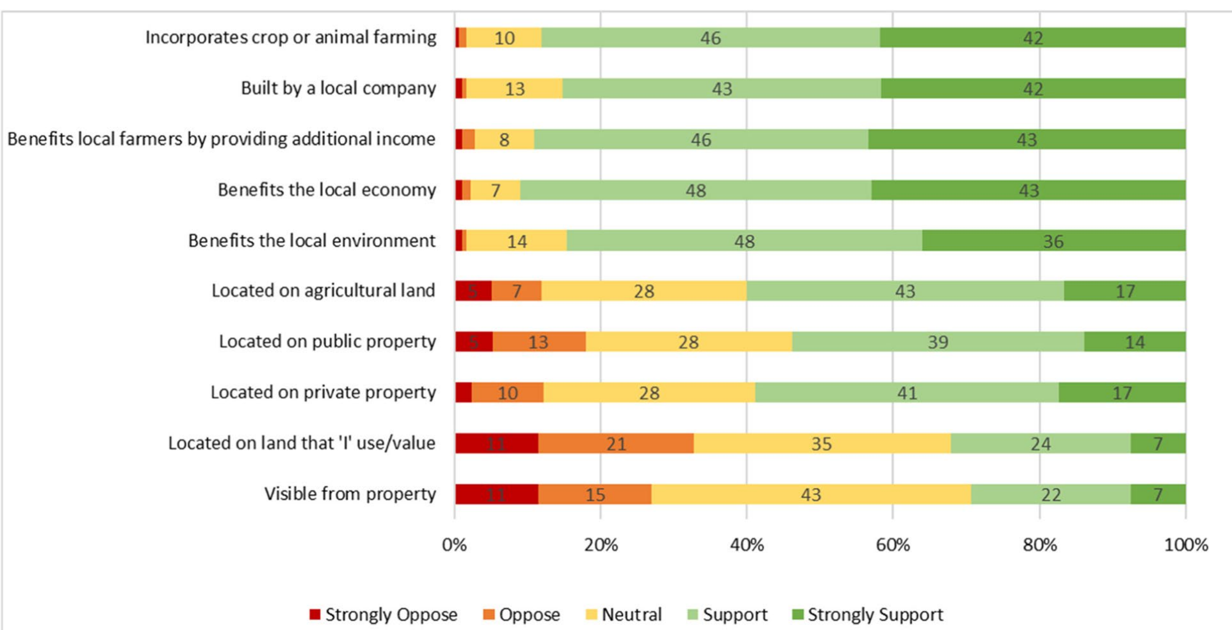

Fig. 1 Responses indicating which factors shape support or opposition to local conventional solar development

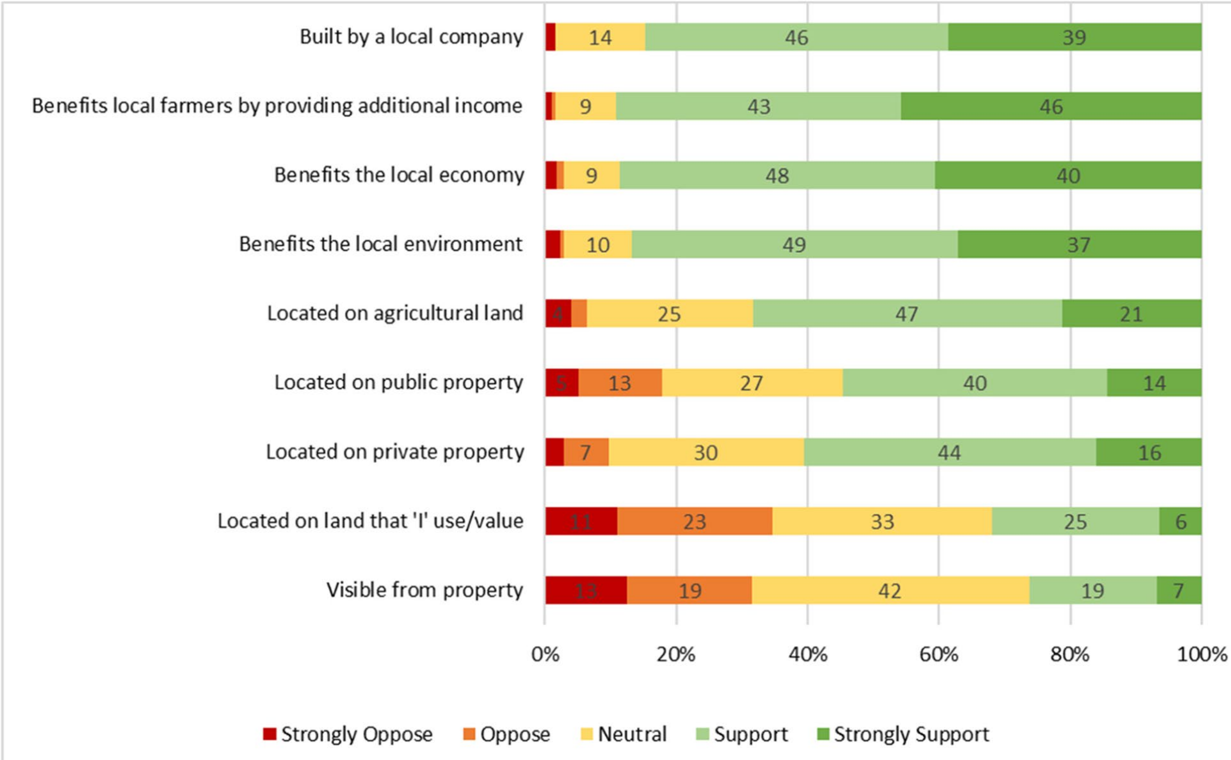

Fig. 2 Responses indicating which factors shape support or opposition to local agrivoltaic development

related to siting. Frequency distribution results show that projects that are developed on land that is valued by the community, visible from one's property, or located on public property increases respondent opposition to solar. The only notable difference between the two scenarios is that respondents who reported opposition or strong opposition for a project that is visible from their property increases by 6% when it incorporates an agricultural function. Given that these values represent respondent opposition as a range plus or minor a margin of error of 7%, this increase in opposition to visibility of an agrivoltaic project is not significant.

When respondents were asked directly if they support solar development generally in their community, 71.8% concur, 6.8% do not, and those who selected "it depends" (14.7%) and provided explanations reveal that perceptions mostly center on opposition to government subsidies that use taxpayer funds to finance solar. These results suggest that some respondents' support for solar is not related to nuances in place-based considerations or siting factors, but is more generally related to government regulation and financing of energy technologies. Of the 25 (14.7%) respondents who declare their support for solar as context-dependent (i.e., "it depends"), seven (28%) discuss opposition to government support and preference for private financing. Because the percentage of participants concerned with government subsidies for solar energy is small relative to the total sample, it is maintained that these concerns are less salient than those associated with localized, place-based considerations and siting factors and are therefore less relevant to assessing change in support for different solar development types.

4.2 Planning for Agrivoltaics: priorities and concerns

To inform the agrivoltaic planning and development process, the survey presented respondents with the following prompt: "When it comes to planning for combined solar and agriculture (agrivoltaic) projects in your community, please rate the following factors in terms of their importance to you." Respondents ranked the importance of factors related to siting, distribution of benefits, economics, environment, and place-protective considerations on a four-category Likert scale from 0 (not at all important) to 3 (extremely important). Frequency distribution results are presented in Fig. 3. When it comes to planning for agrivoltaics, 66.5% of respondents indicate that designing projects to provide jobs and other forms of local economic development is extremely important. Additionally, 55.7% of respondents noted the extreme importance of designing projects that do not threaten or

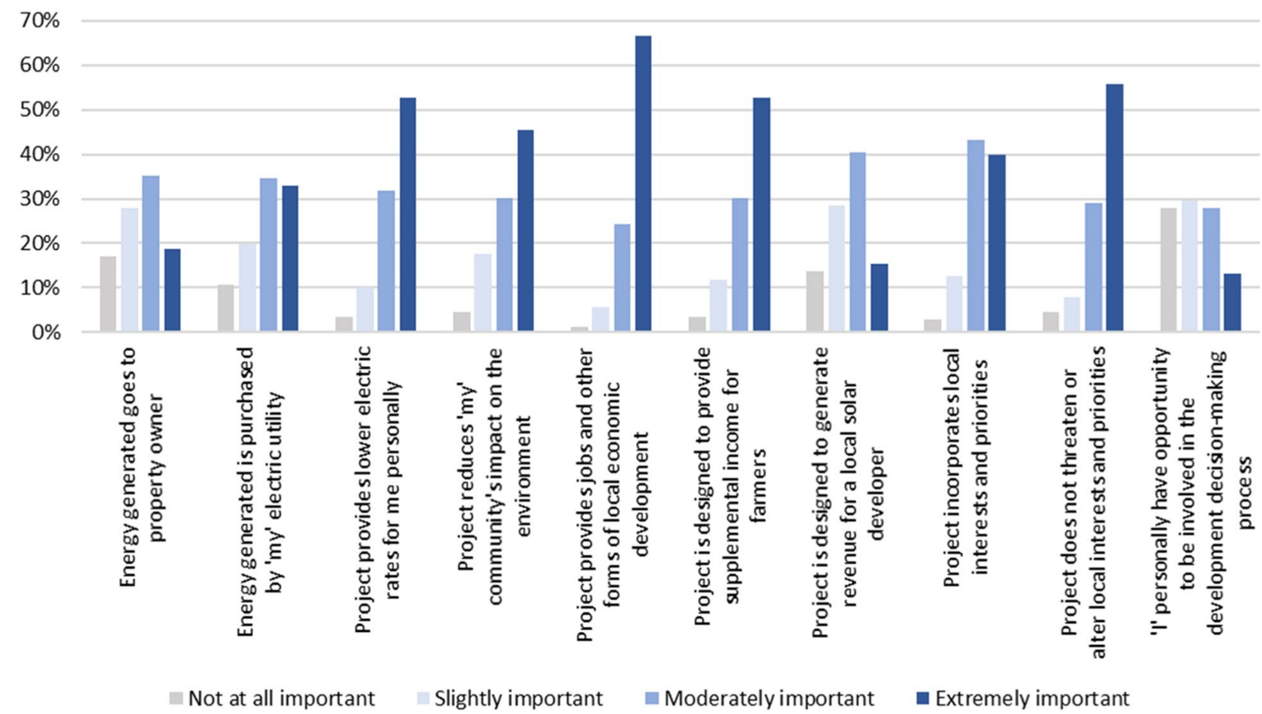

Fig. 3 Factors of importance when planning for agrivoltaic projects

alter local interests. Projects that are designed to provide supplemental income for farmers and to provide lower electric rates for ratepayers were also raised as equally critical, with 52.8% of respondents indicating both of these planning factors are extremely important. Each of these reported percentages has a corresponding 7% margin of error.

Figure 4 illustrates the frequency distribution of respondent's reasons to support agrivoltaic development. Participants were presented with the following prompt: "When it comes to developing a combined solar and agriculture (agrivoltaic) project in your community, which of the following would you identify as benefits or reasons you would not support? (Please select all that apply)." Respondents most frequently reported that providing income to local farmers (75%) and producing local food (75%) are the most important reasons to support an agrivoltaic project. A project that benefits local economies by providing jobs and investment was also frequently reported as important among respondents (73%), indicating that the main reasons for public support for agrivoltaics are related to place-based economic benefits for agricultural communities. It is interesting to observe that "efficient use of land" was the lowest reported reason to support agrivoltaic systems despite their intention to maximize land use. This suggests that drivers of support are more related to local economic benefits and agricultural interests rather than land use efficiency, as indicated by higher frequency of responses for these measures. Each of these reported percentages has a corresponding 7% margin of error.

Figure 5 presents the frequency distribution of concerns related to agrivoltaic development in one's community. Participants were presented with the following prompt: "When it comes to developing a combined solar and agriculture (agrivoltaic) project in your community, which of the following would you identify as concerns or reasons you would not support? (Please select all that apply)." The majority of respondents (47%) expressed that they were not concerned with any of the potential agrivoltaic development issues that were presented. The most frequently identified concern among respondents (35%) is related to unfair distribution of the project's economic benefits, which may reflect distrust in an equitable business model between developers and farmers. Visual impact of an agrivoltaic project ranks second in concern (19%), while all other factors listed were selected by less than 15% of respondents. Each of these reported percentages has a corresponding 7% margin of error.

To assess the social viability of the novel rabbit-based agrivoltaic concept advanced by this case study project and to inform potential mixed-use applications, survey respondents were prompted to rate if they believed rabbits are an appropriate source of meat on a 5-category

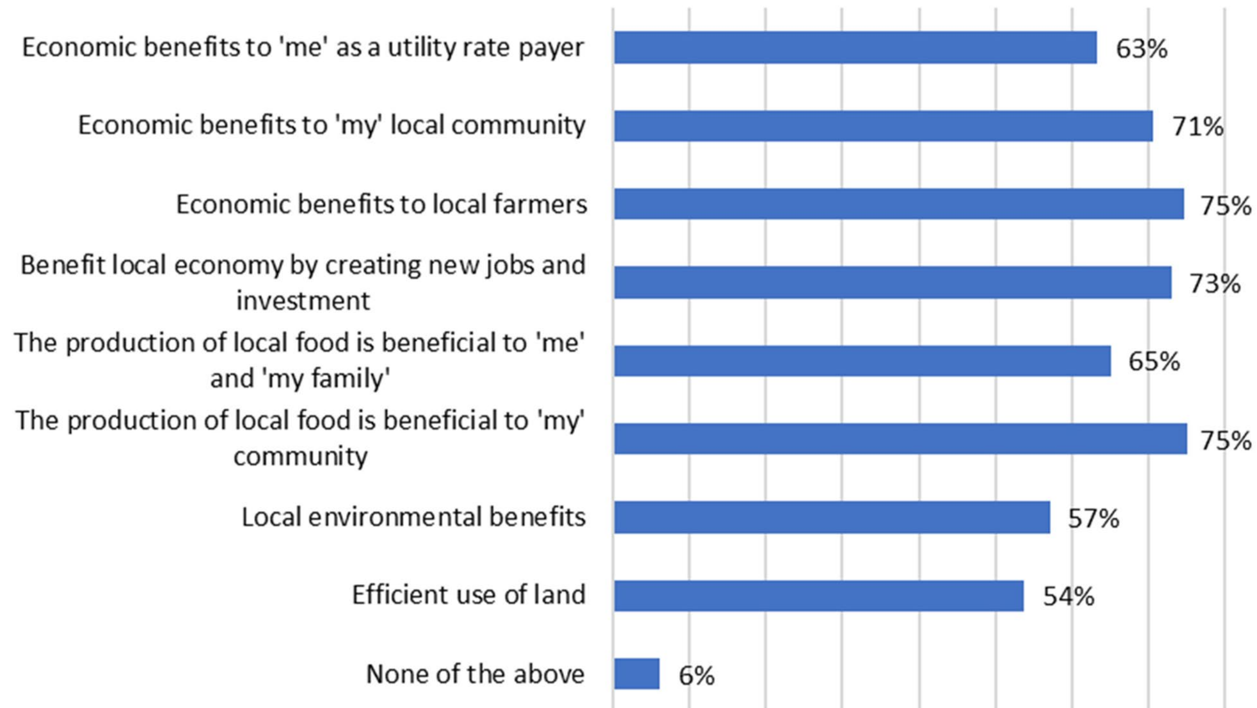

Fig. 4 Frequencies of identified benefits or reasons to support agrivoltaic development

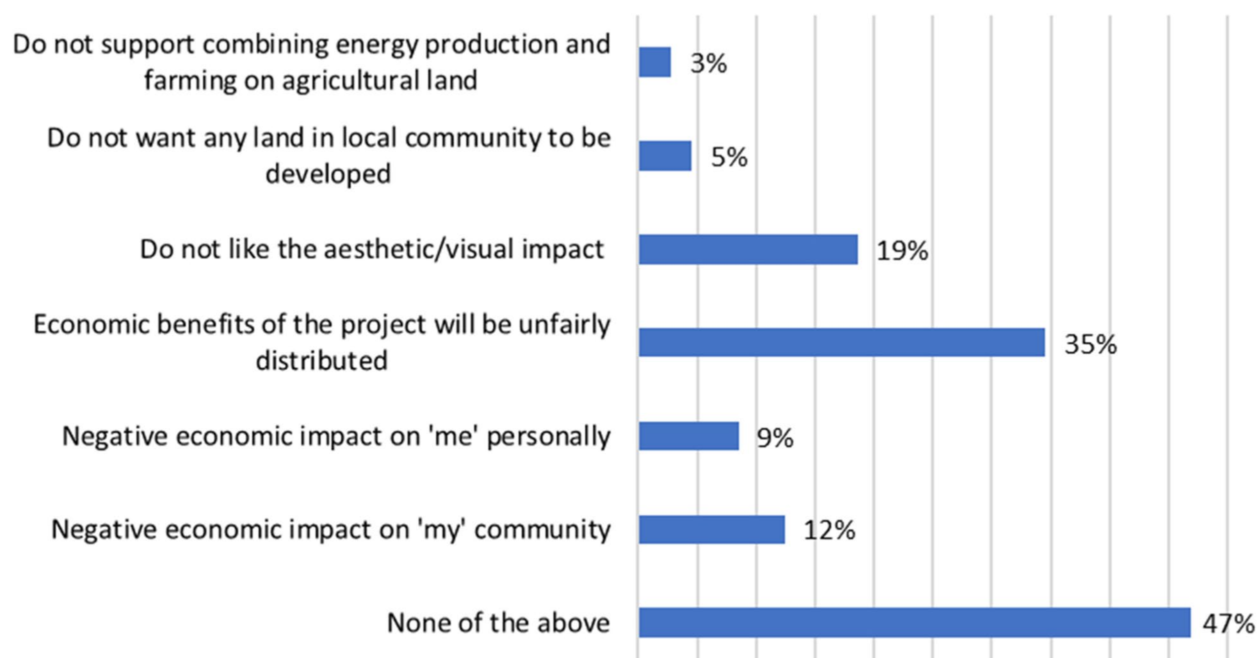

Fig. 5 Frequencies of identified concerns or reasons to oppose agrivoltaic development

Likert scale, and they were asked the following question: "Would you be more inclined to purchase rabbit meat for consumption if it were pasture raised in a combined solar and agriculture system?" A total of 44.4% of respondents agree or strongly agree that rabbits are an appropriate meat source, and 30.7% of respondents declared they would be more inclined to purchase meat that was raised in an agrivoltaic system. This result indicates public inclination towards agricultural products that are grown in conjunction with a solar system.

4.3 Identifying factors that significantly influence support

Multivariate logistic regression was used to investigate which sociodemographic variables, development factors, and perceived benefits and concerns have a statistically significant influence on marginal increase in support for agrivoltaics relative to conventional solar. Moving beyond comparisons of frequency distributions across development factors and planning priorities described in sections 4.1–4.2, this analysis approach was taken to detect the presence and strength of relationships between sociodemographic variables, development factors, and perceived benefits and concerns with respect to increased public support for agrivoltaics over conventional solar. The power of logistic regression is the ability to make logical inferences beyond the study sample, which informs broader trends in public perceptions about alternative solar development types and planning priorities that can be expected in communities with similar characteristics.

Multivariate logistic regression was necessary because the dependent variable (marginal change in support) was considered dichotomously (do not support and less likely to support = 0, more likely to support = 1). The two categories of "no" and "less" support were collapsed into one category for analysis to clearly distinguish between respondents who reported increased support given the agrivoltaic approach against those who have weak or no change in support for alternative solar development types. This dichotomous dependent variable was thus used to detect if the incorporation of an agricultural function to a local solar project increases public acceptance, which is of central relevance to the research purpose. Marginal increase in support for solar given the agrivoltaic approach was measured by prompting participants to answer the following question: "Would you be more likely to support a solar project near you if it combined the production of both energy and food?"

A regression model investigating the relationship between all measured sociodemographic variables and marginal change in support for local solar development given the agrivoltaic approach was constructed. Contrary to the anticipated influence of sociodemographic variables on public support for renewable energy suggested by previous survey research (discussed in subsection 3.4), the results of this analysis found that no sociodemographic variables have a statistically significant influence on increased support for solar given the agrivoltaic approach. The inability to detect any significant relationships between sociodemographic variables and increased support for agrivoltaics over conventional solar development may be a result of low survey response rate or small sample size.

Results of the regression model examining relationships between development factors with marginal change in support for local solar development given the agrivoltaic approach (Table 2) reveal that location on existing agricultural land ($p < .05$) or public property ($p < .05$) and project construction by a local company ($p < .1$) are statistically significant factors that impact support levels. A Nagelkerke R^2 value of 0.41 indicates that this model as a whole explains 41.1% of variance in increased respondent support for agrivoltaics. Individuals who denote project siting on existing agricultural land is an important factor shaping their support are 5 times more likely to experience increased support for local agrivoltaic development versus conventional solar ($\beta = 4.94$). This siting factor is significant at the 95% confidence level. Individuals who are opposed to development on public property are 4 times less likely to experience marginal increase in support for solar given the agrivoltaic approach ($\beta = 0.25$). This siting factor is significant slightly below the 95% confidence level (94.8%). Project construction by a local company was also found as a statistically significant development factor influencing change in support; every 1-unit increase in support for projects built by a local

Table 2 Logistic regression model summary: examining relationships between development factors with marginal change in support for local solar development given the agrivoltaic approach

Independent Variable	β[Exp(B)]
Development factors Visible from property	1.96
Located on land that is valued	0.79
On private property	0.89
On public property	0.25*
On existing agricultural land	4.94**
Benefits local environment	2.09
Benefits local economy	2.82
Income for famers	2.99
Built by local company	0.18*
Nagelkerke R^2	0.42
Constant	6.62

$N = 154$; *$p < .10$; **$p < .05$

company causes respondents to be 5.5 times less likely to experience marginal increase in support for solar given the agrivoltaic approach ($\beta = 0.18$). This factor is significant just below the 95% confidence level (93.6%). Given that this model is moderately strong (Nagelkerke $R^2 = 0.41$) in terms of ability to explain variance in changes in support for alternative approaches to solar development, variables that exhibit statistically significant influence on support up to the 90% confidence level should be considered meaningful for interpreting marginal increases in support.

Two separate regression models investigated the relationship between 1) perceived benefits and 2) concerns with changes in support for alternative development types. The result of the first model found no statistically significant relationships between perceived system benefits and increase in support for solar given the agrivoltaic approach. The results of the second model found that those who do not want any land in their community to be developed are 37 times less likely to experience changes in support levels for alternative development types ($\beta = .027$; $p < .01$). Respondents who were not concerned with any of the development factors presented are 11.7 times more likely to support agrivoltaics over conventional solar ($\beta = 11.71$; $p < .01$). This model resulted in an Nagelkerke R^2 value of 0.419, indicating the 41.9% of the variation in increased support for agrivoltaics relative to solar can be explained by concerns related to local agrivoltaic development. While these findings are intuitive, they indicate that resistance to local development far outweighs all other concerns when it comes to explaining changes in perceptions about alternative development types.

5 Discussion

This survey study provides an initial foundation for understanding public perceptions about agrivoltaic systems in the U.S. and identifies an increase in support for local solar development given the agrivoltaic approach. By determining what the public perceives as prospective opportunities or concerns related to agrivoltaic development, the results offer a novel contribution to discussions about social acceptance and pathways for increased deployment. A better understanding of how the public perceives agrivoltaic technology can help solar developers, policymakers, and land use planners work together to design projects that include community preferences and reduce concerns. Proactively identifying what the public perceives as opportunities and concerns related to agrivoltaic development can help improve the design, business model, and siting of systems in the U.S. These case study findings may be used to inform logical inferences about broader trends in public perceptions about alternative solar development types and planning priorities that can be expected in communities with similar characteristics.

The findings of this study provide further evidence that land use and land type are critical factors that shape the social acceptability of solar development, which is in alignment with relevant survey research [20, 92]. Schelly et al. [92] found that public perceptions about solar development are shaped by the type of land being replaced by a ground-mounted array, a finding that is confirmed by this study as results indicate strong public preference for projects not to be located on public property, whether or not it is a mixed-use system. Results also indicate that leveraging a single plot of land to provide two valuable functions (renewable energy and agriculture) generates an increase in support for local solar development; 81.8% of survey respondents indicated they would be more likely to support a solar project in their community that combines both energy and food production. This suggests that people perceive agrivoltaic systems more positively than conventional solar developments and highlights potential to increase support for solar among rural residents, who are most likely to host agrivoltaic projects. The results of this survey also reveal that individuals value that agrivoltaic projects can provide economic benefit to farmers, create local jobs and investment, and empower the production of local food, which implies the importance of prioritizing these factors in the planning process to increase public support and promote community acceptance [80]. Based on the factors identified as important when planning for agrivoltaic projects (Fig. 3), being deliberate in providing economic opportunities to farmers and the local community in the form of jobs will be influential in gaining public support for a project. Because results reveal that the main concern with agrivoltaic projects is related to the distribution of economic benefits, which was also found by Schelly et al. [92] regarding solar in general, developers seeking receptivity from a community will need to ensure transparency in the planned business model in order to minimize public concerns with distributive justice.

When comparing factors of importance between solar and agrivoltaic projects, nearly identical trends in perceptions are observed. The key factors found to shape support for both solar and agrivoltaics are related to economics, suggesting that communities are most interested in the financial aspects of local energy development. Because the same factors remain important to respondents when conceptualizing their support for solar or agrivoltaic development in their community, the findings of previous survey studies on perceptions about solar [18–20, 92] provide logical representation of perceptions about agrivoltaics. The similar trends in perceptions about solar and agrivoltaic projects is valuable for continued efforts to understand and accommodate societal concerns in the deployment of agrivoltaic projects.

The results of this study align with previous research that acknowledges support for renewable energy is far more nuanced than the simplistic NIMBY theory suggests (e.g., [24]). Because responses reveal perceptions vary according to land type, siting, and financial models, it will be critical to account for these nuances in perception in the agrivoltaic planning and development process to minimize public opposition. Soliciting feedback from the public and incorporating their values and concerns in project development can increase social acceptance [55] and help solar developers design successful projects.

There are some limitations to this research. First, this survey used a general conceptual model to gauge public support for agrivoltaics rather than denoting a specific location in respondent's communities, which limited the ability to capture the effect of place-attachment or proximity on public perception. Future work could address this limitation by providing context-specific detail about a proposed development to capture responses that that are more anchored in place and reflect sentiment towards places of community value, which may help guide regionally-specific agrivoltaic siting practice. In addition, the type of materials used for agrivoltaics could be questioned. For example, recent research indicated that sustainable wood-based racking for agrivoltaics systems may also provide an economic advantage in North America [106, 107]. These types of racking systems could be fabricated in some areas by local materials by local workers that may provide an additional avenue to social acceptability but would need to be explored by a more granular study. Similarly, the public's views on different types of racking geometries could be explored. For example, recent work has indicated that vertical bifacial PV is ideal for some types of agrivoltaics as conventional farm equipment can navigate between the rows [17, 54, 89, 90]. There are also proposals for monofacial PV to be used on existing fences to act as windbreak to provide shelter from the wind and to protect soil from erosion, which are both lower cost than conventional racking and less intrusive [48]. Future work could address some of these issues by showing images of the various agrivoltaic geometries [118] to determine the impact of geometry and aesthetic on public acceptance of agrivoltaics. In addition, the public may be more willing to accept agrivoltaics if they are familiarized with it on the small scale, such as with agrivoltaic cold frames, which have recently been developed [82].

This study focused specifically on land-based PV, however, the same study could be repeated for the burgeoning field of floating PV (or floatovoltaics) [30, 46, 60] with aquavoltaics, which is another approach to maximize surface area utility by combining PV with aquaculture [51, 85]. There is already evidence that this form of PV has the potential to be environmentally superior to the land-based PV [47], which may impact public perception.

While this survey used rabbit-based agrivoltaics as an example to help respondents conceptualize a livestock-based project in their community, it is beyond the scope of this paper to give full treatment to the data collected pertaining to perceptions about rabbits. Future research on public perceptions about agrivoltaics could consider that livestock-based applications add another dimension to social acceptance of these systems, as they entail not only land use and solar development, but meat production and consumption as well. Comparing levels of support for alternative agrivoltaic project types (i.e., crop versus livestock) could identify which sorts of applications are more favorable and less likely to invoke opposition, which may help solar developers better appeal to a community as they pursue mixed-use systems.

5.1 Policy implications

The findings of this survey study can be used to provide guidance for developers and local governments seeking increased deployment of agrivoltaics as they inform the siting, planning, and design of land use policy that prioritizes public preferences and concerns in development. Effective land use policies that intentionally allow solar on designated farmland can be formulated by considering what development factors are important to the public (economic opportunities to farmers and local economy, land type) and what issues are perceived as the biggest concerns (threat to local interests, distribution of economic benefits). As the costs of solar PV have plummeted [37], it is now often economically favorable to replace cash crops like tobacco with PV farms [59]. Although it is a net benefit for society to eliminate tobacco production [115], this is not the case when renewable energy displaces food, which can raise prices and increase hunger of the impoverished [72]. Agrivoltaic systems represent a sustainable solution to this land use constraint [71]. Fortunately, the results of this study indicate that respondents prefer solar projects that are designed to provide multiple benefits. The results also show that respondents prefer solar projects not be located on public property, which can directly advise land use planners in developing agrivoltaic siting criteria. Further, proactively avoiding threat to local interests and priorities was identified as extremely important among respondents when planning for agrivoltaic projects; this highlights the importance of including the public in the planning process to meaningfully incorporate existing agricultural practices in system design and to ensure that the project represents the interests and identity of the host community. Addressing concerns about unfair distribution of project benefits could include the establishment of contracts between solar developers and farmers that are accessible to the public and outline costs and compensation for both parties [81].

Given that local governments have ultimate jurisdiction over energy siting, zoning strategies and land use polices can be leveraged as the most formidable catalyst to facilitate agrivoltaic development in the U.S. [78]. Communities can frame solar development as a means to serve existing goals such as economic growth or farmland preservation by amending or designing zoning regulations that are explicitly permissive of solar [64]. Becker [10] offers examples of such zoning ordinances. To ensure that economic opportunities for farmers are prioritized in solar development, local governments may consider being permissive of solar on farmland if the system meets conditional requirements related to retaining the agricultural function of the land beneath the panels. By designing solar system standards, local governments can influence agrivoltaic development practice in a way that ensures these systems are located on existing farmland or private property and do not compromise agricultural productivity, therefore providing direct economic benefit to farmers. Minimizing development impacts on long term land productivity and providing compensation to farmers will be critical in supporting the deployment of agrivoltaic systems [81], which indicates the need to incorporate these considerations in the design of agrivoltaic projects and policies. Local regulations that are permissive of solar set the initial foundation for communities to further consider the specifics of what type, what scale, and where projects can be developed. It is common for local governments to formulate different zoning requirements that are contingent on the type of development; zoning to allow for agrivoltaics would require land use planners to consider confining projects to certain districts, set standards for decommissioning, and provide flexible site requirements based on the proposed system duration and type [78]. The use of overlay districts may be the most straight-forward policy tool available to land use planners who wish to allow agrivoltaics yet be strategic in controlling the siting of projects. The New York Solar Energy Research and Development Authority (NSYERDA) offers instructions for municipalities to advance solar development while protecting farmland by using special use permits [76].

Local level land use policies that accommodate solar energy siting on agricultural land will be critical to the deployment of agrivoltaic systems. Planners and developers may consider the findings of this survey when they pursue agrivoltaic development; analysis of the survey results indicate that being deliberate in siting these systems in places that are less likely to elicit opposition (private property and farmland), incorporating existing local interests, and prioritizing benefits to farmers and the local economy will be consequential in gaining host community acceptance. Because this study found an increase in support for solar given the agrivoltaic approach, policymakers wanting to encourage low-carbon energy development and solar developers that are challenged with PV siting could simultaneously increase public support and the deployment rate of solar by pursuing agrivoltaic projects.

6 Conclusions

This survey study assessed if public support for solar development increases when energy and agricultural production are combined in an agrivoltaic system. Results show that 81.8% of respondents would be more likely to support solar development in their community if it integrated agricultural production. This increase in support for solar given the agrivoltaic approach highlights a development strategy that can improve local social acceptance and the deployment rate of solar photovoltaics. The key factors identified as most important to respondents in terms of agrivoltaic development in their community include income opportunities for farmers and local economies, siting considerations related to land type (i.e., private versus public) and visibility, and distribution of project benefits, which are comparable to the most important factors related to supporting solar in general. Survey respondents prefer agrivoltaic projects that a) are designed to provide economic opportunities for farmers and the local community b) are not located on public property c) do not threaten local interests and d) ensure fair distribution of economic benefits. These results offer an opportunity to increase solar PV deployment in a manner that produces valuable co-benefits for host communities and to refine local land use policy to support increased agrivoltaic development - an opportunity that should not be neglected, given eminent environmental and societal challenges related to growing energy and food demands, land use constraints, and climate change.

Supplementary Information

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Additional file 1. Complete Survey Protocol.

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Authors' contributions

Conceptualization, A.S. P. and C.S.; methodology, A.S.P., C.S., and M.R.; validation, A.S.P., C.S., and M.R.; formal analysis, A.S.P.; investigation, A.S.P.; resources, C.S. and J.M.P.; data curation, A.S.P.; writing—original draft preparation, A.S.P.; writing—review and editing, A.S.P., C.S., M.R. and J.M.P.; supervision, C.S. and J.M.P.; project administration, J.M.P.; funding acquisition, C.S. and J.M.P. The author(s) read and approved the final manuscript.

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Declarations

Competing interests

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