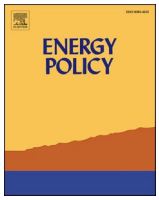
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Regional dynamics of agrivoltaics adoption: Stakeholder perceptions and barriers in Maryland, USA

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A B S T R A C T

Agrivoltaics is touted as a win-win practice that combines agricultural production with solar energy production on the same land. Despite a promising list of associated benefits, previous research documents significant adoption barriers. Prior national-scale studies leave space to identify local or regional factors influencing agrivoltaics practice. Adoption of a novel technology ultimately requires behavioral changes that are shaped by knowledge, attitudes, and practices (KAP). We conducted a series of focus groups to assess the KAP factors of different sectors that shape agrivoltaics in Montgomery County, Maryland. Participants completed a visual survey to assess their interpretation of agrivoltaics. Through these measures, we provide a local and regional understanding of agrivoltaic interpretations, knowledge, attitudes, and practices. Our results indicate a lack of a consensus definition of agrivoltatics, but highlight a strong preference for systems involving crops or grazing livestock over pollinator habitats. Benefits identified by participants reflect key environmental concerns around climate and greenhouse gases, but also extend to economic stability and resilience, and land tenure security. Focus groups revealed skepticism about the applicability of global agrivoltaic research to local contexts. Participant skepticism also reflected the complex socio-enviro-technical aspects of renewable energy transitions. Our results underscore the need for region-specific strategies and educational initiatives (in this case, the mid-Atlantic, USA) to address stakeholder perceptions and facilitate implementation. The social factors identified using an engaged KAP approach is critical for reaching renewable energy goals with the needs and desires of local stakeholders, practitioners, and communities.

1. Introduction

Agrivoltaics grew from the idea that crop production and solar power production could occur on the same tract of land (Jamil and Pearce, 2023). This practice ranges from "solar sharing" systems that marry crop production and solar power production (Tajima and Iida, 2021; Dupraz et al., 2011)) to expanded dual-use models of "cattle-voltaics" or "eco-voltaics." Agrivoltaics has the potential to provide multiple benefits across the Food-Energy-Water Nexus through alterations of ecosystem energetic and water fluxes that result in photovoltaic and ecophysiological efficiencies (Barron-Gafford et al., 2019; Trommsdorff et al., 2021; Malu et al., 2017). With proper design and implementation, agrivoltaics has the potential to address several of the UN Sustainable Development Goals (Ghosh, 2023; Pandey et al., 2025). Recognizing this potential (Adeh et al., 2019), international and local agencies are exploring the inclusion of agrivoltaics in their renewable energy and carbon emissions reduction strategies (Chatzipanagi et al., 2023; ICARDA, 2024; Sutton et al., 2024). In the USA, the potential for agrivoltaics is strong, with the American Farmland Trust (Hunter et al., 2022) estimating that up to 83 % of new photovoltaic solar installed in the USA could be on farmland. By 2040 an additional 40,000–81,000 ha of photovoltaic solar could be added in mid-Atlantic states (DOE, 2021). The State of Maryland estimated that between 3140 and 13,368 ha of farmland (0.4 % and 1.7 % of all agricultural land in the state) would be needed to site photovoltaics to help meet state energy targets (Maryland, 2020). However, the actualized contribution of agrivoltaics will be the result of the interaction of technical factors, such as system design (Toledo and Scognamiglio, 2021; Warmann et al., 2024) and feasibility within specific climates (Widmer et al., 2024), and socio-economic barriers to implementation (Pascaris et al., 2020, 2026; Torma; Aschemann-Witzel, 2023; Moore and Lobell, 2024; Bukchin-Peles and Eitan, 2025; Hu, 2024).

The context and conditions where dual land use can secure community support for solar power is a critical social-science gap in agrivoltaics research and practice (Moore et al., 2022). Importantly, discussions about agrivoltaics implementation is hampered by the variety of names assigned to dual-use systems and arrangements (Willockx et al., 2020). Therefore, it is crucial to specify what agrivoltaics means early in the adoption process (de Falco et al., 2025). For example, in a study of European farmers, participants were divided over whether

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agrivoltaics should be interpreted narrowly or broadly, as "pseudo" agrivoltaic installations could harm the concept's reputation (Torma and Aschemann-Witzel, 2023). This concern is shared throughout the agrivoltaics community (Agir et al., 2023; de Falco et al., 2025). To encourage widespread adoption and consolidation across, Peña-Calzada et al. (2024) suggested using a consensus definition, adapted to each country. It is likely that regional or local adaptations of what is defined as agrivoltaics will be necessary in countries with vast geographical and climatic differences. However, we are unaware of any national, regional, or local studies that assessed interpretations to guide this in practice.

Policies also play a critical role in shaping the adoption of agrivoltaics, (Pascaris, 2021; Jamil and Pearce, 2023; Bosman et al., 2024). Agrivoltaic policies can simultaneously facilitate and hinder deployment (Pascaris et al., 2026). For example, policies focused on reducing yield losses or stringent design requirements may negatively impact progress. Agrivoltaic systems in Japan are required to maintain a minimum agricultural yield; and farmers are required to produce detailed yearly yield reports to remain in compliance with solar permitting requirements. Some argue that Japan's yield reduction restriction acts as a barrier to expansion because it causes farmers, investors, and financial institutions to be hesitant to try innovative agrivoltaic technology and practices (Doedt et al., 2023). Stakeholder assessments of the Massachusetts SMART Program concur with this discourse and criticize costly photovoltaic (PV) panel specifications that must be addressed to qualify for tariff-based incentives (Pascaris et al., 2026). For example, Williams et al. (2025) pointed out that the SMART Program's panel height requirements do not take into account scenarios where farming only occurs between panel rows. As a result, the paper's authors recommend incentive policies that are inclusive of "between row" systems. Taken together, critiques of these policies and of the critiques themselves suggest that stringent technocratic requirements limit innovation, increase liability and financial risk, and discourage stakeholders from investing in unproven, and potentially unnecessary, PV design adjustments. Instead, researchers suggest implementing policies that focus on facilitating land-use conversion, construction best management requirements, reducing permitting headaches, providing financial incentives, funding research and education, and promoting community and stakeholder engagement (Pascaris, 2021; Tajima et al., 2022; Jamil and Pearce, 2023; Macy et al., 2025).

Adoption of a novel technology, such as agrivoltaics, ultimately requires a behavioral change, and it is the knowledge, attitudes, and practices (KAP) of practitioners that shape the adoption of sustainable agricultural practices (Liao et al., 2022). Liao et al. (2022) identified multi-level social and environmental factors that influence the evaluation of new practices and the diffusion and learning about new technologies. Often KAP of practitioners are influenced by social and environmental factors that are tied to their place of origin and local contexts. For example, Seay-Fleming et al. (2025) described how water scarcity influenced land-use transformations in Pinal County, Arizona over the last 40 years. Here, speculative investors consolidated farmland after capitalizing on farmers' urgency to sell land. Some of those investors entered lease agreements with solar companies who operate(d) utility-scale solar projects. Seay-Fleming et al. (2025) argued that energy companies operating in Pinal County are less likely to implement agrivoltaics despite stated intentions. Therefore, they conclude that the socio-economic and environmental conditions of the area give rise to the opportunity for agrivoltaics to be used as a greenwashing scheme. Political and social factors may also interact to affect practitioner KAP related to agrivoltaics. Hu (2025) describes China's centralized government, fueled by domestic food and energy security concerns, initially drove implementation without regard for the social acceptance process. China's agrivoltaics policies resulted in exceptionally large-scale projects initiated by energy corporations and local governments. Hasty implementation created feelings of social injustice and resulted in the eventual suspension of new agrivoltaic projects on farmland. As farmer's KAP of sustainable agriculture are driven by interactions of environment, perceptions, existing institutions, and policies, community engaged outreach and education programs may be necessary to overcome these systemic barriers (Liao et al., 2022).

The early literature on agrivoltaics KAP serve as cautions. Despite the promise of agrivoltaics to ameliorate food, energy, and land-use challenges, it can exacerbate resistance to solar projects if pursued without an understanding of an area's environmental, economic, political, and social factors. Thus, Torma and Aschemann-Witzel (2023) stressed the need to investigate perceived adoption barriers and drivers to inform decisionmakers and enhance stakeholder perceptions. Moore et al. (2022) argue that agrivoltaics is often approached as a 'technological fix' without consideration of stakeholder KAP. They identify KAP work as a research priority to support a collaborative and perhaps more equitable pathway to adoption, emphasizing collaboration and input from farmers and other practitioners to understand attitudes, perceptions of feasibility, and their understanding of costs and benefits. However, there are very few local or regional agrivoltaics social science studies for decisionmakers to draw from. In the U.S., for example, most studies focus broadly on national-scale attitude, practices, and policy (Pascaris et al., 2020, 2021, 2022, 2023a; Moore et al., 2022; Goldberg, 2023). The few exceptions focus on specific geographies (i.e. the Southwest (Swanson et al., 2025; Seay-Fleming et al., 2025) or tribal lands (Moore and Lobell, 2024)) or specific themes (i.e. environmental justice) that do not report the practice of agrivoltaics (Spangler et al., 2024). Such studies do point to the role different land, climate, and social contexts play in agrivoltaic adoption and highlight the importance of local and community based participatory research for understanding these dynamics. However, such local and community based participatory research to explore context-specific barriers and opportunities for agrivoltaics KAP is still in a nascent state.

These examples highlight that KAP studies must be conducted to determine local and regional agrivoltaic factors that affect adoption if realizing the potential for agrivoltaics to solve land-use conflicts, provide clean energy, and improve agronomic outcomes will be realized. Our goal here is to describe the KAP of local practitioners and decisionmakers with respect to agrivoltaics adoption. We ask in this study, (1) what are the KAP factors that shape agrivoltaics in the Mid-Atlantic, USA, and (2) how do these KAP factors vary by stakeholder group that participate in decision-making around agrivoltaics. We seek to establish an understanding of how agrivoltaics is interpreted and defined in the Mid-Atlantic to provide a first of its kind study in this temperate setting and provide an example of applying KAP approaches and models for researchers in other contexts. In doing so, this research assesses how farmers and landowners, advocacy groups, county government officials, and employees the solar sector: (1) balance the ethical, cultural, environmental, political, economic, and logistical tensions of co-locating photovoltaic solar on farmland, (2) perceive the benefits of agrivoltaics to their practice, communities, and landscapes, and (3) perceive the integrated barriers to adoption of this technology.

2. Methods

2.1. Study setting: Montgomery County, Maryland

To answer our questions, we focused on Montgomery County, Maryland, where land conflicts are intense due to prioritization of both solar power development and farmland preservation. Maryland has among the most ambitious renewable energy goals of any state per its Renewable Energy Portfolio Standard Program (RPS). The RPS requires renewable energy sources for 52.5 % of the retail electricity sold in Maryland by 2030. To reach this goal, the RPS put in place a "solar carveout" implying that 14.5 % of electricity sold in Maryland would have to be generated by photovoltaics (Bond and Foxworth, 2024). In addition to the State's renewable energy goals, Montgomery County seeks to eliminate greenhouse gas emissions by 2035 by turning to renewable energy sources.

Due to its proximity to Washington D.C., Montgomery County is home to approximately 1.06 million people and ranks forty-forth out of 3144 U.S. counties for total population ("United States Census Bureau," 2020). Development is concentrated in the urbanized south as opposed to the rural north, where it is limited by an assortment of zoning policies and farmland protection programs to encourage agriculture. These policies came together in 1980 to create Montgomery County's Agricultural Reserve (Ag Reserve), an area prized for its agricultural heritage and recreational opportunities. As it stands today, the Ag Reserve comprises one third of the county.

Most of Montgomery County's 583 farms are located in the Ag Reserve ("Census of Agriculture - State and County Profiles," 2022). The average size of these farms is 120 acres, 92 % are family owned, and 56 % of the land in farms is rented (Maryland State, 2024). Regionally, climate is temperate mid-Atlantic maritime influenced, with hot humid summers and cool winters. Mean annual temperature for Montgomery County, MD is 13.3 °C, with daily summer mean of 22.7 °C (highs of 31.7 °C), and daily winter mean of 2.8 °C (lows of −1.1 °C) (NOAA National Centers for Environmental information, 2025). Mean annual precipitation in the county is 1090 mm/year and is evenly distributed throughout the year (NOAA National Centers for Environmental information, 2025). Dominant crops (determined by the number of acres in production) include soybeans, corn, hay, wheat and sod. Livestock, poultry, and animal products account for only 6 % of overall agricultural sales ("Census of Agriculture - State and County Profiles," 2022). Intense development in the late 20th century, led Maryland to enact the first property tax relief program in 1956 to protect remaining farms. In doing this, Maryland became the nation's leader in farmland preservation doctrine (Freedgood et al., 2020). Twenty years later, Maryland and Massachusetts became the first states to authorize Purchase of Agricultural Conservation Easement (PACE) programs that protect more than 4.1 million acres across the U.S. (Looser, 2024). In 2017, Maryland again ushered a novel farmland protection measure when it passed the Next Gen Farmland Acquisition Program, a program that facilitates farmland transfers to a new generation of farmers. Although Maryland generally gets credited for designing these unprecedented policies, Montgomery County often served as the thought-leader and its farmland preservation policies and Ag Reserve are studied by researchers at home and abroad (Tang and Liu, 2013; Fang, 2021).

These goals, combined with farmland preservation attitudes and policies, heavily influence solar development in Montgomery County. However, agrivoltaics have not materialized in a significant way despite an effort to address the emerging systems in Montgomery County Zoning Text Amendment 20-01 (ZTA). The goal of the ZTA was to expand solar development while protecting the environment and Ag Reserve by increasing the size of solar collection facilities and capping development in the Ag Reserve to 1800 acres. The amendment enumerated the requirements for Conditional Use permits for solar facilities that generate $>$200 % of on-site energy use and $<$2 MW, as long as: (1) sites are not constructed on USDA Class I or Class II soils, in stream buffers, on wetlands, or on slopes $\geq$15 %; (2) topsoil is not scraped or removed and grading is minimized; and (3) the area under the solar facility is either actively maintained as designated pollinator-friendly habitat, grazed, or used for agrivoltaic plant material. As of this writing, only two projects have been permitted in Montgomery County's Ag Reserve. Combined, they take up 20.57 acres—nowhere near the county's 1800-acre limit.

To ensure that state energy goals would be reached, the Maryland General Assembly passed The Renewable Energy Certainty Act in May 2025. The law streamlined the process for solar development and siting standards across the state. Beginning July 1, 2025, local solar siting policies for sites $\geq$1 MW cannot be more restrictive than those enumerated in Statewide policy until construction has occurred on 5 % of a local government's priority preservation areas, which includes the Ag Reserve. As a result, Montgomery County's 1800-acre solar limit expanded to 4650 acres and its 2 MW limit and prime soil ban became unenforceable. To incentivize agrivoltaics, the State lifted boundary restrictions; fencing restrictions; landscaping buffer and vegetative screening requirements; and visual impact restrictions for sites implementing agrivoltaics. Finally, the bill restricted the definition of agrivoltaics by excluding apiaries or pollinator habitat but left in place other policies that support agrivoltaics. Those policies include a solar tax incentive policy (Md. Code, TP § 7–237), which offers agrivoltaic sites a tax exemption in the form of an agricultural use assessment, and a policy that addresses decommissioning (Md. Code § 27.01.14.05). It requires a Decommissioning Plan and a bond or letter of credit to cover costs as part of the permitting process.

2.2. Data collection and analysis

KAP studies typically use questionnaires to assess what is known, believed, and practiced within a study area (Liao et al., 2022; Moore et al., 2022). We assessed the KAP of four stakeholder groups through a web-based visual survey and a series of in-person focus group interviews. We chose to utilize focus groups in this research because discussion and dialogue in this setting can allow a better understand of participant feelings and perceptions that result from open-ended conversations relative to survey instruments (Drimie et al., 2021). Stakeholder groups included: Montgomery County farmers and landowners (2 groups, 9 participants); Montgomery County advocacy groups and non-profits (1 group, 8 participants); Montgomery County government officials (1 group, 11 participants from 7 county organizations); and individuals who work with the solar sector or are employed by the solar sector and have an interest in expanding agrivoltaics in Montgomery County (1 group, 6 participants). Initially, we recruited participants identified by Montgomery County collaborators. After contacting them, we reached out to stakeholders identified either through snowball sampling or online research of prominent Montgomery County environmental, agricultural, and solar organizations.

Thirty-two of the thirty-four focus group participants completed a web-based visual survey prior to the start of their assigned focus group meeting. Agrivoltaic systems were conceptualized broadly to capture participant KAP to explore the potential for application and adoption. System components included ground, stilt, and building mounted panels, inverters and transformers, potential battery use, and systems were discussed both from the perspective of contributing electricity to grid system and on-farm use. The survey assessed individuals' interpretation of the term "agrivoltaics" through a series of pictures that depicted different combinations of specialty crops, commodity crops, grazers, apiaries, or pollinator habitat; AND photovoltaic panels that were either ground-mounted, stilt-mounted, vertically mounted, or mounted on a rooftop within an agricultural setting. Additionally, the survey included questions about participants' stakeholder affiliations, advocacy interests, and environmental concerns (see Appendix).

To further assess stakeholders' interpretation of agrivoltaics, associated feelings, and perceptions of opportunities and barriers, we conducted focus groups interviews in August and September 2024. Each meeting represented one of the four stakeholder affiliations described above. Groups discussed a series of general questions, followed by questions specific to their dominant stakeholder affiliation (see Appendix). We used video recordings to generate transcripts, which we later anonymized. In December 2024, we uploaded transcripts to ATLAS.ti Web, a cloud-based qualitative data analysis software program, to organize, analyze, and visualize participant responses. From there, we manually coded each transcript based on themes that emerged during group discussions. The following month, we used the program's Conversational AI tool (powered by OpenAI models) to summarize select codes.

3. Visual survey results and discussion

Participants included 10 landowners, 9 of whom called themselves farmers. Roughly half (53.1 %) of the survey-takers belonged to an

advocacy group who focused primarily on either agriculture (8), environmental stewardship (5), or solar energy (4). They overwhelmingly cited climate change and its effects as one of their top three environmental concerns (Fig. 1). Concerns over air and water pollution and fossil fuels/the production of greenhouse gasses also ranked high. Despite the attention often paid to food security and soil health in local solar siting discussions (personal observation), these concerns ranked much lower in frequency.

Survey results revealed that all but one survey-taker was familiar with the term *agrivoltaics*. While the majority had an overall positive impression of it (Fig. 2), there were discrepancies in how participants interpreted agrivoltaics based on what occupied the land. When pictures clearly depicted crops or grazers (sheep or cattle) and PV panels, a respective average of 90 % and 89 % answered *yes* to the question: *Is this an agrivoltaic system?* A picture of cattle gathered under PV panels was the only picture to receive unanimous *yes* answers. Overall, pictures depicting pollinator habitat or evidence of bee-keeping generated fewer *yes* answers. For example, only 26 % of participants selected *yes* when shown a picture with bee-boxes in the foreground and solar panels in the background. The percent increased slightly to 36 % when the picture included a beekeeper inspecting beehives. Among pictures showcasing pollinator habitat, a picture of a field in bloom received the highest percent of *yes* answers (55 %) among pictures depicting pollinator habitat. These results demonstrate that Montgomery County stakeholders strongly and consistently consider solar systems that include crops or grazers, agrivoltaic systems. However, they do not feel the same way about pollinator-only solar systems. To shift opinions, educators could consider learning opportunities timed to coincide with peak bloom and educational materials that capture it.

Not only did the type of agricultural activity depicted in photos influence a person's interpretation of *agrivoltaics,* whether that activity was obvious was a factor. For example, the survey included two pictures taken at the same solar-grazing site (Fig. 3). One picture included sheep, but the other did not. *Yes* answers decreased from 90 % to 16 % when sheep were absent from the picture. In addition, a preference for familiar or long-term grazing practices likely affected participants' perception of solar-grazing pictures. For example, the number of *yes* answers dropped to 77 % when a picture of sheep grazing in a solar array included a shepherd in a hard-hat and a trailer in the background. Due to the limited number of survey pictures, it is not clear which factor or whether both factors influenced responses.

Differences in racking systems (ground, stilt, and vertical) did not influence participants' interpretation of *agrivoltaics*. However, they overwhelmingly rejected a picture of rooftop solar within an agricultural setting (only 16 % answered *yes*), indicating that PV panels mounted on storage facilities or arenas would not be an acceptable interpretation of *agrivoltaics*. It is unclear how survey-takers felt about the use of semi-transparent PV panels on greenhouse structures since the visual survey did not include pictures of the aforementioned. However, participants overwhelmingly responded with *yes* answers (90 %) to a picture of a semi-transparent PV system over fruit trees, which indicates that orchards or nurseries would be good locations for promoting agrivoltaics in Montgomery County.

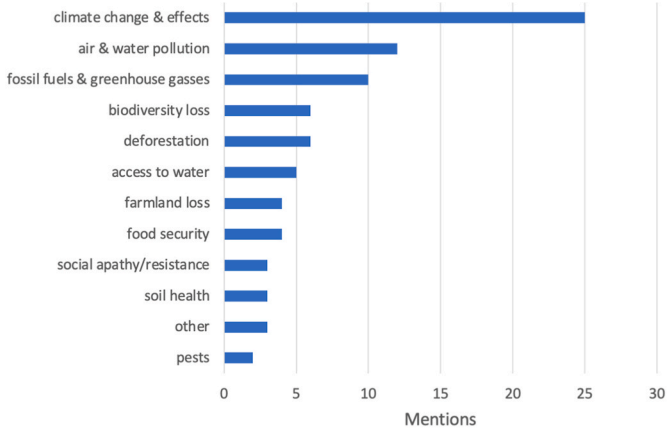


Fig. 1. Montgomery County, MD stakeholders (n = 32) were asked to list their top three environmental concerns. Responses were categorized based on themes. Bars in this graph represent the number of times themes were mentioned.

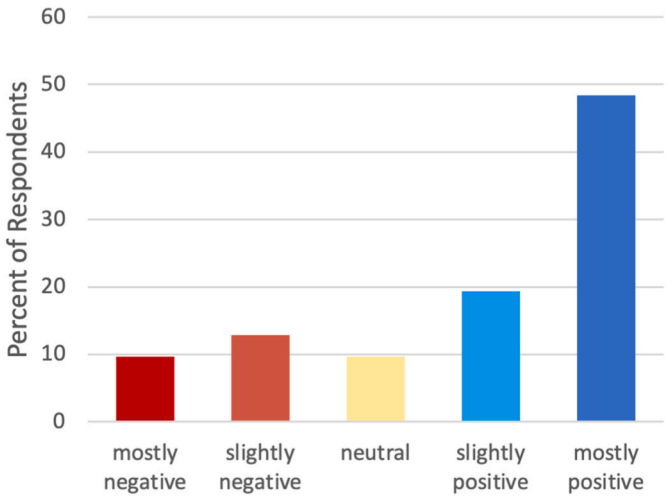


Fig. 2. Participants were asked to rate their overall thoughts and feelings on agrivoltaics on a five-point Likert scale, ranging from mostly negative to mostly positive. Results are presented based on the percent of respondents who selected each category.

4. Focus group results and discussion

4.1. Defining agrivoltaics

Focus groups spent a considerable amount of time discussing the definition of agrivoltaics and acknowledged that a firm consensus did not exist. Participants from each group expressed that agrivoltaics should involve measurable agricultural production in conjunction with solar energy production.

Pollinator Habitat: Those holding this view generally excluded the creation and preservation of pollinator habitat from their interpretation of agrivoltaics because it was not perceived as a genuine agricultural activity. These feelings were reflected in the results from the visual survey discussed above since the average number of *no* answers for pictures of solar-pollinator habitat was 61 %. It is important to note that the focus group meetings were held before the Renewable Energy Certainty Act was introduced. This means that the eventual exclusion of pollinator habitat and beekeeping activities from the state's definition of agrivoltaics did not influence participants' viewpoints. Therefore, the results of this study indicate that Montgomery County stakeholders will generally support Maryland's new definition of agrivoltaics which excludes pollinator habitat and bee-keeping activities. Consensus may help reduce stakeholder resistance to agrivoltaics and facilitate productive conversations moving forward (Willockx et al., 2020).

Solar Grazing: Many participants held the opinion that *raising* or *grazing* livestock on agrivoltaic sites are the most practical approaches to immediate implementation of agrivoltaics in Montgomery County. A variety of perspectives on the integration of grazing with solar energy systems arose from county officials and advocates even though participants largely agreed upon solar-grazing as an acceptable, often preferred, form of agrivoltaics. Differences in opinions were based on how much time grazers spend on solar sites; but it is unclear how many

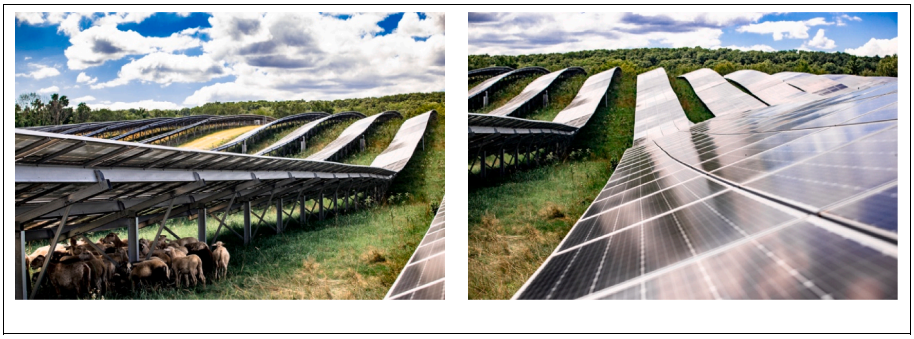


Fig. 3. These pictures were included in the visual survey, courtesy of the AgriSolar Clearinghouse. They were taken at the same location. One includes sheep, the other does not. Participants were asked, "Does this image depict an agrivoltaic system?" for each picture. They were given "yes" and "no" options for answers.

participants held conditional views of grazing. Some county officials and advocates were concerned that temporary grazing management plans were more akin to land management plans than true agricultural production plans. As one county official put it:

> *We've heard about an example of somebody who could just bring sheep around, and they could graze. To me, you could think of someone who brings sheep to graze around panels as not agricultural activity, but just a better form of lawn mowing.*

Torma and Aschemann-Witzel (2023) found that solar-livestock combinations on good soil are perceived as a loss of arable land for productive crop cultivation. This line of thinking elicited concerns that agrivoltaics could be used as a greenwashing scheme. Vaughan et al. (2019) provided evidence that solar grazing elicits fear of greenwashing in other places and suggested defining agrivoltaics as a precautionary method to avert negative perceptions. Since grazing was included in the Maryland's definition of agrivoltaics at the time the interviews took place, our results indicate that clarification of grazing practices may be a helpful addition to current policy to address stakeholder concerns.

Crop and Food Production: Participants largely supported agrivoltaic systems that produce crops and food. However, many participants were unconvinced that agrivoltaics could be integrated with commodity crops. County officials and farmers reasoned that fruit and vegetable farms would be better suited for agrivoltaics. Justifications fell into two categories. First, participants believed that standard commodity farming practices (i.e., the use of large, motorized equipment) could not be executed under solar panels, whereas practices associated with fruit and vegetable farms would be less likely to be impacted by the physical constraints imposed by solar arrays. Commodity farmers remained skeptical even when vertical panel systems were mentioned. Second, participants—especially farmers—felt like fruit and vegetable farmers would receive more benefits from implementing agrivoltaics than commodity farmers. Those benefits included the use of electricity produced onsite to power cold storage or irrigation systems; shading benefits for crops, animals, and workers; crop protection from extreme weather vis-à-vis solar panels; and perimeter fences, rebranded "deer fences" by farmers, to reduce wildlife predation.

4.2. Perceptions of benefits and barriers

Someone from each group suggested that agrivoltaics could diversify the agricultural products produced in Montgomery County, which are a currently dominated by commodity crops. County officials and advocates were hopeful that a higher degree of crop diversity would positively affect local food security. However, many felt that farmers would have to trade current practices for other practices for agrivoltaics to succeed (e.g. converting commodity farms to pasture for grazing). This potential outcome elicited concern for the stability of the local agricultural system in which the Maryland's commodity farms support Maryland's livestock farms, with one famer stating:

> You know it's not directly from my commodity field to your table, but it went to the Eastern Shore. That chicken barbecue you had, that was, that was me. Or, you know, to other feedstock for other sorts. So it's a, you know, a two-step process instead of directly from farm to table.

Those that held this concern, fear that the state's poultry farms will suffer, leave the state, or shutdown altogether without affordable access to grains. Others dismissed these fears under the presumption that many of the landowners considering solar do not have land in active production.

When it came to more direct benefits, participants cited clean energy more frequently than other agronomic benefits (Table 1). The emphasis on clean energy production reflects a general deference to local renewable energy goals. Even so, most responses to prompts about benefits focused on economic opportunities, such as additional farmer income and the advantages it affords—including the ability to maintain farmland and farming practices. The emphasis on economic benefits (as opposed to agronomic benefits) is congruent with the Pennsylvania study results, where revenue from solar-leases was reportedly much higher than farming revenue (Spangler et al., 2024). Participant focus on the economic benefits of agrivoltaics suggests that they view performance of the system in terms of energy yield and efficiencies, and to a lesser degree the ability of systems to impact agricultural yield and quality or water use efficiencies (Willcokx et al., 2020).

There is no formal study on the earning potential for solar leases in

Table 1
The agrivoltaic benefits and opportunities most important to focus group participants included.

Economic Stability for Farmers	Stakeholders agree that farmers will benefit from long-term agrivoltaic contracts that provide reliable revenue and higher profit margins.
Clean Energy Production	Agrivoltaics contributes to the production of clean energy, which helps to reduce reliance on non-renewable energy sources and aligns with broader environmental goals, namely greenhouse gas reduction.
Land Tenure Security	Many stakeholders believe that agrivoltaics can help farmers secure land tenure. This is particularly beneficial for those who do not own land but access it through agrivoltaic contracts.
Increased Crop Value	Growing crops under solar panels can lead to better marketability and higher value due to improved growing conditions, such as shade that benefits certain plants.
Local Food Production	Many stakeholders hope that the integration of local farmland into agrivoltaic projects will enhance food resiliency and address concerns about farmland loss.
Positive Agronomic & Environmental Effects	Stakeholders have heard that agrivoltaics can reduce plant/animal stress, improve growth, and provide environmental benefits such as soil and water conservation.

Montgomery County. However, one county official reported that:

> *Solar companies are offering approximately four times the amount of money that the farmer could otherwise lease the land for agricultural production.*

Another said $4000 a month is generally expected for solar leases as opposed to $150 for farm leases. We spoke with Montgomery County farmers, who did not participate in this study, who reported receiving offers as high as $10,000 per acre from solar companies (personal communication, February 4, 2025). The land and lease values of Montgomery County farms, in conjunction with the diminishing availability of farmland and Maryland's farm tax assessment incentive for agrivoltaic community solar sites, provide strong motivation for landowners to maintain agricultural activity. This is in opposition to Arizona, where solar developers are more likely to deal with real estate developers looking for the highest offer or farmers who do not see a future in farming.

Conversations about solar leases illustrate how agrivoltaics is viewed as both an economic win and loss. On one hand, all participants were encouraged by the advantages greater economic stability could provide individual farmers. On the other, county officials, farmers, and advocates expressed concerns related to the unintended consequences of economic gains. They mostly worried that solar leases would drive up land values. This could make it harder for new farmers to access land since farmland would be considered too valuable to give up, as was noted in the Pennsylvania study (Spangler et al., 2024). Advocates added that if this were to happen it could exacerbate existing inequities, a phenomenon consistent with those described in other studies (Horst and Marion, 2019). However, it remains to be seen how these offers will affect land values and whether they will have any effect on the value of farms deemed too far from transmission lines to illicit interest from solar developers.

Interestingly, the high value of solar leases in Montgomery County may act as barrier for agrivoltaics. This inadvertent result was best described by one of the solar developers:

> The established older generation of farmers typically are just looking to maximize revenue per acre. They might be willing for there to be some agrivoltaic activity as long as it doesn't reduce their lease payment. They are considering solar on land for the additional revenue, not because they want to add agrivoltaics to their existing operation … They're just trying to maximize revenue. So, for those folks, we're sometimes trying to talk them into allowing us to let some other farmer bring sheep onto the property. They're fine with that as long as they get the same capacity out of the site and the same lease rate.

Under these circumstances, solar companies that successfully convince farms to implement agrivoltaics may actually improve the accessibility of farmland, at least for livestock farmers.

A developer made a particularly powerful statement about farmland access, tenure, and preservation that holds a high degree of relevance in Montgomery County considering its commitment to farmland preservation:

> *At the end of the day, I think bar none, the biggest thing that agrivoltaics has the ability to bring to farmers is land tenure security, because it is hard for solar owner-operators to figure out how to work with an agrivoltaic operator. They don't want to be entertaining year-to-year contracts. They want long-term contracts. That puts the farm operator in a different situation than just competing in the cash rental market for agricultural land. Personally, that's what brought my family to it initially. We didn't own land. We saw the ability to get long-term access to land. At the end of the day, we're talking about 30-year contracts with reliable revenue attached to them. That is basically the same thing as farmland protection for the purposes of a generation. That's an absolute game-changer. There are landowners who are not going to go into the farmland protection programs—ever. It's just not something they're going to do. They are willing to sign a solar contract; and that solar contract can make that land available to another farmer for a whole generation. It's farmland protection.*

Given that Maryland has been a pioneer in farmland preservation, describing agrivoltaics as a means to protect additional farmland from permanent development could improve overall perceptions and attitudes. This strategy may be applicable beyond Maryland, especially throughout the Mid-Atlantic and East coast, where the rate of farmland loss has been high.

4.3. Knowledge of agrivoltaic feasibility as a barrier

Altogether, the benefits discussed in the previous section help explain why 68 % of visual survey participants reported having a positive view of agrivoltaics. Despite participants' general sense of optimism about agrivoltaics, focus groups spent more time discussing agrivoltaic barriers. Overall, participants cited unproven practices and inadequate research most often in response to prompts about agrivoltaic barriers (Fig. 4). Groups expressed a general sense of skepticism about the quality and applicability of current agrivoltaics research, which they said had mostly taken place at small scales in dry environments. Several participants also shared the concern that there is a significant gap in research comparing different agrivoltaic practices to each other, especially practices associated with commodity farms. Farmers were concerned with potential loss of agronomic productivity and other economic costs. Participant concerns about agrivoltaics also included technical issues, such as interconnectivity challenges, and cultural concerns, such as the impact of technology on viewsheds in agricultural and rural landscapes.

Participants' research concerns are validated by existing literature. While the focus of agrivoltaic research has shifted from engineering considerations to agronomic considerations (Al Mamun et al., 2022), agronomic data is limited. To underscore this point, Widmer et al. (2024) summarized the agronomic findings of research papers and identified no Mid-Atlantic studies. In the peer reviewed literature published since 2022, only one study was identified (Sturchio et al., 2025), and found that the reduction in irradiance within an agrivoltaics array decreased the total biomass of radish and radicchio crops. Beyond agronomic studies, comprehensive studies (i.e. economic, environmental, etc.) are limited, especially for projects >1 MW (Al Mamun et al., 2022).

As a result of these concerns, participants called for local research projects that focus on how to effectively farm within solar arrays and more practical field-scale studies rather than small-scale studies and academic studies that do not reflect real-world agricultural conditions. Farmers and solar developers emphasized the importance of doing research that identifies agronomic practices that optimize crop production under solar panels, rather than research that merely confirms that farming is possible in a solar array. Each participant group also pointed out a dearth of locally available educational resources and opportunities. They expressed a strong desire for demonstration sites to help alleviate concerns, shift perceptions, and build trust within the community.

The importance of local research for agrivoltaic outreach and adoption is consistent with emerging trends in agrivoltaic research (Seay-Fleming et al., 2025; Spangler et al., 2024), where critical differences in land context and climate emerge that stipulate which agrivoltaic barriers and opportunities materialized in each area. Spangler et al. (2024) reported that solar leases often pay 3 to 4 times more per acre than crops in Pennsylvania. Therefore, solar leases make Pennsylvania farmland too valuable to give up. Additionally, Pennsylvania farmers view solar leasing to protect the land itself from development and the decision to farm it in the future. These prospects are less likely for Arizona farmers experiencing the effects of water scarcity and the

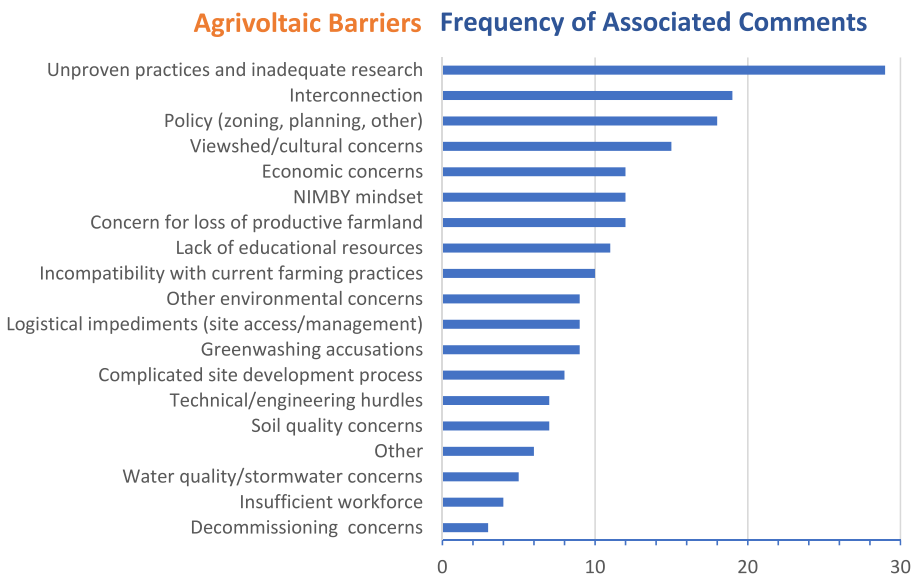


Fig. 4. Montgomery County farmers, advocates, government officials, and solar developers identified barriers to adoption of agrivoltaics in Montgomery County during focus groups that met in August and September 2024. Barriers are arranged from top to bottom by the frequency of associated comment themes.

mounting difficulties associated with climate change. On the other hand, agronomic benefits such as water conservation and higher crop productivity may play a bigger role in Arizona than in Pennsylvania.

4.4. Practices and policy

Policies: Across groups, participants felt strongly that interconnection challenges negatively impact adoption of agrivoltaics in Montgomery County. County officials, advocates and developers explained that current policies do not adequately address this barrier. The challenge is partly due to geographic constraints (as in a suitable line is not within a feasible distance) and partly due to the costs developers face for interconnection (which can make projects financially unviable). A County official said,

> We're not going to have a massive push on building solar in the Ag Reserve because there isn't any more free capacity available.

Another clarified,

> The way the grid has been built, the assumption is that the cost should always be borne by the entity that wants to feed power into the grid. It's a happy accident that there is enough [grid] capacity to let a small number of projects actually plug in and feed energy into the grid.

County officials talked about how an effort had not been made to stay ahead of future capacity needs through policies that ensure availability. They spent several minutes discussing who should be responsible for upgrading utility lines, debating:

> Should we be helping the solar industry and the utility companies with the capacity issue or not?

Doing so could mean that rate-payers or tax payers-pay for grid upgrades to be done in advance to enable low-cost solar connection. This in turn would help the state/county reach solar and greenhouse gas goals. Regardless of who should be responsible for expanding interconnection access, advocates and developers expressed the desire for: (1) clearer information on costs during the planning stages to help landowners and developers make informed decisions; and (2) more supportive policies that facilitate connection. Without grid reforms, solar development, i.e. agrivoltaics, will be severely limited.

Overall, participants were much more concerned about the loss of productive farmland than about the effects of agrivoltaics on soil quality. Developers identified zoning restrictions, including prime soil bans and setback/sightline requirements as significant agrivoltaic barriers. These concerns were summed up with the following comment:

> We've done a couple meet and greets with farmers who are interested and coming to us on [agrivoltaics}; and it's Class 2 soil every single time [that stops conversations]. And that is something [that] we've been able to work with farmers in Frederick County, for example, [who] were on a Class 2 [soils] in Frederick, and it was not an issue … And then, the broad interpretation of, hey, what's a site line? You know, you can't destroy the view of someone's property. That one kills it as well.

Developers demonstrated why conditional use zoning policies and long permitting timelines are significant agrivoltaic barriers. Several gave examples of experiences they had with various conditional use zoning policies (in Montgomery County and elsewhere), all of which complicated the development process and extended the time needed to issue permits. They further explained why permitting delays are particularly pernicious for agrivoltaic proposals.

> The biggest challenge with agrivoltaics in terms of bringing in new entrants to agriculture or disadvantaged farmers, helping them expand and grow, is that the timelines on these projects are agonizingly long. And it's very, very hard for those folks to, candidly, survive, economically, as a farm operation during those timelines.

As mentioned, these focus group interviews took place before the Renewable Energy Certainty Act was introduction and passed in Maryland. Many of the provisions of the bill respond to policies that hindered agrivoltaics. In recognition of permitting, siting barriers, and design barriers, the state reduced permitting requirements and timelines, and eased siting and design requirements by standardizing them across the state for sites >1 MW. The bill also mandated statewide protection of agricultural soils by limiting grading and prohibiting the removal of topsoil from project sites. To further assure landowners that sites would remain viable for agricultural uses in the future and that landowners would not be saddled with decommissioning concerns, the bill increased the mandatory decommissioning bond from 100 % of the cost to disassemble a project to 125 %. Spangler et al. (2024) identified decommissioning concerns as a ubiquitous barrier for farmers in Pennsylvania considering agrivoltaics. So, it should be noted how infrequently

decommissioning concerns were mentioned during our focus group interviews (see Fig. 4). This is evidence that Maryland's solar decommissioning requirements may have successfully minimized this potential agrivoltaic barrier but follow up studies are needed to confirm if this is the case. Other requirements include a decommissioning plan and reevaluation of the bond amount every five years to keep up with changes in the industry and economy. A summary of the key implications of the Renewable Energy Certainty Act is included in the supplemental material.

All stakeholder groups acknowledged that logistical impediments, such as site access and management, necessarily complicate the site development processes along with technical and engineering hurdles. However, they resoundingly agreed that collaboration between farmers, developers, and county officials could resolve many of those issues. Solar developers said that logistical impediments and technical considerations are much more complicated for agrivoltaic sites, especially sites intended for crops as opposed to grazers. They also spoke about how securing financers and long-term site owners or operators is harder for agrivoltaic sites (again, especially those intended for crops). To mitigate these hardships, developers stressed that inviting farmers into the planning process early provides assurance to third parties and results in better designs. Researchers also note that policies that foster "interactive learning processes" help overcome challenges to implementation and maximize agrivoltaic opportunities (Pascaris et al., 2023b; Seay-Fleming et al., 2025).

Finally, viewshed and cultural concerns sparked worries about the impact of a NIMBY mindset. Montgomery County residents hold a strong cultural attachment to the pastoral landscape of the Agricultural Reserve. Because of that, county officials, farmers and advocates expressed that the visual impact of solar panels is a significant barrier. Many participants across groups spoke of how resistance to solar projects manifested in organized opposition, making it challenging for developers to gain approval for agrivoltaic sites. Solar developers addressed zoning requirements for viewshed protection. They complained that such policies "*bar none*" make agrivoltaic systems harder to develop and limit agricultural capacity in favor of optics. To combat NIMBY mindsets and shift perceptions, participants suggested framing solar energy as a complementary use of agricultural land, rather than a competing one. They also called for showcasing successful agrivoltaic projects to counter negative perceptions. Governmental officials suggested implementing impact fees for PV-only installations on high-quality soils, which could provide economic incentives for agrivoltaics. If implemented, this plan would allow solar development on USDA Class 1 and 2 soils but with financial penalties to mitigate the loss of agricultural production. A participant suggested that collected fees could be used to fund agrivoltaic resources, which could include collaborative demonstration sites. As mentioned earlier, the Renewable Energy Certainty Act removed many of the solar siting restrictions and building requirements that the developers tagged as barriers. The bill also eliminated county-level restrictions to soil bans; but it added soil protection measures. It remains to be seen what effects these policies will have on the implementation of agrivoltaics in Maryland.

5. Policy and practice recommendations

KAP studies can help to identify gaps in knowledge and barriers to implementation (Liao et al., 2022; Moore et al., 2022). A key finding from our study is that all categories of stakeholders perceive that agrivoltaics is an unproven practice in the mid-Atlantic region. Due to this lack of information, stakeholders were less likely to identify specific policies as barriers to adoption. As the knowledge base in the region changes, the role for policy to shape adoption will likely shift (Pascaris et al., 2026). KAP studies also serve as baselines of information prior to a new policy. Because our study took place before Maryland adopted the Renewable Energy Certainty Act in 2025 (see Appendix), we provide a KAP baseline for this act. The Act contains several provisions to streamline solar siting and design standards across the state.

The social, political, and environmental factors shaping agrivoltaics KAP in Montgomery County, MD are more akin to the KAP of Pennsylvania (Spangler et al., 2024) than Arizona (Seay-Fleming et al., 2025), suggesting that socio-political and environmental differences across the U.S. call for regional agrivoltaic KAP studies. Studies should include investigations into stakeholder interpretations of agrivoltaics to facilitate policy discussions and outreach activities. For example, our study showed that Montgomery County stakeholders largely support the inclusion of crops and grazing practices in the definition of agrivoltaics. However, they diverged on whether grazers should reside onsite long-term to qualify for agrivoltaic incentives. On the other hand, stakeholders mostly agreed that pollinator habit and beekeeping activities were not included in their interpretation of agrivoltaics. We suggest the creation and implementation of solar grazing standards to further improve stakeholder perceptions; and we suggest differentiating solar-pollinator habitat from agrivoltaics to improve stakeholder perceptions in areas where stakeholders do not associate pollinator habitat and bee-keeping activities with agrivoltaics.

Pathways to agrivoltaic system components begin to emerge from our work with stakeholders. A diversity of crops that stakeholders perceive as candidates for agrivoltaics, including, fruits, berries, vegetables, sheep and cattle grazing, and poultry production were identified. This supports a diverse potential of photovoltaic panel types and installations that stakeholders recognized as potentially viable. This includes vertically mounted panels in livestock operations, and agrivoltaics on chicken houses given the strength of the poultry industry. We recommend that research explore this potential combined panel design and crop selection in a systematic way to provide information to support future policies and decision-making.

Stakeholders identified compelling economic, agronomic, community, and environmental benefits of agrivoltaics. Of the benefits discussed, comments on farmer financial security and land tenure security were most prevalent. With the value and length of solar leases in mind, land tenure security was equated to farmland protection. This argument is particularly significant for areas in Maryland, Pennsylvania, and perhaps the Mid-Atlantic more broadly, where prioritization of farmland protection is driven by intense development. We suggest strategies that emphasize agrivoltaics to preserve farmland to improved stakeholder perceptions of agrivoltaics in these areas.

Significant agrivoltaic barriers include interconnection challenges and a lack of local research and educational resources. In practical terms, Maryland's interconnection barriers supersede all other barriers. Therefore, policymakers should focus on policies that expand grid access in terms of cost, grid capacity, and geographic access to expand agrivoltaics. Policies should also focus on (1) reducing permitting timelines, which make it hard to collaborate with farmers during the design phase of projects; (2) siting restrictions and building requirements, which add to the complexity of agrivoltaic projects; and (3) decommissioning plans to reassure landowners that they will not be straddled with decommission costs and the long-term option to farm will remain intact.

6. Conclusions

We used a series of focus groups to study the knowledge, attitudes, and practices (KAP) of farmers and other stakeholder groups to understand the barriers to adoption of agrivoltaics in a temperate, Mid-Atlantic setting. Working across sectors allowed us to explore how these KAP factors vary among stakeholder groups that participate in decision-making around agrivoltaics. In contrast to broad, national-scale studies, we explored what agrivoltaics means to stakeholders located in one region. This study contributes to the growing body of literature on adoption and acceptance of agrivoltaics, a novel hybrid sustainable agriculture and renewable energy technology, specifically in the eastern United States and other temperate regions. Our findings highlight the need for context-specific and stakeholder-engaged approaches to

renewable energy solutions and relate to:

(A) Definitions of agrivoltaics: Visual surveys and discussions revealed that stakeholders hold varying interpretations of what they consider to be an agrivoltaic system. A lack of consensus definition was influenced by agronomic activity on site (i.e., the type of cropping system or perceptions about the degree of obvious agricultural activity), but not the design of the photovoltaic system. The need for clear definitions highlights opportunities for education and outreach, as well as a definition co-produced by farmers and other practitioners.
(B) Stakeholder perception of benefits: The dominant environmental challenges identified by stakeholders included climate change, greenhouse gas emissions, and air & water pollution, and the benefits of agrivoltaics (clean energy production) identified by stakeholders reflected these concerns to some degree. Stakeholders also identified the potential for agrivoltaics to contribute to economic stability and resilience, and land tenure security. However, there was considerable discussion of uncertainties around the scale at which these benefits may be realized and if it will be farmers who reap the benefits agrivoltaics may provide.
(C) Barriers emerging from stakeholder perception and knowledge: While a strong majority of participants had a positive view of agrivoltaics when looking at pictures of existing systems, more time in focus groups was spent discussing barriers than benefits. All groups expressed some degree of skepticism about the applicability of the growing global literature on agrivoltaics for their specific setting, role, or context and expressed concerns for the loss of productive farmland. Participant skepticism reflected the complex socio-enviro-technical aspects of a novel technology and included the lack of knowledge on agronomic productivity impacts, logistic concerns of power grid interconnection, zoning and planning policies, and cultural concerns about impacts on viewsheds and community character.

Our results demonstrate that regional environmental, political, and social factors shape agrivoltaic KAP. Some of the specific factors our research identified regarding permitting and design requirements and the preservation of agricultural soils is being addressed with recently implemented policy at the state level. The current lack of existing knowledge of the feasibility and effectiveness of agrivoltaics is a key influence on KAP. Policies to promote research demonstration collaboratives or consortia, as well as investment in test sites could help to fill this knowledge gap. Identification of meaningful factors and those critical to specific regions, in this case, a temperate mid-Atlantic setting, will allow the crafting of regionally appropriate policies and strategies for improving the implementation of agrivoltaics. The social factors identified using an engaged KAP approach are critical for aligning renewable energy goals with the needs and desires of local stakeholders, practitioners, and communities.

CRediT authorship contribution statement

Jennifer D. Morash: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mitchell Pavao-Zuckerman:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare no conflicting interests with this research and publication.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2025.115066.

Data availability

The data that has been used is confidential.

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