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The Social Dimensions of a Technological Innovation: Agrivoltaics in the U.S.

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THE SOCIAL DIMENSIONS OF A TECHNOLOGICAL INNOVATION: AGRIVOLTAICS IN THE U.S.

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Author Contribution Statement

This thesis includes previously published materials that were developed collaboratively. Three manuscripts are republished in their entirety as separate chapters in this document. These materials consist of two published journal articles and one article that is in review.

Chapter 2 was co-authored with Chelsea Schelly and Joshua Pearce and is published in a special issue of *Agronomy* titled: “Photovoltaics and Electrification in Agriculture.” My role as the first author involved recruiting participants and conducting in-depth interviews, manually transcribing and coding data, formal data analysis, and original draft preparation. My co-authors provided editorial and supervisory support throughout the development of this paper.

Chapter 3 was co-authored with Chelsea Schelly and Joshua Pearce from Michigan Tech, as well as Laurie Burnham from Sandia National Laboratories. This article is published in *Energy Research & Social Science*. I was responsible for conducting in-depth interviews, manually transcribing and coding data, formal data analysis, and original draft preparation. My co-authors contributed much editorial, technical, and supervisory support.

Chapter 4 was authored by me and has been submitted for review in *Energy Policy*. My role in this work involved conceptualization, data collection, formal analysis, and manuscript preparation and completion. I would like to gratefully acknowledge Roman Sidortsov, Chelsea Schelly, and Richelle Winkler for their guidance, support, and willingness to engage in insightful discussions throughout the development of this paper.

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Thesis Abstract

This thesis lays the groundwork for the broader realization of agrivoltaics by identifying the socio-political opportunities and barriers to development. Combining theoretical frameworks on technology diffusion and social acceptance of renewable energy with expert perspectives, this work seeks to understand, address, and accommodate the role of society and policy in combining solar energy and food systems. Three empirical studies are presented that first investigate the impediments to farmer adoption of the technology, then explore the challenges to development from the perspective of solar industry professionals, and conclude by outlining a comprehensive legal framework for agrivoltaics in the U.S. The findings identify the key socio-political opportunities for agrivoltaics include: the retention of agricultural land and rural interests, and increased local level acceptance of solar development. The key barriers include: ensuring long term agricultural productivity is not compromised, and subnational localized zoning strategies. This thesis can inform agrivoltaic decision making, solar development practices, land use management, and policy making in a way that supports the furtherance of the renewable energy transition, conserves arable land, and utilizes innovative solar photovoltaic technologies.

Chapter 1: What Are the Socio-political Opportunities for and Barriers to Agrivoltaics?

1. Introduction

Technological innovations can be wielded as either a creative or destructive force. Advances in fossil fuel resource extraction and industrial agriculture, for example, can be perceived as both a blessing and a curse. Together these two critical human endeavors have fueled and fed a growing global population of 7.8 billion but have become recognized as the predominant sources of anthropogenic greenhouse gas emissions and drivers of climate change (IPCC, 2013). While resource depletion, pollution, fossil fuel dependency, land degradation, and climate change are among the most outstanding challenges faced by humankind, the intentional utilization of manmade technologies can also play a key role in their resolution.

A technological approach to sustainable development maintains that technological innovation can remediate and reverse the wicked challenges facing contemporary societies (Aguilar et al., 2019). Through the lens of this paradigm, solar photovoltaics (PV) can be viewed as a promising and key component of renewable energy transitions. Solar PV can produce electricity at a competitively low cost (Green, 2019; Barbose & Darghout, 2019), provide rural and decentralized electrification opportunities (Chaurey & Kandpal, 2010; Ravi et al., 2016; Nasir et al., 2017), reduce environmental impacts of energy production compared to other forms (Pearce, 2002; Fthenakis & Kim, 2009; Agostini et al., 2020), and is continuously experiencing efficiency gains (Tyagi et al., 2013; Pandey et al., 2016). In the last decade, solar technology has propelled considerable growth in renewable energy generation and is exhibiting a 49% average annual growth rate (SEIA, 2021). However, spatial constraints in large-scale PV deployment are eminent, as taking advantage of high solar resource availability implies continued open space development and competition for land that receives abundant solar insolation, such as agricultural land (Dias et al., 2019; Adeh et al., 2019). Research by Dias et al. (2019) found that PV electric generation potential could be cut in half in areas where land is favored for agriculture rather than solar deployment. This conflicting land use trade-off between energy and agriculture has inspired a technological innovation that has become championed as an effective land optimization technique: agrivoltaics.

Agrivoltaic systems purposefully maximize a single plot of land by super-positioning solar PV with agricultural production. This co-production strategy is capable of reducing land use competition (Adeh et al., 2019), increasing land productivity up to 70% (Dupraz et al., 2011; Weselek et al., 2019), enhancing economic value of farms (Dinesh & Pearce, 2016; Mavani et al., 2019), and producing valuable synergistic effects for plants (Marrou et al., 2013; Bousselot et al., 2017; Valle et al., 2017; Hassanpour et al., 2018; Elamri et al., 2018; Barron-Gafford et al., 2019). Exploration of agrivoltaic technology is relatively nascent, occurring predominantly in experimental research settings (e.g., Sekiyama & Nagashima, 2019) with a handful of commercial deployments budding globally (e.g., Rem Tec, 2017; Tonking New Energy, 2018). Tested and potential applications are diverse, ranging from animal husbandry (e.g., REW, 2014; Ouzts, 2017; Mow, 2018; Andrew, 2020; Lytle et al., 2020) to crop production (e.g., Dupraz et al., 2011; Amaducci et al., 2018; Sekiyama & Nagashima, 2019; Marrou et al., 2013; Elamri et al., 2018; Ravi et al., 2016; Malu et al., 2017; Barron-Gafford et al., 2019; Hassanpour Adeh et al., 2017) and integration with green roofs (Bousselot et al., 2017). As research advances in this field, agrivoltaic systems are consistently demonstrated as a viable, practical, and advantageous land optimization technique and it is anticipated that they will be a vital element of future renewable energy production systems in a world grappling with climate change (Weselek et al., 2019).

While regarded highly for their technical and economic benefits, there remains a gap in knowledge about how these systems operate within a social context, which underlines the need to investigate the social dimensions of agrivoltaics. Scholars who have studied the diffusion of technology (e.g., Rogers, 1962; Grübler, 1996; Roberston, 1967; Guerin, 2001; Karayaka et al., 2014) emphasize that no matter how innovative a technology may be, social factors play a deciding role in its realization. Empirical research that places the agrivoltaic technology in a socio-political context remains sparse (e.g., Ketzer et al., 2019; Pascaris et al., 2020, 2021; Li et al., 2021; Pascaris, n.d.; Pascaris et al., n.d.), leaving questions about the role of social acceptance, policy, and legal frameworks in the diffusion of agrivoltaics unanswered. Continued consideration of this technology from a social science perspective will be critical for a comprehensive identification of the opportunities and barriers to the diffusion of agrivoltaics. This thesis therefore aims to answer: *what are the socio-political opportunities for and barriers to agrivoltaics?*

2. Placing Technology in a Social Context

2.1 Diffusion of Innovations

Contrary to expectations, the emergence of an innovation does not guarantee its diffusion and adoption (Grübler, 1996; Guerin, 2001). The diffusion of an innovation is a temporal and spatial phenomenon and scholars who study this phenomenon explain that it is a process rather than a linear occurrence (e.g., Rogers, 1962; Roberston, 1967). This process of translating an innovation with potential into a technology with societal utility is known as diffusion, and it requires tailoring, filtering, and accepting (Grübler, 1996). Because innovations do not develop in isolation of societal context, understanding interactions and conflicts among new and existing technologies and practices is consequential for diffusion. Through early identification of barriers to diffusion and adoption of an innovation, the technology may be improved and refined in such a way that responds to societal concerns (Grübler, 1996). Originally studied from a sociological perspective (Rogers, 1962), the diffusion of innovations theory has been increasingly applied in other disciplines such as economics, marketing, management, and policy (Karayaka et al., 2014), all of which provide insight into the complexities and challenges associated with placing technology in a social context. The characteristics of the innovation, the adopters, and the environment have been found to greatly affect diffusion and adoption (Karakaya et al., 2014).

The diffusion of an innovation is often challenged in the short and long term by economic, operative, social, or institutional barriers (Jarach, 1989). Jarach (1989) details an important distinction between macro and micro barriers to the diffusion of renewable energy (RE) technology in agriculture, identifying both national-level inhibitors such as government policy or energy costs as well as individual-level considerations such as daily management and operation as fundamental to the adoption of RE among farmers. When it comes to solar technology in agriculture, social, legal, and political barriers such as public acceptance, land use, and restrictive zoning ordinances have been identified as critical issues that influence the rate and success of diffusion (Jarach, 1989). Numerous studies have demonstrated the role of public acceptance and policy in the RE diffusion process (e.g., Chowdhury et al., 2014; Ketzer et al., 2019; Karakaya et al., 2014; Li et al., 2021), which suggests that these barriers will be of consequence in the diffusion of the agrivoltaic technology as well and therefore warrants serious investigation. Application of the diffusion of innovations theory (Rogers, 1962) to agrivoltaics will help identify the socio-political barriers that may hinder its realization, thus potentially enabling widespread diffusion.

2.2 Social Acceptance of Renewable Energy

Among the various factors that impact the diffusion of RE technologies, social acceptance is considered as one of the most critical (Wüstenhagen et al., 2007; Sovacool, 2009; Batel et al., 2013). The social component of RE system development has been demonstrated to have the potential to either catalyze or inhibit the success of a project (e.g., Boyd & Paveglio, 2015). The significance of social acceptance in RE development has been studied in various contexts such as wind (Firestone et al., 2009; Rand & Hoen, 2017) and hydropower (Tabi & Wüstenhagen, 2017), all of which elucidate the interplay between technology and society and point towards the local social context as consequential for project realization. This interplay is understood to have three dimensions (market, community, and socio-political), and these dimensions are generally recognized among scholars in this field as the foundation of social acceptance of RE (Wüstenhagen et al., 2007; Sovacool & Ratan, 2012; Simpson; 2017).

In the context of solar PV development, there is strong support for large-scale deployment of RE in America yet opposition to local projects (Carlisle et al., 2016). This dissonance suggests that support for solar is context-dependent and that there are social nuances related to place-protection (Devine-Wright & Howes, 2010; Carlisle et al., 2014) and land use values (Bergmann et al., 2008; Boyd & Paveglio, 2015) that transcend the so-called NIMBY response to local development (Devine-Wright, 2009). Empirical research continues to identify that support from local populations is arguably the most critical component to the actualization of RE developments, demonstrating the importance of designing locally appropriate projects that uphold community preferences and values (Simpson, 2017; Devine-Wright & Wiersma, 2020). Because agrivoltaic projects require the development of existing or new arable land, it is anticipated that localized resistance may challenge the diffusion of this innovation, which indicates the need to purposefully design systems that align with rural identities and interests in order to gain broad acceptance among communities and farmers.

2.3 The Function of Policy in Technology Diffusion

Because technology transfer, adoption, and development occur within a socio-political context (Guerin, 2001), policy makers and related stakeholders can play a central role in shaping a supportive regulatory environment for the diffusion of an innovation. Effective incentives and regulations have shown to facilitate the diffusion of RE technologies (Jarach, 1989; Karakaya et al., 2014), which exemplifies the potential for policy to act as a supporting mechanism for an energy innovation. More specifically, empirical research has found that energy policy support schemes have had a significant impact on the diffusion process of solar PV (Jarach, 1989; Chowdhury et al., 2014). Recognizing the function of policy in RE technology diffusion entails accounting for multi-level government interactions, considering their implications on project realization, and using policy tools to promote adoption (e.g., Shrimali & Jenner, 2013).

For the case of the agrivoltaic innovation in the U.S., development occurs at a nexus that is inherently governed by different sectors and levels of government, suggesting that an intentionally comprehensive legal framework that harmonizes laws on energy, land use, and agriculture at multiple scales will be instrumental to its diffusion (Ketzer et al., 2019). Decisions about this multi-sectoral and multi-level development challenge is constitutionally deferred to subnational governments, as authority over private property and land use fall under the rights of state and local governments (Zoning in the United States, 2020). Given that federal and state-level policies are relatively stable and supportive of solar technology (e.g., IRS Business Energy Investment Tax Credit, 2014), county or municipal level jurisdiction over energy development on agricultural lands is of critical importance to the diffusion of agrivoltaics. This localized variability in the regulatory environment related to solar development demonstrates that the ability of policy to act as either an opportunity or barrier to agrivoltaics differs spatially and is contingent on socio-political context.

3. Organization of Thesis

The papers presented here are organized in logical succession based on the correspondence between the opportunities and barriers to agrivoltaics identified: technology, society, policy. This thesis begins by investigating the impediments to farmer adoption of the technology, then explores the challenges to development from the perspective of solar industry professionals, and concludes by outlining a comprehensive legal and regulatory framework for agrivoltaics in the U.S. Drawing from theories on the diffusion of innovations (Rogers, 1962) and the social acceptance of renewable energy

(Wüstenhagen et al., 2007), these papers lay the groundwork for the broader realization of agrivoltaic systems by taking the technology out of the laboratory and placing it in a social context.

Chapter 2 offers insight into the agriculture sector perspectives on the opportunities and barriers to farmer adoption of agrivoltaics. This chapter recognizes the fundamental role of farmers in the diffusion of agrivoltaics and regards their perspectives as supreme, as they are the ones who will directly interface with the technology. Through application of qualitative interview methodology, this study engaged 11 participants in the U.S. whose experience in animal husbandry, crop farming, solar grazing, or agriculture policy are logically representative of the agriculture sector and directly relevant in identifying challenges to the adoption of agrivoltaics by farmers. The findings are generally aligned with the innovation characteristics defined by Rogers' diffusion of innovations theory (1962), as observability of benefits, relative advantage, and compatibility with current practice were raised by participants as key considerations of adoption. The most commonly identified barriers to agrivoltaics from the perspective of the agriculture sector are centered on certainty of long-term land productivity and the need for predesigned system flexibility to accommodate different scales, types of operations, and changing farming practices. Opportunities to address these barriers include the establishment of contracted agreements to return land back to prelease form after decommissioning of the solar system and the application of innovative PV solutions such as removeable ballasted foundations (Lorenz, 2016), open-source flexible racking systems (Buitenhuis & Pearce, 2012; Wittbrodt & Pearce, 2017), or semitransparent modules (Riaz et al., 2019; Thompson et al., 2020), all of which minimize potential impacts on land and crop productivity. The opportunities and barriers to adoption of agrivoltaics by farmers identified by this study can be used to refine the technology to accommodate and address the technical, economic, and environmental concerns of the agriculture sector and therefore increase the rate of diffusion.

Chapter 3 takes an exploratory approach to investigate the opportunities and barriers to the development of agrivoltaic systems based on the perspectives of solar industry professionals. This chapter acknowledges industry professionals' experience in navigating solar development and considers the points they raised as relevant to agrivoltaic development more broadly. Using in-depth interviews, 14 participants were asked generally about opportunities and barriers to development and the themes that emerged from analysis of these interview data were largely organized around Wüstenhagen et al.'s (2007) three dimensions of social acceptance: market, community, and socio-political factors. From the perspective of solar industry professionals, the most notable barriers to agrivoltaics involve developmental and operational complexity, risk, safety, liability, costs, and community resistance. Responses also highlight that the potential for an agrivoltaic project to retain agricultural interests and consequently increase local support for development is the most significant opportunity. These findings suggest solar developers can assume an active role in increasing social acceptance of solar by intentionally upholding local agricultural interests by designing an agrivoltaic project. The opportunities and barriers to agrivoltaics from the perspective of the solar industry identified by this study can be useful for developers, land use planners, and municipal governments in making informed decisions about siting practice, community relations, and the local bylaws surrounding the integration of solar and agriculture.

Chapter 4 provides an analysis of the legal and regulatory framework related to agrivoltaics in the U.S. Based on recognition of the role government and policy play in energy technology diffusion (e.g., Chowdhury et al., 2014), this chapter details an investigation of the opportunities and barriers to a comprehensive legal infrastructure to support agrivoltaic systems. Because the agrivoltaics transcend niche organizations of the U.S. government, this study asserts that the development of an integrated multi-level and multi-sectoral legal infrastructure will be requisite to support this technology. The primary data source consisted of regulatory documents that were examined using a Legal Framework Analysis method. This analysis tool supports inquiries about legal coherence and is typically used by legal scholars (e.g., Von Bogdandy et al., 2010; Rytova et al., 2016), and was therefore applicable to help identify the extent to which the existing regulatory framework in the U.S. allows, encourages, constrains, or prevents the diffusion of agrivoltaics. The State of Massachusetts was used as a case study to understand what elements of their regulatory regime contribute to their novel agrivoltaic policy, while also considering the surrounding federal and local government dynamics in which this state program is embedded. Based on the analysis results, a supportive policy framework for agrivoltaics should arguably include a combination of federal-level subsidies from both the energy and agriculture sectors; a state-level renewable portfolio standard with solar carve-out provisions and a feed-in tariff specifically for agrivoltaics; and local government application of zoning techniques that allow for mixed land use between solar and agriculture. Specific local zoning strategies for increased agrivoltaic development include the establishment of overlay districts; agrivoltaic land use provisions; context-specific site requirements; and adoption of Smart Growth principles. This paper points towards local level land management strategies as the crux of solar development on agricultural land, and therefore advises that future agrivoltaic initiatives should prioritize establishing a supportive regulatory environment at this level of government.

4. Conclusions

These empirical studies have identified agricultural interests, social acceptance, and subnational governance as key socio-political opportunities and barriers for agrivoltaics. The findings suggest that the advancement of agrivoltaic technology cannot be pursued absent of acknowledgement of the local social context of development and that successful diffusion may be contingent on community acceptance and a favorable regulatory environment. This thesis further demonstrates the need for deeper investigation of the opportunities for and barriers to agrivoltaics from interdisciplinary perspectives so that this emerging and promising technology may become broadly realized. By uniting expertise from technical, economic, environmental, and social disciplines, agrivoltaic research may be of use to engineers, regulators, municipal governments, solar developers, agriculturalists, land use planners, and entrepreneurs of all sorts. Policy recommendations and directions for future work are provided in the conclusion chapter of the thesis.

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Chapter 2: A First Investigation of Agriculture Sector Perspectives on the Opportunities and Barriers for Agrivoltaics

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Abstract

Agrivoltaic systems are a strategic and innovative approach to combine solar photovoltaic (PV)-based renewable energy generation with agricultural production. Recognizing the fundamental importance of farmer adoption in the successful diffusion of the agrivoltaic innovation, this study investigates agriculture sector experts' perceptions on the opportunities and barriers to dual land-use systems. Using in-depth, semi-structured interviews, this study conducts a first study to identify challenges to farmer adoption of agrivoltaics and address them by responding to societal concerns. Results indicate that participants see potential benefits for themselves in combined solar and agriculture technology. The identified barriers to adoption of agrivoltaics, however, include: (i) desired certainty of long-term land productivity, (ii) market potential, (iii) just compensation and (iv) a need for predesigned system flexibility to accommodate different scales, types of operations, and changing farming practices. The identified concerns in this study can be used to refine the technology to increase adoption among farmers and to translate the potential of agrivoltaics to address the competition for land between solar PV and agriculture into changes in solar siting, farming practice, and land-use decision-making.

Keywords: agrivoltaics; solar energy; agriculture; energy innovation; technology adoption; photovoltaics

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) Carbon and Other Biogeochemical Cycles report [1] reveals the predominant sources of anthropogenic greenhouse gas (GHG) emissions are the use of fossil fuels as sources of energy and land use changes, particularly agriculture. Agrivoltaics, the strategic codevelopment of land for both solar photovoltaic (PV) energy production and agriculture, can meet growing demands for energy and food simultaneously while reducing fossil fuel consumption [2,3,4]. Integrated energy and food systems have the potential to increase global land productivity by 35–73% [2] and to minimize agricultural displacement for energy production [5,6,7]. Agrivoltaic systems are a strategic and innovative approach to combine renewable energy with agricultural production, effectively addressing the predominant sources of anthropogenic GHG emissions as identified by the IPCC.

The viability of emerging agrivoltaic innovation has been investigated in various contexts. In conjunction with solar PV, there are emu farms in Australia [8] as well as sheep grazing [6,9,10] and pollinator-friendly sites proliferating in the U.S. (e.g., [11]). There is also the potential to use agrivoltaics with rabbits [12] and aquaponics (aquavoltaics) [13]. Experimental agrivoltaic research is occurring in diverse locations and climates. Examples include cultivation of corn and maize [14,15], lettuce [16,17], aloe vera [18], grapes [19], and wheat [20]. Mow [6] describes agrivoltaics as low-impact solar development that can alleviate agricultural displacement and assume varied designs: a solar-centric design that prioritizes solar output while growing low-lying vegetation; a vegetation-centric design that prioritizes crop production but incorporates solar panels and a colocation design that integrates both solar and agriculture for equal maximum dual output. Colocation designs have produced an estimated 3–8% per watt reduction in overall installation cost during site preparation due to cost reductions in land clearing and grubbing, soil stripping and compaction, grading and foundation for vertical supports, when compared to conventional solar industry development practices [6]. Further, Mavani et al. [4] found over a 30% increase in economic value for farms deploying such systems. Previous studies demonstrated that the dual-use of land for both PV and agriculture generates a mutually beneficial partnership that provides unique market opportunities to farmers and reduced operation and maintenance fees to solar developers, particularly in the case of grazing livestock [3,6,21,22,23].

The growing land footprint of solar PV presents social and spatial challenges, which are exacerbating the competition for land between agriculture versus energy production [5,23,24,25]. The U.S. Department of Energy Sunshot Vision Study forecasts that solar energy capacity will be nearly 329GW by 2030, which will necessitate approximately 1.8 million acres of land for ground-mounted systems [26]. Guerin [23] posits that the colocation of energy and agriculture will be stunted if there is absence of support from farmers and rural landowners, as the potential of agrivoltaic systems to address land-use competition will be contingent on farmer acceptance of agrivoltaics as a sociotechnological innovation. Brudermann et al. [27] found that PV adoption by farmers is primarily driven by environmental and economic considerations, which suggests factors that will be critical in agriculture sector decision-making concerning agrivoltaics.

Diffusion is a spatial and temporal phenomenon by which an innovation disseminates amongst adopters through a gradual process of filtering, tailoring and acceptance [28,29,30]. Rogers' [28] diffusion of innovations theory explains how and why some technological innovations are widely accepted while some are not, specifically referring to the adoption of an innovation by farmers over time in a rural diffusion model. The diffusion of innovations theory has been used to study diffusion of an innovation among physicians [31], among industrialized firms [32] and in terms of policy diffusion [33], among many other applications. Wilson & Grübler [34] applied the theory distinctly to energy innovations and described four phases of diffusion in which agrivoltaics can be categorized as existing in the first stage of an extended period of experimentation, learning, diversity of designs and small unit and industry-scale technologies. Grübler [30] warns that the existence of an innovation in itself does not promise proper diffusion, and while innovations have the capacity to induce change, it is the process of diffusion that realizes this potential as changes in social practice. By applying the diffusion of i theory to the agrivoltaic innovation, this study seeks to offer insight into potential refinements to the innovation of agrivoltaics in terms of its social acceptance to enable continued diffusion. This study uses Rogers' theory [28] as a practical framework for informing the diffusion of agrivoltaic innovation to discern the future potential and challenges for this technology to diffuse sufficiently to address energy and agricultural demands sustainably.

While the technical viability of colocating solar PV and agriculture has been demonstrated [2,3,16,17], research in this field is incomplete with regard to placing the innovation within a social context to determine barriers to diffusion as perceived by industry experts.

Recognizing the fundamental importance of farmer adoption in the successful diffusion of agrivoltaics, this study investigates agriculture sector experts' perceptions on the opportunities and barriers to dual land-use agrivoltaic systems. Using in-depth, semistructured interviews, this study seeks to further the potential of agrivoltaics by identifying challenges to farmer adoption in an effort to address them by responding to societal concerns. In the following sections, the results are discussed, and conclusions are drawn on barriers to be overcome for agrivoltaic diffusion as identified by industry experts. The organization of the results and discussion are based on concepts from the diffusion of innovations theory [28], with a focus on relevant innovation characteristics (observability, relative advantage and compatibility), stages of the adoption process and categories of adopters. Finally, the implications of these findings for the future development of agrivoltaics and farmer adoption are considered.

2. Methodology

This study investigates agriculture sector experts' perceptions of the opportunities and barriers to agrivoltaics using in-depth, semistructured interviews. Interview methodology is exploratory by nature and, most appropriately, collects and analyzes data about perceptions, opinions and attitudes of people [35]. Aimed at providing an inclusive and nuanced perspective of the phenomenon under study, interviews were employed to directly engage relevant informants related to agriculture and agrivoltaics.

Prior to commencement, this research obtained approval from Michigan Technological University's Institutional Human Subjects Review Board (code: 1524021-1) to ensure compliance with institutional ethics in human subjects research. The initial interview protocol can be found in Appendix A. Email was used to introduce the agrivoltaic concept and the study while inviting prospective participants to video conferencing discussions, which resulted in 10 online interviews lasting between 30 to 90 min. All participants provided informed consent for the recording of conversations, which were anonymized for the protection of their privacy. Data collection occurred between February and July 2020 until saturation was attained, known as the point when no new additional insight is derived from conversations with participants and stabilization of data patterns occur [36,37].

A total of 10 interviews were conducted with 11 agriculture sector professionals (one interview engaged two individuals simultaneously), including livestock and crop farmers, solar grazers (individuals who graze their livestock underneath solar panels) and an agriculture policy expert. Sampling for logical representativeness, variance, diversity, and relevance to agriculture, participants were pursued based on their potential to provide insight into the opportunities and barriers to agrivoltaics because they have direct experience in the agricultural sector. Both theoretical and snowball sampling methods are nonprobability techniques that were employed to construct a sample capable of representing a wide range of perceptions. Theoretical sampling intentionally captures individuals with certain characteristics [38,39], whereas snowball sampling progressively follows a chain of referrals from study participants to other potential contributors [40,41]. Table 1 details the sample of participants that was generated using these sampling methods, ranging in profession, geographic location and gender. While credible and valuable, samples constructed through nonprobability sampling do not lend themselves to generalization [42], nor are the findings generated through interview methodology suitable for statistical generalization or analysis. However, all of the themes discussed as findings were raised by the majority of participants and identify the primary opportunities and barriers to agrivoltaics according to this sample but cannot be quantified or suggested to represent a broader population. Therefore, the findings are not discussed quantitatively to steer clear from suggesting these results are statistically generalizable to the entire agriculture sector.

Table 1. Interview Participant Characteristics

Profession	**Geographic Region (U.S.)**	**Gender**
Livestock farmer: 5	North East: 4	Male: 5
Crop farmer: 1	South East: 1	Female: 6
Solar grazer: 4	Midwest: 5	
Policy: 1	South West: 1	

Drawing from grounded theory methodology [41,43], data collection and data analysis occurred in parallel to strategically shape subsequent inquiry. Responses that emerged in initial interviews instructed the development of ensuing questions, allowing for gradual pursuit and refinement of relevant issues. Interview themes were generally organized around: (1) the participants' experience in agriculture and details of their current operation; (2) experience with and perceptions of agrivoltaics (e.g., attitudes, opinions, perceived opportunities and barriers); (3) willingness to engage in an agrivoltaic project (e.g., perceived benefits and challenges). Interview protocol matured over time to explicate what agriculture sector professionals perceived as relevant opportunities and barriers to agrivoltaic development.

All interviews were recorded, manually transcribed and analyzed using the qualitative data analysis program NVivo 12 Pro (QSR International, Melbourne, Australia) [44]. Data were studied on a line-by-line basis using a series of coding and analytic induction to explore relationships, patterns, and processes. Line-by-line coding is the fundamental step in interview analysis that moves beyond concrete statements to make analytic interpretations [41]. Coding in grounded theory methodology helps anchor analysis to participants' perspectives, explore nuances of meaning, identify implicit and explicit issues, as well as cluster similarities and observe differences among responses [41]. As outlined by Znaniecki [45] and Robinson [46], analytic induction involves identifying patterns, themes, and categories in qualitative data in preparation for comparison amongst the varied findings. Employing rigorous, iterative, and comparative grounded theory techniques, analysis of these data has captured and condensed the most relevant opportunities and barriers to agrivoltaics according to this sample of agriculture sector professionals.

3. Results

This section organizes findings based on frequency and expressed magnitude of the barriers and opportunities to agrivoltaics as defined by study participants. Both direct quotations (italicized) and analysis of results are presented jointly. Section 3.2 and Section 3.3 are aligned with three of the five innovation characteristics defined by Rogers' diffusion of innovations theory [28] (observability, relative advantage and compatibility), which were identified by participants as the most critical when considering the adoption of agrivoltaic technology. These results offer insights into the main challenges to farmer adoption of agrivoltaics and suggest opportunities for interested stakeholders to further diffuse this innovation. A discussion considering the implications of these results is followed in Section 4 and Section 5.

3.1 Long-Term Land Productivity and Planning

The underlying fundamental challenge of agrivoltaic systems, as perceived by participants, concerns long-term land viability. Land viability is intrinsically proportionate to the livelihood of agriculturalists, as farmers explained that the quality of their land is of critical importance and cannot be compromised. Interviews with farmers revealed their temporal approach to decision-making as they prioritize the protection of long-term land viability above all. One farmer expressed this concern when considering the use of an agrivoltaic system:

I'm concerned too, if you're pouring a bunch of concrete and putting in permanent structures, what does this look like in the end of 20 or 30 years?

Encompassed within concerns of long-term land viability are more nuanced challenges related to land productivity in the presence of permanent solar panel structures. Participants explained that in order to maintain their agricultural land status and thrive in their farming venture, land must stay actively agricultural. The challenge that permanent solar structures could potentially impose on land productivity was unsettling:

Given the permanency of all of the solar panels and the permanency of the size of the plot, maintaining it to be continually productive for the animals would be a challenge. One of the challenges that I foresee is learning how to get the production that you want navigating around all of those structures.

When considering an agrivoltaic system, participants' concerns were largely technical and economic in nature, reflecting their dependence on land productivity. Considerations about long-term land use and farmland preservation constituted the basis for decision-making, suggesting that anything that jeopardizes land viability will not be tolerated by farmers. Thinking beyond protecting the soil itself, various participants expressed potential opportunities that agrivoltaic systems could bring to agriculturalists:

When we talk about farmland preservation, it's not just about preserving the physical ground, it's also about preserving the viability of the farm. If a farmer is going to go under *because of lack of revenue, why wouldn't you want them to open up an additional revenue stream to be able to actually preserve that land?*

There's going to be ground that goes into the solar panels and I think the idea that here you can integrate mixed-use with this makes a lot of sense. I think you have to have the right farmers and the right producers that are committed to making some of these things work.

Participants explained that long-term land viability and productivity implies required long-term planning. When discussing the prospect of engaging in an agrivoltaic project, participants proposed that incorporating some type of land-use agreement or long-term plan would relieve concerns around the future of their farm. Providing certainty of farmland preservation surfaced as a recurring consideration of agrivoltaic adoption, as articulated by one participant:

Restoring the land back to what it was having the right land agreements to where when that lease is up, they have to return it to prelease form.

To address the need for long-term planning and prioritization of agricultural interests, agrivoltaic project contracts are widely used by current stakeholders. As described by interviewees who identify as solar grazers, agrivoltaic contracts provide certainty and prevent against loss for both parties involved. The temporal concerns of agriculturalists with regards to long-term land viability can be reassured by agreement and engagement on both sides, as a solar grazer explains:

You can't have any business planning when you have that degree of uncertainty. So, it was getting people to have contracts. What the contract did is give certainty to both sides. It meant the farmers could plan their businesses, because there is a whole bunch of this remote targeted grazing, there's tons of mechanics, tons of money, staffing, and planning around breeding schedules, you name it. And then on the other side you got people wanting to make sure that the insurance is okay, and that their wiring is going to be okay, and how they'll interface with all their service work, the whole picture. I just knew the contract was the first key to the puzzle.

If you don't have a real contract and if you don't have someone really interested engaging in a 10-year kind of way on both sides, the whole thing is not going to work.

The majority of participants communicated that to the extent that the solar infrastructure of an agrivoltaic project does not threaten long-term land productivity, there are opportunities for increased revenue to farmers and mutually beneficial land-use agreements. These interviews reveal that addressing concerns about the viability of land after project decommissioning and protecting the livelihoods of farmers will involve long-term planning and partnership between agriculture and solar industries. The establishment of agrivoltaic contracts has proven valuable to current solar grazers and provides a direct way to alleviate uncertainties in land-use planning.

3.2 Market (Un)Certainty and Observability of Benefits

When considering barriers to farmer adoption of agrivoltaics, economic concerns were raised by participants only second to concerns described above regarding long-term planning for technical considerations. At a basic level, farming is a business, and is thus accompanied by a set of risks, uncertainties and investments. Participants explained that risk is especially unwelcome in the business of farming and that certainty in productivity and security in investment are vital. One participant articulated that the market unknowns are potentially more critical than the technical unknowns of agrivoltaics:

There's a lot of unknowns for the producer in this as well. Having established markets, alleviating some of the unknowns and the risks are probably as much of a piece of this as anything. So, sketching out the long-term financial return of like, "Here's what these markets look like for livestock production." And what the guaranteed revenue is for solar panels, for instance. In terms of just making it happen out there in the field, there's some requirements to make that happen, but they aren't insurmountable, I wouldn't imagine.

Others stressed the need for a secure market for an agrivoltaic system to be successful:

You would probably want to package it more as, "Do we have a food and farm system in place that allows somebody to have solar and grow these crops that are tolerant to that condition?" And then importantly, "Do we have a market to send that stuff to?" Because then all of a sudden it becomes this closed loop, kind of circular economy feel to it. But *without that end market side of it, I think people would say, "That's great if you want to grow that stuff."*

As long as the market is there, I would think a lot of these things could work.

As business owners, considerations of financial return and security in the marketplace are at the forefront of decision-making for farmers. For the majority of participants, the agrivoltaic innovation is unfamiliar and imposes constraints on business planning borne of unknowns and uncertainties. Building flexibility into the system to accommodate for changes in market conditions and farming practice could potentially alleviate some of the concern of uncertainty, as explained:

If we're looking at a 25-year kind of investment with the solar panels and when you're talking about integrating them within the livestock species too, that market for livestock might look totally different within 10 years. So, implementing some flexibility there that if we're not going to run rabbits, maybe we're running something else in there in 20 years. But having some flexibility in the system that you could respond to the livestock markets in there as well, I think is important.

Flexibility and adaptation to changing market conditions emerged as key elements to be incorporated into planning for an agrivoltaic system, highlighting again the temporal component to farmer decision-making and identifying concerns to be addressed for successful adoption. While the future unknowns of market acceptance of a product are difficult to ascertain, participants suggested that integrating flexibility into system design would reduce financial unease.

Coupled with concerns of a stable and reliable market for their product, were expectations for just compensation and tangible benefits from participation in an agrivoltaic project. When considering the adoption of the agrivoltaic innovation, participants also questioned if such an endeavor would be justified in terms of monetary gains. Participants perceived the adoption of such technology as an increased labor commitment and thus expected to reasonably gain from it. When asked if they would engage in an agrivoltaic project, one participant answered:

Essentially, they would have to pay me if they wanted me to be there because it's so much work to remediate soil and bring it up to a productive level, especially if this has been formally row cropped conventionally. So, it would really depend on what it had been earlier, how much I trusted the people who were starting this operation, and how much I felt that there would be ease of incorporating it into my schedule. I also think that it's not free pasture, you know what I mean? Even if they didn't charge me a single thing, there would be a lot of investment. So, I'd be going for like- I don't even know- I almost want to see like co-ownership, we own this land together, you get the profits from the solar and I get whatever everything else is. Or putting the solar panels on my own farm and then I get the revenue from the solar panels.

When judging the adoption of agrivoltaic innovation, participants expressed critical valuations of its worth and asserted that observable and substantial benefits would have to be derived in order for them to commit. Of the 10 farmers interviewed, four were already engaging with the technology and five others said they would get involved if they would derive more benefit than cost from it. Thus, the vast majority (nine of 10) of the farmers interviewed were open to using or already using agrivoltaics. Improving the agrivoltaic innovation to increase diffusion to these interested farmers will require establishment of just compensation for farmers, as explained by two solar grazers:

The biggest misconception to clear up immediately when people start thinking about this is that it can be anything like free grass. Because there's so much commitment on my end, and the cost of setting up all that equipment is very high. The time and labor of going there and servicing the sheep is a big commitment.

I'm really trying to get out of is the idea that the farmer should be doing all this work for free. The solar firms are making—maybe not tons of money—but reasonable amounts of money off these investments. For them, they need to know that the performance guarantee is there, the sun has to shine on their panels, there shouldn't be interference with that. They need that steady assurance. And the farmers need to get paid for recognizing that there is a performance guarantee to meet.

Participants explained that their willingness to be involved with the agrivoltaic innovation would be contingent on the near-term observability of direct benefits to them and the long-term certainty and security in the marketplace for their product. Observability is an innovation characteristic explained by Rogers (1962) that concerns the degree to which the results of an innovation are visible to potential adopters. When assessing their potential adoption of agrivoltaics, agriculture sector experts framed their considerations in terms of direct and tangible benefits, suggesting that observability of benefits is a characteristic of the agrivoltaic innovation that is of decisive importance to adopters. As discussed by participants in Section 3.1, agrivoltaic contracts are currently recognizing the rights and duties of involved parties, and provide opportunity to establish legitimate, mutually beneficial partnerships. With nine of 10 farmers inclined to partake in an agrivoltaic partnership, the above concerns about economic uncertainty and gains are active considerations for all involved stakeholders in project development.

3.2.1 Relative Advantage

The degree to which agrivoltaics are perceived by participants to be advantageous to current practice was identified as important when considering adoption. While participants expressed that financial compensation for farmers is both necessary and attractive, they also spoke of other benefits they anticipate as a result of engaging with the agrivoltaic technology. Participants discussed potential marketing advantages:

It's got a great story; it's got a wonderful marketing edge from that perspective. So, your advantage is a great story to tell from a marketing standpoint.

I think that's where you have a very unfair advantage for whoever would be doing this rabbit production, you might be getting paid for land maintenance and then have rabbits for free. So, your profitability could be way up or your price could be way lower because you wouldn't have land expenses. There's a lot of opportunity to create some advantage from a production standpoint. From that perspective they may sell better or have an [edge] in the marketplace because of that aspect.

Another participant expressed other technical synergies when grazing animals underneath solar panels:

I think it sounds like a great idea. It sounds like a great way to maintain, and not have to mow. I can see the panels providing shade and protection from the rain in a way that seems very valuable.

Perceiving a multitude of potential benefits, participants speculated how the adoption of the agrivoltaic innovation could provide them benefits and competitive advantages in the marketplace. Foreseeing a unique opportunity to derive a revenue stream from land maintenance, some participants postulated that there were economic gains associated with combined solar and agriculture systems. Rogers' (1962) innovation characteristic, relative advantage, explains that innovations that are perceived to be superior to business as usual have higher potential for adoption. Participants described the relative advantage of agrivoltaics worthwhile, and thus identified this innovation characteristic as critical when considering the adoption of the innovation, suggesting that if an agrivoltaic system could provide an advantage to a farmer, the likelihood of adoption would be greater.

3.3 Compatibility with Current Practice

A considerable opportunity for farmers in agrivoltaic projects is the potential for integration of the innovation into their current practice. Participants expressed disinterest in increased complications in their business, and rather actively seek ways to reduce labor through harnessing the synergies of innovative practices. The ease of integration and compatibility of solar with current production was frequently considered amongst participants, highlighting the opportunity to plan overlapping operations to increase farmer acceptance. The attractiveness of agrivoltaic integration was explained by two participants:

Most of my exposure to this is from sheep, and I think that it's a great idea. For my own particular system, it would definitely reduce the amount of labor for one aspect of the system, which is moving the fencing. So, I'm all for it. I think it'd be a really nice mesh.

Alternative energy is expensive to people like us. But it's something that I guess, if it could be integrated into something I'm already doing and could potentially help protect the animals, or do whatever, and then also run the homestead, it's just another perk of having something like that. It's another reason to have it besides just having the electricity.

As elucidated by participants, compatibility of the agrivoltaic innovation with current practice could reduce labor and create an incentive to engage in the technology. When considering the value of agrivoltaics to them personally, farmers offered calculated and context-dependent perspectives, making judgments on the benefits in terms of their own operation rather than speaking generally about dual-use solar systems. Speaking from a place of personal considerations and interests, participants revealed that there is a context-dependent nature of success for agrivoltaic projects. Reflecting their own practices, one participant stated:

I've also heard them say in meetings the fact that we're going to farm soybeans underneath solar panels, which is just asinine. Like, it's not going to happen. The size of our equipment doesn't permit that kind of thing. Putting livestock under, kind of a grazing operation, seems to make sense.

Compatibility with current practice not only includes size of equipment, but also scale of the farming operation, as explained by one participant:

The work that would be involved with that, I think, or potentially having to hire someone to manage them, it would decrease our profit so much that it wouldn't make sense. I could see how that would be to someone's benefit though, but not at our scale.

To justify the labor involved in engaging in an agrivoltaic project, farmers evaluated their own enterprise by mentally applying the innovation and determining the potential compatibilities. As suggested by participants, the benefits of agrivoltaics are noteworthy, but will only be fully realized if there is ease of integration into their current farming practice. Compatibility is an innovation characteristic defined by Rogers (1962) that explains the degree to which an innovation is perceived to be consistent with needs, norms and sociocultural values is decisive to potential adopters. The theme of compatibility among most participants was viewed as an opportunity rather than a barrier for agrivoltaics, suggesting that the innovation’s context-dependent nature provides flexibility and potential to leverage the solar system to derive synergistic benefits to compliment current farming practices.

4. Discussion: The Opportunities & Barriers for Agrivoltaic Diffusion

This research provides insight from the agricultural sector into the challenges and opportunities for farmer adoption of the agrivoltaic innovation. Results indicate that participants see potential benefits for themselves in combined solar and agriculture technology and identify barriers to adoption including desired certainty of long-term land productivity, market potential and just compensation, as well as the need for predesigned system flexibility to accommodate different scales of operation and adjustment to changing farming practice. The findings suggest that these barriers to adoption are not insurmountable and can be sufficiently addressed through prudent planning and mutually beneficial land agreements between solar and agriculture sector actors. Table 2 below organizes the identified barriers and opportunities to address them. All of the participants of this study assented to agrivoltaics as a synergistic and innovative approach to combined land-uses, while nine of the 10 participants who are currently active farmers stated they would engage in the use of a dual-use system given the discussed concerns are considered (four of the nine already are). Interviews with industry professionals informed the current state of diffusion of the agrivoltaic innovation and identified opportunities to further stimulate farmer adoption of the technology. These findings may be used to translate the potential of agrivoltaics to address the competition for land between solar PV and agriculture into changes in solar siting, farming practice and land-use decision-making.

Table 2. Barriers, opportunities, and directions for future work regarding the diffusion of agrivoltaics.

Barrier	Opportunity	Future Work
End-of-life impacts from solar infrastructure	-Driven piles (constructed of galvanized steel I-beams, channel-shaped steel or posts), helical piles (galvanized steel posts with split discs welded to the bottom at an angle) and ground screws (galvanized steel posts with welded or machined threads) can be removed and recycled [47,48]. -Photovoltaic (PV) racking can be put on removeable ballasted foundations or skids of precast or poured-in-place concrete ballasts to minimize land disturbances [47]. -Impacts from modules such as leaching of trace metals [49,50,51] and compromised future agricultural productivity [52] have been proven highly unlikely. -Contracted agreements that establish plans to return land back to prelease form after decommissioning of solar system.	-Empirical research investigating the magnitude of long-term impacts of solar infrastructure on land (e.g., [53]), soil, and pasture-grass productivity.
Permanent structures interfering with agricultural production and future farming practice	-A variety of plants have proven to maintain higher soil moisture, greater water efficiency, and experience increase in late season biomass underneath PV panels [54]. -Improvements in water productivity and additional shading are projected to increase crop production in arid regions experiencing climate change [55]. -Semitransparent PV [56] (Thompson et al., 2020) or vertical bifacial PV [57].	-Empirical research aimed at understanding the implications of solar PV infrastructure on perennial pasture grass maintenance. -Optimized agrivoltaic PV

	-Raised racking systems provide clearance for agricultural equipment, which could allow for nearly any crop to be used in agrivoltaic production [58]. -Design flexible open source racking systems [59,60] that have adjustable panel height, tilt angle and spacing [61], as well as a combination of permanent and portable fencing. -East-west tracking array configurations allow optimal conditions for plant growth when compared to conventional south-facing designs [62].	-Cost-benefit analysis of open source PV racking systems designed with adjustable panel height, tilt angle and spacing. -Cost-benefit analysis of permanent and portable fencing for animal grazing agrivoltaics.
Uncertainties in operation and business planning	-Legitimate partnerships and contracts that establish up-front costs and compensation for both parties -Local government policy aimed at supporting development of solar PV [63,64] -Education and outreach from PV industry to farming industry to reduce barriers to knowledge and increase trust.	-Policy research focused on market mechanisms to incentivize agrivoltaic systems for both solar and agriculture sector. -Increased efforts from university extension programs to increase information sharing and partnership between energy and agriculture.

4.1 Diffusing the Agrivoltaic Innovation-Where Are We Now?

The diffusion of innovations theory [28] identifies five stages in the process of technology adoption. Participants of this study predominantly fell into the decision or evaluation stage of adoption, which is understood as the stage in which an individual mentally applies an innovation to their present and perceived future circumstances to arrive at a decision to try it or not. Beyond the initial knowledge or interest stages of Rogers' adoption model [28], the majority of participants (six of 11) considered their potential adoption of agrivoltaics beneficial but dependent on factors related to context. Speaking from a place of receptivity, these participants saw value in the innovation and felt inclined to engage with it, while voicing a few concerns about compatibility with their practice and uncertainties about long-term land productivity. Four of the 11 participants were already functioning in the confirmation or adoption stage of the adoption process, making full use of the innovation. Based on these findings, it is observed that the current state of the diffusion of agrivoltaics is advancing towards wider implementation and has surpassed initial phases of information gathering and persuasion. Participants in the decision or evaluation stage of adoption identified barriers to their engagement with agrivoltaics, giving interested stakeholders the ability to directly respond to these concerns by improving the technology to enable further diffusion.

Further, most participants of this study were early majority adopters, characterized by wanting proven and reliable applications, reference from trusted peers and being prudent in financial risk and uncertainty. Rogers [28] asserts that an innovation must meet the needs of all categories of adopters, making clear in the context of agrivoltaic adoption where efforts should be focused to successfully move early majority adopters into acceptance of the innovation. Technological diffusion is a process of filtering, tailoring and accepting [30], and the identified concerns of the agriculture sector professionals in this study can be used to tailor or refine the technology to increase adoption among farmers. The following section will elaborate upon the critical characteristics of agrivoltaic systems as identified by participants and suggest recommendations for improvement with the intention of facilitating accelerated diffusion.

4.2 Diffusing the Agrivoltaic Innovation-What Needs to Happen?

Rogers [28] posited that there are five distinct innovation characteristics that help explain why some innovations are widely accepted and some are not. Understanding the characteristics of the agrivoltaic innovation is valuable for interested stakeholders when assessing areas for improvement and pursuing further acceptance of the technology. The results of this study identify the most critical characteristics of agrivoltaics and point to opportunities to directly respond to farmers concerns.

Of these five characteristics, observability of benefits, relative advantage and compatibility with current practice were identified by participants as the most critical when considering their personal adoption of the agrivoltaic technology. What this means for further diffusion is that the solar industry actors involved in the development of agrivoltaic systems must devise mutually beneficial land agreements with farmers that establish compensation for their labor, articulate plans for land restoration after the decommissioning of the system and be sensitive to contextual differences among agriculturalists by designing a system that is flexible enough to meet the needs of the current and future users. Participants in this study saw immediate value in personal adoption of the technology but sought long-term security in terms of farmland preservation and financial return.

There are a handful of practical actions to be taken to enable further diffusion of agrivoltaics. Table 2 presents a summary of the identified barriers, existing opportunities to overcome them and directions for future work. First, the establishment of agrivoltaic contracts has proven valuable to current solar grazers. Robust and forward-thinking land use agreements will provide a direct way to alleviate uncertainties in land-use planning and secure compensation for farmer's labor. Second, system designers need to integrate flexibility in design by accommodating current land practices and allowing for future changes. Concerns about market uncertainty and rigid systems can be addressed by crafting a combined solar and agricultural project that is adaptable to changing market and farming conditions. Third, agrivoltaics systems should be designed with compatibility in mind. By strategically harnessing the synergy of compatibility with current practice, these results suggest that farmers would be more inclined to engage with a project if it generated advantages in their operation. Being sensible in scaling a system to current practice, rather than creating increased labor burden on farmers, will increase the likelihood of their participation with the technology.

The potential for increased utilization of the agrivoltaic technology is ripe. While previous research has demonstrated its technical viability, this study recognizes that technology innovations exist within a social context and thus depend upon social acceptance and adoption. It is concluded that continued farmer adoption of agrivoltaics is likely, yet contingent on observable benefits in farming practice and assurance of financial gain. Future research should investigate how perceptions vary across geographic regions and agriculture professions (i.e., animal versus crop farming) to study the unique opportunities and barriers for agrivoltaics in the context of local climate and agricultural practice. Increased education and outreach concerning the end-of-life impacts, negligible effects of solar PV on agricultural productivity and potential for agrivoltaic systems to protect crop production during climate change, is necessary to inform and stimulate further farmer adoption. Empirical experimental research should investigate the long-term impacts of solar PV infrastructure on perennial pasture grasses to better understand the possible effects of agrivoltaic systems on future grazing productivity. Economic cost-benefit analysis will be valuable for quantifying the potential cost disadvantages of designing flexible PV arrays that can be adjusted to accommodate different panel heights and spacing requirements. Future policy research can investigate the role of market mechanisms, such as incentives, in prompting further development of agrivoltaics. Based on these findings, policy makers should consider implementing financial instruments that stimulate both solar and agriculture sector adoption of the technology, while building flexibility into such policies to allow diverse, innovative and contextually appropriate system designs. To do this, agrivoltaic proponents can model their efforts on the successful diffusion of wind farm/solar farm integration that focuses on local support [65,66]. Previous research examining diffusion of solar as an innovation among residential adopters highlighted the role of communities of information sharing for promoting adoption [67]. The study presented here is unique in examining the diffusion of agrivoltaic solar innovation as a community level consideration, but also demonstrates how diffusion of innovation can occur within a social context. Moving forward, placing the agrivoltaic technology in a social context will be essential to identify the barriers to its diffusion and will offer relevant solutions to increase its adoption.

5. Conclusions

Agrivoltaic systems are a strategic and innovative approach to combine renewable energy with agricultural production. Recognizing the fundamental importance of farmer adoption in the successful diffusion of agrivoltaics, this study investigates agriculture sector experts' perceptions on the opportunities and barriers to dual land-use systems. Results indicate that participants saw potential benefits for themselves in combined solar and agriculture technology and identified barriers to adoption including desired certainty of long-term land productivity, market potential and just compensation, as well as the need for predesigned system flexibility to accommodate different scales and types of operations and adjustment to changing farming practice. The identified concerns of the agriculture sector professionals in this study can be used to refine the technology to increase adoption among farmers and to translate the potential of agrivoltaics to address the competition for land between solar PV and agriculture into changes in solar siting, farming practice and land-use decision-making. Ultimately, building integrated energy and food systems can increase global land productivity, minimize agricultural displacement and reduce greenhouse gas emissions from fossil fuels. Informed and concerted efforts at enabling further diffusion of this innovation are imperative for meeting growing demands for energy and food simultaneously.

6. Appendix A

Initial interview protocol as approved by IRB

1. Please tell me about your experience as a farmer.
    a. What is your geographic location?
    b. How long have you been doing it?
2. Who [markets, restaurants] are your biggest customers?
    a. How do you go about opening new accounts with potential customers?
    b. What is your greatest barrier to gaining access to new markets/customers?
3. How large is your operation? Would you consider it small-medium-large?
4. Are you familiar with both crop and animal farmers that incorporate solar panels on their land?
    a. If so, what are your thoughts on this?
5. Would you ever consider embracing the mixed-use of solar on your farm to harness co-benefits of solar energy generation and agricultural production?
    a. If so, why?
        i. What is your minimum acceptable rate of return?
    b. It not, why?
        i. What type of barriers are there?

6. Would you consider renting land on a pre-fenced solar-farm meant for agricultural production?
    a. If so, why?
        i. What is your minimum acceptable rate of return?
    b. It not, why?
        i. What type of barriers are there?
7. What is needed to make a mixed-use solar farm more attractive to you?
8. A new study that is sponsored by the D.O.E. has shown an opportunity to incorporate rabbit farming with solar photovoltaic farms that make electricity. This study has shown substantial economic opportunity from this mixed-use scheme: upwards of 24% increase in site revenue. Now I would like to ask you specifically about mixed-use solar involving farmed meat rabbits.
    a. What do you think are the biggest opportunities for this kind of mixed-use solar development?
    b. What do you think are the biggest barriers for this kind of mixed -use solar development?
9. Do you anticipate solar farm pasture-raised livestock selling for a premium or increasing sales?
10. Is there anything else you would like to tell me about your perspectives of mixed-use solar PV development?
11. Do you have suggestions of other experienced farmers I should speak with?

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Chapter 3: Integrating Solar Energy with Agriculture: Industry Perspectives on the Market, Community, and Socio-Political Dimensions of Agrivoltaics

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Abstract

Large-scale development of solar-generated electricity is hindered in some regions of the U.S. by land use competition and localized social resistance. One approach to alleviate these coupled challenges is agrivoltaics: the strategic co-location of solar photovoltaics and agriculture. To explore the opportunities and barriers for agrivoltaics, in-depth interviews with solar industry professionals were conducted and findings suggest that the potential for an agrivoltaic project to retain agricultural interests and consequently increase local support for development is the most significant opportunity of dual use solar. Capable of increasing community acceptance, participants expect agrivoltaics to play an important role in future solar endeavors, especially in places where development may be perceived as a threat to agricultural interests. The results further reveal the interconnections among the various dimensions of social acceptance and suggest that the growth of agrivoltaics is contingent on market adoption of the technology through community acceptance and supportive local regulatory environments. As solar photovoltaic systems transcend niche applications to become larger and more prevalent, the dimensions of social acceptance, including the opportunities and barriers associated with each dimension, can help inform decision making to enhance the growth of agrivoltaics and thus photovoltaic development. The findings can help land use planners, solar developers, and municipal governments make informed decisions that strategically and meaningfully integrate agriculture and solar, and in turn provide multiple benefits including the retention of agricultural land, local economic development, and broad adoption of solar energy technologies.

Keywords: agrivoltaics; social acceptance of solar technology; solar development; solar energy policy

1. Introduction

Despite the mature and promising potential for solar photovoltaic (PV) technology to retrench global reliance on fossil fuels, large-scale PV development is experiencing complex challenges, including land use conflict [1-3] and — as the scale of solar has increased — social resistance, which has previously been more commonly associated with large-scale wind farms [4-6]. Growth in large-scale PV development can create land use disputes, especially in instances of competition between land for agriculture versus energy production [1, 7, 8]. This history and growing concern over land use highlights the challenge of meeting the soaring demands for solar power while conserving rural and agricultural lands [9]. It is posited that the impact of solar development on land will be diminished by siting PV in a manner that is compatible with multiple uses [10], suggesting changes in conventional practices will be necessary.

Agrivoltaics, the co-development of land for both agriculture and PV, is an innovative and increasingly popular approach to solar development [11-14]. This deliberate co-location of agriculture and PV is intended to alleviate land use competition [2] and boost revenues for landowners [15], among other benefits. Numerous empirical studies have investigated the technical viability of agrivoltaic systems, examining PV with plant cultivation [11, 16-22], aquaponics [23], and livestock production [24-28]. Overall, agrivoltaic systems have been demonstrated as a technically and economically practical use of agricultural land, capable of overcoming the dominant separation of food and energy production and increasing land productivity by 35-73% [11].

This work is part of a larger study of agrivoltaic technology [27] that involves technical and social research as well as life cycle assessment (DE-EE0008990). Interviews were conducted with both solar industry professionals and agricultural industry professionals [30]. Interviews with agricultural professionals suggests that the effective diffusion of the agrivoltaic innovation is strongly related to the acceptance of farmers [30], which further emphasizes the need to study the technology within a social context to identify and address relevant barriers. Analysis of both interview datasets was conducted inductively, meaning that a conceptual framework for making sense of the data was not applied prior to empirical examination of the interview transcripts. Inductive coding revealed that within the broad category of opportunities and barriers, solar industry professionals and agricultural industry professionals are focused on different considerations; agricultural industry professionals see agrivoltaics as an innovative technology and the diffusion of this innovation was discussed based on dimensions highlighted in the diffusion of innovations framework [30]. Solar industry professionals, in contrast, were also asked about opportunities and barriers, but their responses focused on the potential for agrivoltaics to improve the social acceptance of solar technology. The value of taking an inductive approach to this research is the opportunity it provides to reveal this divergence, the implications of which are considered in the discussion.

The specific intent of this study was to draw insight about solar development from participant experience, and responses indicate that the most considerable opportunities and barriers center on social acceptance and public perception issues. Perspectives about the opportunities and barriers to agrivoltaic development were captured via interviews with solar industry professionals, and inductive analysis revealed that interviewees were most focused on opportunities and barriers that correspond with Wüstenhagen et al.'s [4] three dimensions of social acceptance: market, community, and socio-political factors. The social acceptance of renewable energy is shaped by a complex interplay among market, community, and socio-political factors [e.g., 4]. While this framework is constructive for understanding the varying dimensions of social acceptance, Devine-Wright et al. [31] assert that it is weak in terms of the relationships between dimensions, suggesting that further research should apply a holistic approach for discerning the interdependence among factors shaping social acceptance of renewable energy. The purpose of this study is therefore to explore the perceptions of industry professionals in the U.S. and consider the implications of the identified opportunities and barriers from a social science perspective.

While the participants of this study discuss this technology specifically in the context of their experience, which is primarily with grazing and pollinator applications, the results are relevant to agrivoltaics more broadly. By grounding to relevant solar industry professionals' experience navigating solar development, the insights drawn from this study speak to the opportunities and barriers of various agrivoltaic applications through analytic generalization [29]. The findings can help land use planners, solar developers, and municipal governments make informed decisions that strategically and meaningfully integrate agriculture and solar and in turn provide multiple benefits including the retention of agricultural land, local economic development, and broad adoption of solar energy technologies.

2. Literature Review

Social acceptance of renewable energy (RE) infrastructure plays a critical role in the furtherance of the RE transition and social science research helps to better understand the factors that impact acceptance and expansion of such technologies [4, 6, 31-33]. While many previous studies are focused on renewable sources of fuels and electricity including ethanol, wind, and hydro and are not specific to solar, they are nonetheless broadly applicable, emphasizing energy development as a social matter with technical components rather than a technical matter with social components. Wüstenhagen et al.'s [4] three-dimensional social acceptance framework moves beyond designations of people as simple supporters or opponents and recognizes that the acceptance of RE is a complex social response [34]. Although Wüstenhagen et al.'s [4] work is based on wind energy and renewables in general, the constructs developed are applied here to agrivoltaics because of the similarities between large tracts of agricultural land being appropriated for solar energy generation and large tracts of land appropriated for wind and other large-scale RE projects. As new energy technologies such as agrivoltaics transcend niche applications to become more prevalent, the dimensions of social acceptance, including the opportunities and barriers associated with each dimension and their interconnections, can help inform decision making to enhance the growth of agrivoltaic development.

Recent research maintains that the social dimensions of developing energy systems are perhaps the most critical, as previous endeavors in the U.S. reveal that the social component to development can ultimately determine the success of a solar project [3, 32, 35-40]. Bell et al. [41, 42] describe a “paradoxical social gap” between high public support for wind energy but low success for concrete local developments, highlighting a discrepancy that is limiting the proliferation of RE. Public opinion surveys conducted by Carlisle et al. [37] confirm this social gap with regard to solar energy, finding strong American support for large-scale solar yet eminent opposition to local projects. The overall positive attitude towards solar has effectively (mis)led relevant actors to overlook social acceptance as an invaluable element of development [4], further widening the gap between project proposal and ultimate implementation. Because social acceptance is pivotal to energy transitions, this study reflects a proactive attempt to understand agrivoltaics from a solar industry professional’s perspective to better understand the opportunities and barriers of agrivoltaic systems; the responses centered on themes related to social acceptance and public perceptions, therefore this paper places the findings from this research into the context of Wustenhagen’s social acceptance framework.

2.1 Market Acceptance

The market dimension of RE acceptance includes market adoption [43] and the acceptance of a technology by consumers, investors, and firms [4]. Devine-Wright et al. [31] explain that the proliferation of RE innovations depends on how the technology fits into markets and stimulates investment and that issues regarding business and revenue models, including siting decisions, play a pivotal role in acceptance by different market players. Wüstenhagen et al. [4] assert that acceptance can be expressed as investment. From an investor's perspective, the reliability of a RE technology is paramount for its implementation. However, the lack of reliable information for stakeholders is understood to be the most typical barrier to market acceptance [44]. To investigate conditions that promote market acceptance, three factors are particularly relevant: competitive installation/production costs; mechanisms for information and feedback; and access to financing [32].

2.2 Community Acceptance

Building on the significance of the local context of RE, research has turned towards addressing community-level resistance and siting conflict [e.g., 3]. Many studies have shown that successful implementation of RE systems necessitates sensitivity to local community preferences and values [38, 45, 46]. More than 25 years ago, Walker warned that the pursuit of RE expansion should not happen at the expense of local impacts, stressing the importance of "locally appropriate" projects [47]. Research focused on the community dimension of RE finds that support from local populations is arguably the most critical component to the actualization of projects [48]. It turns out the classic NIMBY (not-in-my-backyard) perspective does not adequately characterize the disconnect between high levels of general support for RE and localized opposition. Studies have found that place-based elements impose a major influence on community perceptions and attitudes [48, 49]. Thus, considering and accommodating community preferences and values is consequential for gaining social acceptance of a localized solar project.

Yet there may be other community acceptance drivers, looking at wind energy as an example. Bergmann et al. examined preferences for RE (specifically wind and hydro) among rural and urban residents and found that rural residents perceive RE to be threatening to current economic interests associated with natural amenity tourism [50]. Mulvaney et al. [51], however, found that rural residents perceive wind turbines as an opportunity to protect their farmland from other land uses, thus preserving rural identity. Guerin [52] asserts that without support from rural landowners and farmers, large-scale PV will be severely limited and that the successful implementation of agrivoltaic systems lies in farmer acceptance. Because solar projects that represent local communities are expected to have higher levels of acceptance [44], it will be important that the design and scale of agrivoltaic systems align with rural identity and interests.

2.2.1 Stakeholder Engagement

Within the domain of community acceptance, stakeholder engagement and participatory decision making are well recognized strategies that contribute to higher levels of acceptance and successful RE developments [6, 38, 53]. Soliciting participation from the public effectively ensures local voices are heard, considered, and incorporated into a project [54], giving developers direct opportunity to reflect local priorities in a RE project. Upholding community values and goals, both better understood and addressed through public participation, is thus invaluable and strategic, as a system that is designed inclusively lends itself to local acceptance rather than resistance [38]. Chrislip & Larson explain that failure to include all affected stakeholders in the development process impacts both the legitimacy and viability of a project [55]. Consideration of all involved stakeholders through participatory energy planning can contribute to the design of a project that generates localized benefits: the monetary gains from a RE project remain in a community [56] and a sense of cohesion and pride tends to mature amongst residents [57]. Simpson suggests that meaningful engagement with local communities and relevant stakeholders has the capability to build trust in both RE and developers [44]; trust is also considered a prerequisite to project support. Therefore, a democratic and collaborative approach to development may be a key consideration for the social acceptance of agrivoltaics.

2.3 Socio-Political Acceptance

The socio-political dimension of acceptance encompasses policymakers and key stakeholders. Wüstenhagen et al. [4] assert that this may be the predominant dimension, given that policies and regulations create an institutional framework for RE, which effectively shapes market and community acceptance. Research on the socio-political acceptance of RE has sought to understand this dimension by using both public opinion research aimed at measuring factors that influence support for RE [e.g., 37, 58, 59] and investigation of government policies and incentives [e.g., 60, 61]. According to Simpson

[43], policies that provision financial incentives generate the most social acceptance of solar, especially if the hosting communities benefit the most. Implementation of solar is ultimately a local political decision as municipal governments and zoning boards include members of the relevant community and provide a forum to incorporate the views of the public, therefore an awareness that solar projects operate within a local policy context is necessary for successful development [38]. Application of these research findings to the emerging agrivoltaic concept requires investigating how policy measures, public participation models, and social institutions can help stimulate social acceptance of such developments.

3. Research Methodology

In-depth, semi-structured interviews with U.S. solar industry professionals were selected as the most suitable methodology to explore perceptions regarding the opportunities and barriers to agrivoltaics. Interview methods establish validity of measurement by soliciting credible responses from participants and providing a means to gather nuanced descriptions surrounding the phenomenon under study [62-64]. While appropriate for the purpose of this study, interview methodology as a data collection technique inherently has limitations. Perhaps of most relevance is social desirability bias, which can be understood as the tendency of study participants to forego providing responses that truly reflect their feelings, choosing to answer in a way they perceive as "socially desirable" [65]. Additionally, interviews happened virtually rather than in-person, which may have altered the interview environment, thus impacting the authentic flow of respondent's replies. Despite these limitations, this research adhered to established techniques for data collection and analysis, rendering the data as objective and systematic as possible [66].

This study specifically engaged solar industry professionals, primarily developers, as they have firsthand knowledge and direct experience with solar development and the factors that shape the success or hinder their projects. Because the majority of interviewees are experts in solar energy development, their responses focused on the components of agrivoltaics associated with solar energy rather than focusing on specific dimensions associated with the agricultural component of such projects. These key informants were selected to share their relevant experience and speak specifically to the dynamics involved in solar energy development and the opportunities and barriers involved in integrating agricultural production with solar energy, rather than directly representing the opinions of the general public.

Fourteen interviews were conducted with people who self-identified as solar developers, solar performance engineers, and energy policy experts, 10 of whom had some experience with agrivoltaics, with most of that experience involving passive grazing or pollinator-friendly planting systems. Recruited through existing research networks, participants were engaged via email invitation that included a brief introduction to the agrivoltaic concept and an overview of the study. The interviews lasted from 30 to 90 minutes, occurring virtually through video conference. Data collection was completed between February and April 2020 and continued until saturation was reached. As is customary among researchers applying grounded theory analysis techniques, data saturation is sought as the point where no additional new information is extracted from participants and novel patterns in the data stabilize [67, 68].

Theoretical and snowball sampling methods were purposefully used to select study participants, as these sampling strategies are deliberate in capturing a sample with certain characteristics [67-70]. Theoretical sampling is a non-probability technique used to select participants based on specific characteristics that align with the research purpose [67, 68], whereas snowball sampling is an accumulation process that builds a sample based on referrals from study participants to other acquaintances who have the potential to contribute to the research inquiry [70]. For this study, the aim was to interview solar professionals to achieve logical representation of a wide range of diverse and relevant perceptions related to agrivoltaics. These sampling strategies captured a heterogeneous sample of participants representing different professions, geographic locations, and gender (See Table 1).

The geographic regions in Table 1 are defined in accordance with standard regional classifications in the U.S., in which a region is established based on its geographic position [71]. Of the five regions commonly considered in the U.S. (West, Southwest, Midwest, Southeast, Northeast), this sample includes participants from the West, Midwest, Southeast, and Northeast regions. A map of the U.S. geographic regions is presented in the Appendix (Figure 1), sourced from National Geographic Society [71].

Further, the participant classification of "policy experts" is inclusive of a University extension agent based on their relevant experience.

By use of semi-structured interview protocol and grounded theory methodology, data collection proceeded concurrently with data analysis [66, 72]. Striving to understand the social dimensions of agrivoltaics, interview questions were loosely organized around three themes: (1) solar development and important factors that stimulate or challenge a project; (2) experience with and perceptions of agrivoltaics, including its benefits, opportunities, barriers, and risks; (3) potential for growth of solar energy through agrivoltaics. As is standard in practice of utilizing interview methods and a grounded theory approach [e.g., 66], responses derived from the first interviews conducted then informed the evolution of subsequent questions, which naturally progressed over time to address specific factors involved in agrivoltaic development. The baseline interview protocol (see Appendix) was used consistently, but additional questions and prompts matured based on previous interviews.

Driven by the flexible and durable approach of the grounded theory method, interviews were analyzed on a line-by-line basis to explore nuances of meaning [66]. A series of coding combined with analytic induction and constant comparative analysis were used to analyze data for insight into patterns, processes, and connections. Analytic induction is the procedure of identifying patterns in qualitative data by establishment of themes and categories, followed by progressive distillation of those themes and categories by repeated comparison against new observations [73].

Research received approval from Michigan Technological University's Institutional Human Subjects Review Board prior to initiation. Interview participants provided consent for the recording of conversations, which was followed by manual transcription and input into the qualitative data analysis program NVivo 12 Pro for analysis [74]. Data has been anonymized for the protection of participant's privacy. By virtue of interview methodology, these findings do not lend themselves to statistical analysis or generalization. Given the nature of the sample, findings are presented descriptively to avoid suggesting that they are directly generalizable in the sense that a random and representative sample may be. However, only themes raised by the majority of participants are discussed as findings, revealing the core themes most commonly advanced by interviewees (see Table 2).

Table 1. Interview Participant Characteristics

Profession	**Geographic Region (U.S.)**	**Gender**
Solar developer: 8	North East: 5	Male: 11
Performance engineer: 3	South East: 3	Female: 3
Policy expert: 3	Midwest: 4	
	West: 2	

4. Findings: Understanding Opportunities & Barriers to Agrivoltaics

The findings are organized below according to each dimension of social acceptance: market, community, and socio-political acceptance. Exact quotations, indicated in italics, are provided along with analysis. The results, which build directly on previous research on the social acceptance of renewable energy, offer the first insights into the social acceptance of agrivoltaics and identify opportunities, such as public perceptions, as critical. Section 5 provides a discussion of the implications of these results, including an overview of key findings and recommendations.

4.1 Market Acceptance

Participants spoke directly to the market challenges associated with agrivoltaics. Themes related to development including complexity, risk, safety, liability, economic profitability, and non-monetary benefits surfaced frequently during interviews, providing insight into the most relevant market opportunities and barriers to agrivoltaics as perceived by industry experts. Based on the magnitude and frequency of market factors raised by participants, this dimension of social acceptance is considered most challenging in the context of agrivoltaic development.

4.1.1 Complexity, Risk, Safety, Liability

Solar industry professionals in this study view agrivoltaic projects as complex and requiring extra effort to actualize, including added layers of intricacy in system design and increased coordination with stakeholders. Concerns of complexity range from the technical details of accommodating a dual use under the solar array, the impact, of say, non-optimal tilt angles on electrical production, and other considerations such as balancing stakeholder interests, all of which encumber project development, as stated by one developer and one engineer:

You add something, it's more cost, more maintenance, more complexity, more work, more *training, more people, more stuff. It's harder to pull it off.*

The problem is you have to do all of the things you normally have to do to get a solar project, and then you burden yourself on top of it by having to do a mixed-use site.

Participants detailed the elaborate development process for new solar installations. Adding another layer of complexity is perceived as “more headache than it’s worth,” as one developer expressed, making pursuit of agrivoltaics unattractive from this perspective, and potentially financially burdensome, presenting a barrier to market acceptance. Although the majority of participants (13 of 14) spoke of the commendable benefits of agrivoltaics, half of the interviewees said the extra effort needed for development is effectively a deterrent; one policy expert with experience in agrivoltaic development explained:

The challenge there is trying to get people to want to pay the time and effort to now go through an added level of design. Now I've got to sit with [a farmer] and figure out what she needs so that my system accommodates her farming equipment, the crops she might want to grow. Developers, they already have enough layers, they don't need another layer, they don't need to be educated on something else.

Despite the barriers imposed on development associated with the perceived complexity of agrivoltaic installations, participants reveal a potential trade-off between complexity and coordination. Expending substantial effort and resource to manage the logistics of a dual use project and involve farmers in the planning stages may be key to the success of agrivoltaic projects, as suggested by three different developers:

On the operational side it creates complexity, but on the development [side] it helps you build partnerships, it helps you get community approval, it helps you benefit the local environment with pollinators or animals or whatever they're doing to help the land.

If it is a local partnership opportunity, then it puts a different personality on the project rather than being a nuts and bolts thing. It's actually something that could help the local community, or at least members of the local community.

It probably slightly hurts your operating expenses due to the complexity and not really making any money on it, but it helped you build the project.

Speaking from experience, many participants perceived the value of stakeholder engagement as potentially greater than the added burden of development complexity. Almost 80% (11/14) of participants discussed that actualizing the benefits of agrivoltaic systems has clear trade-offs: building relationships and gaining support for solar come at the price of time and effort. The importance of community relations as expressed by participants is further discussed in subsection 4.2.

Further, participants also raised concerns around risk, safety, and liability, which represent notable market barriers to the realization of agrivoltaic projects. Both developers and engineers were thoughtful about the logistics of hosting a farmer on an electrical site. Considerations of designing an agrivoltaic site that is both safe and agreeable is explained by one developer who has experience with dual-use projects:

A big hurdle too is just having that third-party liability insurance, that is huge from both a safety and a legal perspective on the developer side. Because any one person or thing that's on your site, not that an animal would have insurance, but a farmer or somebody that is on site, they have to have a certain amount of coverage to protect themselves and the developer from any type of safety risks, hazards, things like that.

In the face of safety hazards, risk, and potential liabilities, some participants are skeptical about adding an agricultural function to a conventional solar site, but two other developers point out that deliberate coordination in project design could address these concerns:

We would just want to work something out where we both have proper access, proper liability coverage, in case his animals do any damage, in case he gets electrocuted.

As long as there is some agreement in place between us and the farmer about not stepping on each other's toes, then I don't really see any problems with it.

While challenges associated with risk, safety, and liability are apparent to participants, those with experience in agrivoltaic development suggest that due diligence through collaboration with involved parties can overcome them. In short, the significant barriers to market acceptance of the technology as explained by participants are related to complexity and risk. This finding illustrates how different market players perceive the reliability of the technology, suggesting that market acceptance of agrivoltaics is influenced by anticipated costs and risks.

4.1.2 Economic Profitability

Participants lamented the constraint economics pose on project fulfillment, explaining that a development has to "pencil financially" in order to be realized. Some participants expressed doubts that investors would finance an agrivoltaic project because dual use has the potential to compound risks and uncertainties. Similarly, participants stated concerns about the costs associated with the increased coordination required to actualize a dual-revenue stream. Skepticism that an agrivoltaic project would generate additional revenue for solar companies was recurrent, but participants explained that savings could be of greater utility than profit; two different developers without experience in agrivoltaic described a potential economic benefit of agrivoltaics involving animal grazing:

I think at the bare minimum it would need to either offset or displace whatever the current vegetation management program costs are. I don't think I really expect them to necessarily make money off of it, but if it could eliminate or reduce some cost, that would be helpful.

On the other hand, you have these animals who need to be fed- they come in and in a matter of weeks they can completely manage that vegetation. So, it's kind of a win-win for the farmers and the owners of the powerplant. It offloads the need to manage that vegetation.

Doubtful about sizable earnings but interested in potential savings, participants postulated that synergies derived from grazing animals underneath the panels could save on operations & maintenance (O&M) costs. While agrivoltaics aren't perceived by participants to provide an ensured revenue generation stream for solar companies, they are widely considered by participants to be a money-saver, highlighting an opportunity for dual use development to be a benefit rather than a burden. One developer without experience in agrivoltaic projects explained that the benefits could be manifold:

I think financially it would be huge for everybody. The investor wouldn't care as long as they're saving. I don't think the solar system owner would care as long as it doesn't negatively affect them- they have something in writing to cover themselves for liability and injuries and insurance, and their O&M is significantly reduced. The farmer is more profitable and/or is able to sell their meat for less. And its, you know, free range, natural, grass fed, outdoor meat.

One policy expert and one developer both with experience in dual use systems reflect on the opportunity for developers to directly benefit financially from an agrivoltaic project:

We are seeing sheep farmers creating new value-added business. They just rent their sheep, they bring them there and leave them there and do a solar project in two to three weeks. And I think that's something that is probably another level to this business that a lot of the developers were hoping could be a creative way to overcome that added maintenance that goes into these projects.

If you have an additional revenue stream that is associated with that solar plant, I think it potentially can actually benefit the solar industry because it can help absorb some of the incremental costs and provide the developer an incremental revenue stream and a motivation to do solar.

While participants explained that economic constraints are eminent in solar development and that they do not expect large economic returns from agrivoltaic ventures, they also anticipate that the opportunities that such developments could provide are beyond the bottom line. These findings suggest that the significant benefits related to agrivoltaic development transcend increased profit, as further discussed below. Issues related to revenue models and investment in solar development have been identified by these participants, highlight both economic uncertainties and opportunities as important to the market acceptance of agrivoltaics.

4.1.3 Non-Monetary Benefits

Generating an added revenue stream for farmers surfaced as a primary rationale for undertaking an agrivoltaic development. This indicates the importance of the market dimension of agrivoltaics, especially because participants presume prioritizing increased revenue for farmers may positively impact other dimensions of acceptance. Solar industry professionals exalted the idea of benefitting the agricultural community as a chief reason for deploying a dual use system:

I think the biggest reason for us wanting to do this was trying to give farms another option.

Trying to tell them, "Look, you got prime land, why not try to do both?" We'd love to see farms contribute to our state environmental goals, greenhouse gas reduction, renewable energy goals. We'd love to see them be part of it and get a diverse income stream.

Considerations apart from revenue broadens the horizon of potential benefits agrivoltaic projects can produce. Some participants explained that the competitive edge resulting from local acceptance of a proposed development can be more valuable than increased revenue. Participants posited that forgoing economic optimum projects to better appease a community by retaining relevant agricultural interests may increase local acceptance of solar. For some developers, an agrivoltaic project may be worthwhile if it simply facilitates the development process, as indicated by discussions with three different developers with varying levels of experience with agrivoltaics:

I don't imagine Mr. rabbit farmer really contributing a lot in terms of revenue to us, or even paying us. But I would hopefully, in this ideal world, like to see that if we put together this mixed-use partnership that helps both parties, that it helps us get through the development phase to build the project. I don't think we would be in this because we wanted to collect revenue from the farmer.

If we are doing practical mixed use in agricultural areas, I would love to see some benefits in the development process, it would really incentivize this type of project. So, maybe they help you in the zoning approval process, or the interconnection process.

It might be a good negotiating point for the solar developer when they're talking to the *township about all this at a preliminary stage. They say "Hey, why don't you give me a break on the property taxes in return for co-locating or some kind of agrivoltaic situation."*

This potential advantage in the development process was discussed by multiple participants as a "development selling-point." Agrivoltaics are regarded by participants as an approach to development that can leverage local interests strategically to cultivate advantageous community relations and build a positive reputation. Agrivoltaic development may generate branding and marketing benefits, as two policy experts expressed:

There's also the perception and the branding and marketing benefit, right? So, "We are a solar developer that cares about land, farms, local food, supporting local economies, and supporting farmers, and we have a social mission." Again, I'm speaking for some theoretical developer that might want to be benefiting from the perception and the reality of supporting local economies and local farms and local production. I can imagine, I haven't seen this, but "Hey, we graze solar cows, we are making clean energy and we're making organic food" or whatever. So, a branding perspective from both the farmer's point of view, but probably also from the developers saying, "We are good local citizens, and we're doing good."

Its more about competition. So increasingly, businesses, communities, towns, big energy buyers, they weren't just getting one proposal for solar, they were getting two or three or *four, and they were like, "Well I narrowed it down to these two developers, they're both in roughly the same price range, which one do I like more?...Which one's going to make our company look better? Which one is going to make our brand look better?" So, it was a competition as people were looking to have additional environmental attributes that were fairly cheap.*

Participants explained that changing the narrative about solar, to include the above benefits of agrivoltaics, may help shift public perceptions towards support for local developments. Existing at an important nexus between market and community dimensions of acceptance, agrivoltaic projects are viewed by participants as capable of producing savings on O&M costs, generating revenue for farmers, creating advantage in the development process, and establishing a positive brand reputation.

The market opportunities and barriers identified by participants illustrate that this dimension of acceptance is inclusive of the other two dimensions, being intricately tied to community relations and the local permitting process. The interlinkages among the dimensions of social acceptance are further detailed in subsections 4.2 and 4.3 and identify the most notable opportunities and barriers for agrivoltaic development as discussed by industry professionals.

4.2 Community Acceptance

The potential for an agrivoltaic project to retain local community interests and consequently increase support for a proposed development emerged as the most significant opportunity solar industry experts perceive of co-locating solar and agriculture. Linked to the market dimension of acceptance, community acceptance legitimizes market player's development pursuits as participants explained that public perceptions towards solar are a pivotal determinant of project success. The market barriers identified by participants align with the community opportunities they discussed, in which issues associated with complexity and risk were suggested as addressable through meaningful community engagement and collaboration with stakeholders.

4.2.1 Retaining Agricultural Interests

The importance of local communities in determining the success of a solar development is a major theme in the interview results. Participants spoke from experience as they described instances in which their development pursuits were halted by localized community resistance, highlighting a key relationship between market success and public attitude towards solar. Postulating about the potential for an agrivoltaic project to increase social acceptance of solar, two different developers expressed:

Some community benefits might be useful. So, it's not necessarily a monetary benefit, but this is where you could have something that's maybe less desirable from the community that a dual use might cause people to be a little more accepting. I can see that as a potential benefit.

There's definitely a kind of public acceptance side of it that possibly the mixed-use can be a benefit for.

Multiple participants discussed the strategic appeal of leveraging an agrivoltaic project to preserve the agricultural function of land, aiming to uphold local interests in order for a solar system to be realized in that community:

These are towns [where] really farming is their pride and joy, and I think they feel like, "Hey, we've been seeing these things go into the ground and cover it up, if this is something that can actually keep agriculture alive and well, let's give it a try."

You're going to get at least some more cooperation from people who really want to see their farm survive, and they realize that a system like this can provide them with a diverse income, not just for agriculture but for the dollars that can be made on the electrical generation side.

By retaining local agricultural interests rather than threatening them, participants foresee agrivoltaic projects as being in a critical position nested in local values and community acceptance. Representing a righteous way to change the narrative about solar development, two developers explain how agrivoltaics may better appeal to agricultural communities:

By being able to come into that community and say, "Hey, we're not only doing the clean renewable energy portion of this, but we'd also like to provide a little bit more of an economic background and crop yield improvement."

You need to tell the story in a better way, which is, "this is good for the farmer, this is good for you the consumer because we're making low-cost power, it's renewable and we're doing what we can to impact climate change."

By design, the objective of an agrivoltaic project is to generate both electricity and agricultural products on the same plot of land, which solar industry professionals perceive as an advantageous alternative to conventional development practice in agricultural communities. The ability to preserve local values in solar development by retaining the agricultural function of land through an agrivoltaic installation was identified by participants as the most notable opportunity. Capable of increasing community acceptance, participants expect agrivoltaics to play an important role in future solar endeavors, especially in places where development may be perceived as a threat to agricultural interest.

4.2.2 Community Relations

Participants discussed a notable trade-off between the effort invested in community outreach and the payback in terms of enhanced community relations. The time and energy devoted to stakeholder engagement can have potentially huge returns, as one developer with experience in dual use development explains:

Just having that support and making sure that you're making those local connections at the community level is- I cannot harp on how crucial that is because without the local buy-in and approval your project is going nowhere.

If I were to show up at a town hall meeting trying to sell this idea of having a dual use system in that community, it's going to be a lot more believable coming from somebody from that town that is supportive of it, or a third liaison that is an expert in agriculture or whatever it may be. Rather than myself, who no matter how much background and expertise I have in it and drive to make it happen, I'm still the developer in the room. So, getting those third parties involved is really crucial because they are seen, and they are the true experts.

Solar professionals spoke of the absolute importance of community relations in development, explaining that local partnership opportunities are invaluable and potentially accretive to the long-term growth of the solar industry. One policy expert suggests this importance:

[We are] trying to always be candid with helping solar developers realize that the biggest benefit is that they as developers will have a local partner.

Participants commonly identified community engagement as a worthwhile investment of their resources during the development phase. By stimulating local relationships founded upon preservation of agricultural land, participants see agrivoltaic projects as an opportunity to meaningfully engage communities and uphold their values. While increasing complexity during the design phase, deliberate community and stakeholder engagement may be important element of agrivoltaic development, as one policy expert explains:

If you have a farmer who's got to work under these panels on a day-to-day basis, then you really need to be thoughtful and invest a lot of time upfront on thinking about how that's going to work and how the farmer will continue to be able to farm at some level, while your panels are making power.

Despite the increased effort needed to foster worthwhile community relations, participants understand from experience the importance of local partnership in solar development. While the complexity may represent an added barrier, the opportunity for enhanced relationships was identified by participants an important part of agrivoltaic development that may be consequential in community acceptance.

For the case of agrivoltaics, participants of this study revealed that community acceptance is fundamental to successful development. Existing at a nexus between market and socio-political dimensions of social acceptance, the community dimension of agrivoltaic development was identified as the critical link between market adoption of the technology and favorable local regulatory environments. By purposefully retaining local agricultural interests in project development, participants see the potential for agrivoltaics to increase community acceptance of solar as the greatest opportunity.

4.3 Socio-Political Acceptance

In the context of solar development, local regulatory environment was the aspect of socio-political acceptance most identified by participants. Drawing upon the significance of community acceptance, participants described how public attitude and the localized policies that have implications on solar projects are linked. Participants illustrated how community acceptance implies the existence of local zoning bylaws that are favorable of solar development, indicating that socio-political acceptance is embedded within the community dimension of social acceptance of agrivoltaics. Absent of supportive local policy, participants expect agrivoltaic development to encounter challenges and therefore frequently referred to the importance of gaining community acceptance and establishing beneficial partnerships. Speaking of the consequence of policy on solar development, developers and policy experts explained:

We just do not have the environment right now at the regulatory state level that allows that type of development.

They can stop a project, no matter how good it could be, just being local. Local rule is big in our state, and we have cities and towns, after their first experience, some people in the towns are strong enough politically to now write by-laws that say, "No more large-scale projects, you can't do anything over 100kW, that's it, we're done, we're tired of seeing this land get covered up with solar panels."

There definitely is a community element to it. Because your neighborhood and your community, both in the local and state level, have a lot of sway in the process. They can shut down your zoning permitting, they can shut down your building permitting.

As the policies that are impeding solar on agricultural land are a product of past community decisions and reflect local values, many participants asserted that engaging communities in project development can positively influence attitudes and regulatory environments to accommodate, rather than restrict, solar. Participants speculated that agrivoltaics present an opportunity to reinvigorate local policy to be more accepting of solar, as agricultural interests are deliberately upheld rather than threatened in dual use development. Giving a project "personality," as articulated by one solar developer, can provide a project that would otherwise be met with regulatory hurdles, support from local communities.

Participants discussed how communities may strategically use agrivoltaic systems to allow for solar development while simultaneously preserving agricultural land. For communities that want to increase their solar generating capacity yet strongly value their arable land, different policy experts identified an opportunity for agrivoltaic installations to be leveraged as a sort of development stipulation:

Counties have ordinances and they say, "Well we have X amount of prime farmland in our county and so we want that land use to be beneficial, and so we will approve your solar project, but we want it to be pollinator friendly."

Is it more just that a community wants both of these things? They want the solar and they want to have an opportunity to do some local farming or gardening- and placing the two in the same place makes it possible for them to do both. It certainly seems feasible.

When you start to introduce things like dual use and try to bridge this really difficult niche with solar and agriculture industries, this whole dual use concept, it's typically a *lot of times at the requests of that community.*

Participants suggested that there may be an opportunity for agrivoltaic projects to become the prevailing norm of solar development in communities with conflicting land use interests. Through preservation of local agricultural interests, participants discussed that agrivoltaics may be an impetus to revise local policies that currently restrict or prevent solar development on agricultural lands, given they meet conditions set forth by the community. Majority of solar professionals posited that the two-fold objective of agrivoltaic systems could considerably soften localized opposition to solar, therefore capable of stimulating the design of local policies that are intentionally supportive of solar development.

Participants communicated that the socio-political acceptance of agrivoltaics is directly related to local regulatory environments. More specifically, the socio-political factors of agrivoltaic development described by participants are tied to local zoning bylaws, identifying a barrier to be addressed to increase acceptance along this dimension. While predominantly discussed by participants as barriers to solar development, the identified socio-political factors reveal opportunity to leverage local interests in project design to increase community acceptance and consequently encourage supportive local policy for agrivoltaics.

5. Discussion: Social Acceptance of Agrivoltaics

This research adds to an existing literature on the social acceptance of renewable energy by cataloging what industry professionals perceive to be the market, community, and socio-political dimensions shaping the opportunities and barriers associated with agrivoltaics. Results indicate that alignment among all three dimensions of acceptance will determine successful adoption of agrivoltaics; community acceptance was identified as the critical link bridging market adoption and socio-political factors, as community support can lead to advocacy and implementation of socio-political conditions like favorable policies that promote profitable development. Findings also suggest that agrivoltaics are potentially accretive to the solar industry, possessing the capacity to shift public perceptions and local policy towards support for solar developments. Although concerned about developmental complexity, study participants expressed that the agrivoltaic innovation may be key in retaining agricultural interests, consequently fostering local acceptance. Interview findings also cast light on the barriers to agrivoltaic development and identify opportunities to harmonize land use for both energy and agricultural purposes.

While essential, research that focuses solely on the technical aspects of agrivoltaics will ultimately be constrained by social factors related to project implementation. This study emphasizes agrivoltaic development as a social matter with technical components rather than a technical matter with social components, providing new insight into opportunities and barriers beyond technical and economic dimensions.

This research holistically explores the various dimensions of acceptance related to the emerging agrivoltaic innovation, exemplifying how the interconnections between them may be aligned to increase social acceptance and dual use solar development.

Table 2 below provides an overview of key findings and recommendations that emerged from interviews with 14 solar industry professionals. Each finding identifies opportunities for building the market, community, and socio-political framework needed to actualize agrivoltaics. These results are based primarily on solar industry professionals' perspectives and thus do not represent the opinions of the general public. The recommendations stated in Table 2 are aimed at a broad coalition of stakeholders, including solar developers, policy makers, municipal land use planners, and local governments interested in pursuing agrivoltaics. Table 3 (see Appendix) presents representative quotes around significant themes that surfaced during interviews. Themes are organized in descending order of relevance based on the data and are aligned with the three dimensions of social acceptance.

Table 2: Overview of key findings and recommendations

Theme	Major Finding	Recommendation	Relevant Actors
Complexity	Agrivoltaic projects are considered complex and requiring extra effort to actualize, including added layers of intricacy in system design and increased coordination with stakeholders.	Offer financial incentive to solar companies pursuing agrivoltaics to ease the burden of increased developmental complexity.	State government Local government Solar developer
Safety and liability	Safety hazards to people and livestock and potential for damage to electrical equipment	Prior to commissioning, design a contract between involved stakeholders that protects against risk and establishes liability.	Solar developer Farmer Third party insurer

	is concerning to developers and investors.	Model contracts off established wind developments on farmland.	
Economic profitability	Solar developers can save on O&M costs by accommodating grazing animals; farmers can receive revenue from a contracted vegetative maintenance service.	Develop a mutually beneficial business model that supports both parties financially, drawing insight from existing agrivoltaic projects in the U.S.	Solar developer Farmer
Non-monetary benefits	Enhanced reputation, competitive advantage, and ease in the permitting process are potential opportunities for solar developers.	Pursue development in a manner that purposefully upholds local values to enhance marketability and attitudes towards solar. Provide solar companies an expedited permitting process if undertaking an agrivoltaic project.	Solar developer Local community Local government
Community acceptance	Agrivoltaics can leverage local agricultural interests to elicit community support for development.	Prioritize local interests in project development by designing systems that are locally appropriate through incorporating existing agricultural practices.	Solar development Local community Farmer
Local partnerships	Agrivoltaic projects can strengthen community relations.	Invest resources in stakeholder engagement and pursue meaningful partnerships to improve the development process.	Solar developer Farmer Local community
Policy	Local zoning ordinances can be used to support or restrict solar development, especially development on prime farmland.	Revise local bylaws to accommodate solar on farmland, including provisions for retaining the agricultural function of land in PV system development. Develop state zoning enabling laws that explicitly preempts local solar restrictions in favor of agrivoltaic development.	Local government State government Policy makers

5.1 Market Acceptance: Motives for Agrivoltaic Development

Previous research regards agrivoltaics as an opportunity to establish a dual-revenue stream for involved parties [12], yet the participants in this study expressed disinterest in profit, which they perceived as negligible, and instead spoke of the benefits beyond finance. Participants generally agreed that agrivoltaic projects may stimulate community acceptance of solar, easing the development process, which is perceived as a motivator equal to added revenue. Put another way, participants deem community relations as advantageous to project completion and suggest that there is value in, and motives for, agrivoltaic projects beyond economic returns.

The findings from this study suggest that the market dimension of agrivoltaic acceptance is the most relevant and complicated, being inclusive of community and socio-political factors and consequential for successful technology adoption among developers. From the perspective of participants, market opportunities of agrivoltaics are directly linked to benefits such as retaining local interest, establishing community partnerships, and ultimately increasing local acceptance of a development, suggesting that future research should focus further on this market dimension. Specifically, the value of agrivoltaic development needs to be investigated and quantified beyond simple economic rates of return, including its potential for job creation and investment in host communities [e.g., 75].

5.2 Community Acceptance: Retaining Local Values

As demonstrated by Wolsink's [76] U-curve of local acceptance, the lowest levels of acceptance are observed during the siting phase of RE development. This insight implies that efforts to align projects with community values should be concentrated on the siting and planning phases of a solar project. Interviewees spoke about the siting phase as a particularly pivotal point in project development. In many cases, developers recalled instances where local resistance during the siting phase completely halted projects from moving beyond conversation to construction. Based on warnings from developers and previous research [e.g., 38], stakeholder engagement during the siting phase is key for reducing conflict and should therefore be seen as requisite for successful agrivoltaic development.

Agrivoltaic projects necessitate sensitivity to local nuances, interests, and values. Increased focus on retaining local identity through stakeholder engagement in agrivoltaic development may be effective in achieving community acceptance. Literature that discusses the role of place-based identities and attachments in social acceptance of renewable energy [e.g., 77] maintains that projects that represent local communities are expected to have higher levels of support. The findings of this study suggest that agrivoltaics are an opportunity to connect solar developers with farming communities in a way that is rooted in local values.

While this study demonstrates that its participants believe that local partnerships are significant to agrivoltaic acceptance, it simultaneously demonstrates that community outreach includes increased time and effort. Participants explained that actualizing the benefits of agrivoltaic systems has clear trade-offs. Relationships, a positive reputation, and ultimately community support for solar come at the price of time and effort, but the expense is considered worthwhile. Ultimately, the potential for agrivoltaics to increase local acceptance of solar will depend on the developer's ability to incorporate local interests in the project design.

Designing agrivoltaic projects that consider the production of energy and food as equally important can ensure that future food production capacity is maintained and may provide a tool for community engagement and community acceptance. By considering case studies in which agrivoltaic development has been successful versus cases in which it has failed, future research may support forthcoming agrivoltaic initiatives by identifying challenges across various contexts. Similarly, future research should examine case studies that exemplify how stakeholder engagement successfully improved the agrivoltaic development process so that the opportunities and challenges of participatory planning and procedural justice in dual use projects may be ascertained. Drawing from previous studies that investigate public perceptions of various energy technologies [e.g., 35, 36, 46, 50], future work on agrivoltaics could compare both public and stakeholder attitudes towards different types of agrivoltaic applications, such as crop versus livestock production.

5.3 Socio-Political Acceptance: Local Regulatory Environments

Prior research demonstrates the consequential role policy plays in solar development [e.g., 78, 79]. Policy can operate as either a barrier or an opportunity for agrivoltaics. Conversations with solar developers reveal that successful development is contingent on local regulatory environments, suggesting that policy exists at the nexus between local attitudes and project realization. In fact, a few solar developers explained that in response to unfavorable policy, they no longer pursue ground-mounted solar systems and are especially restricted from development on agricultural land. Policies that impede solar on agricultural land reflect local opposition to development but suggest an opportunity for agrivoltaics. This assertion is based both on insight from participants and from the nature of lawmaking in the U.S., specifically local level zoning. Many states [e.g., 80] grant clear participation rights to citizens during the development of local land use laws and permit review process, in which the general public can express support or opposition for a proposed development and insist on specific outcomes. Given that local governments and zoning boards include members of the relevant community and provide a forum to incorporate the views of the public, citizen attitudes towards a development are considered critical with regard to the establishment of policies that shape the local regulatory environment around solar energy.

The role of policy in agrivoltaic development suggests the power of local regulation as an opportunity rather than a barrier if local stakeholders can appreciate the added value of dual-use solar. Interviewees noted minimized land impacts and preservation of farmland as commendable advantages that could alter perceptions about development. State and local governments interested in increasing solar generating capacity and harnessing dual use benefits should design financial incentives to explicitly encourage agrivoltaics as well as ease regulatory burdens for agrivoltaic deployments. Governments could, for example, ensure that all agrivoltaic systems within their jurisdiction continue to be zoned and taxed agriculturally, given they maintain the agricultural function of the land. Future work is needed to determine the impact of such tax policy on PV system economics. Similarly, a short tax holiday could be used as an incentive to deploy agrivoltaics and thus maintain local agricultural employment on the land. This may be particularly appropriate where additional capital costs are needed for agrivoltaics (e.g. extra fencing for pasture fed rabbit-based agrivoltaics). At the state or federal level, feed-in tariffs can be used by regulators to encourage agrivoltaic development by providing long-term investment security to solar developers that specifically pursue agricultural co-location. In addition, energy policy that centers on energy sovereignty may be beneficial to agrivoltaic deployment. This type of energy policy promotes community level decision making about the sources, scales, and forms of ownership that characterize the energy services system [81]. Agrivoltaics can represent a means for communities to obtain energy sovereignty and can be coupled with initiatives for energy sovereignty such as those policies that support community solar projects [82].

Future research on the socio-political dimension of agrivoltaics should include an investigation into policy mechanisms that could incentivize the development of dual use solar projects. To leverage the power of local ordinances in solar development, future work should explore the potential for policy to act as both an incentive and a restriction-allowing solar development on farmland, for example, only if it meets set standards for an agrivoltaic system. Future investigations of socio-political barriers to agrivoltaics should determine the diversity of challenges present in various regions of the U.S., identifying context-specific distinctions that can provide regionally relevant insight to actors interested in dual-use development, especially regarding state and local level policy variations. Moving forward, addressing the socio-political concerns of agrivoltaic development will require a discrete focus on localized energy policy that is targeted at restricting solar on farmland.

5.4 Implications for Decision Making

Taking an inductive approach to research means allowing the conceptual themes and argument to emerge from the empirical data rather that applying a framework to the analysis of those data. In this research, an inductive approach reveals that solar industry professionals are focused on how agrivoltaics can shift the social acceptance of solar energy development, providing “projects with personality” that local communities may be more likely to support as they generate multiple local benefits that align with community priorities. However, they also acknowledge the complexity of these projects, particularly the complexity of working and navigating regulatory regimes across two different sectors (energy and agriculture).

This complexity becomes especially salient in the grounded context of decision making for agrivoltaic development. The study presented here is part of a larger interdisciplinary, multi-method project, and other work associated with the larger project [30] suggests that agricultural industry professionals are thinking about very different issues regarding the opportunities and barriers associated with agrivoltaics. Perhaps understandably, they did not discuss how agrivoltaics could support solar development by promoting social acceptance. Rather, they raised concerns associated with the adoption and diffusion of technological innovations, such as market potential and ease of integration into existing land management regimes and farming practices. They also raised concerns about the desire for fair and just compensation and about the potential impacts on long-term land productivity.

The different opportunities and barriers raised by these two different groups of actors highlights the potential for complex interactions in agrivoltaics decision making. If actors come to the table with divergence in their motivations, their concerns, and what they view as the opportunities and barriers, it may be more difficult for them to work together and ensure that each group has their needs and priorities addressed. By revealing the divergence in these two groups, this larger study can help both groups of actors better understand the other so that they have a foundation for working together on agrivoltaic decision making.

6. Conclusions

To address global demands for both food and energy, the relationship between critical land uses must become complementary rather than competitive. Because social acceptance of renewable energy technology is pivotal to energy transitions, this study reflects a proactive attempt to understand agrivoltaics from a solar industry professional's perspective to better understand the significant opportunities and barriers to development. This research suggests that agrivoltaics are potentially accretive to the solar industry, possessing the capacity to increase social acceptance of local solar developments. While the agrivoltaic concept is widely supported by the participants in this study, popularity of an emerging technology among industry experts may not indicate local level acceptance of a specific development. As new energy technologies such as agrivoltaics transcend niche applications to become more prevalent, localized resistance is to be anticipated and the dimensions of social acceptance, including the opportunities and barriers associated with each dimension, can help inform decision making to enhance the growth of agrivoltaic development.

This study found that solar industry professionals perceive the potential for an agrivoltaic project to retain agricultural interests and consequently increase local support for development as the most significant opportunity of dual use solar. This indicates that solar developers can play an active role in cultivating social acceptance of agrivoltaics through public engagement. The results further reveal the interconnections among the various dimensions of social acceptance and suggest that the growth of agrivoltaics is contingent on market adoption of the technology through community acceptance and supportive local regulatory environments. Ultimately, agrivoltaic projects present an innovative opportunity to preserve the agricultural function of land while increasing solar generating capacity. This potential to increase local acceptance of solar gives both developers and policymakers reason to design public participation models and policy measures that support agrivoltaic development. These findings can help land use planners, solar developers, and municipal governments make informed decisions that strategically integrate agriculture and solar, and in turn provide multiple benefits including the retention of agricultural land, local economic development, and broad adoption of solar energy technologies.

7. Appendix B

Initial interview protocol as approved by IRB

1.Please tell me about the solar development decision making process:

i. How does the process start?

ii. How does the process proceed?

iii. Who is involved in the process?

iv. What are some of the most important factors that shape whether or not a project will be successful?

2.For solar developers only:

i. At what scale do you develop?

ii. How do you take care of vegetation management?

iii. How much do you spend per year on vegetation management?

3.Can you tell me about your experiences or perceptions of mixed use solar development, where solar PV is sited in a way that is used for multiple purposes? (e.g. agrivoltaics)

i. Do you have experience with this kind of development? (If so, please tell me about that experience)

ii. What are your perceptions of this kind of development?

iii. What do you think are the biggest opportunities for mixed use solar development?

iv. What do you think are the biggest barriers for mixed use solar development?

4.Are you familiar with solar farms hosting grazing animals?

  i. If so, what are your thoughts on this?
  ii. What is needed to make this idea more attractive to you?

5.A recent study has shown substantial economic opportunity for rabbit agrivoltaics. The Department of Energy has sponsored this study, which includes field tests on a solar farm in Texas that is ongoing. Given that this is a novel concept, would you be willing to answer some questions about mixed use solar involving farmed meat rabbit? If yes:

  i. What do you think are the biggest opportunities for this kind of mixed use solar development?
  ii. What do you think are the biggest barriers for this kind of mixed use solar development?
  iii. How much additional revenue per year would you need to see to consider allowing rabbits on your solar site?
  iv. To install a rabbit farm additional fencing is needed along the base of the PV arrays. What are thoughts about this additional expense and what is your minimum acceptable rate of return (MARR) for the added investment?

6.What do anticipate will be the primary siting challenges for agrivoltaic “solar farms”?

  i. Would you anticipate an agrivoltaic farm helping you with zoning and permitting?

7.Would you anticipate an agrivoltaic farm reducing community pushback to solar development?

8.Is there anything else you’d like to tell me about your perspectives of mixed-use solar PV development- in general or combined with meat rabbit farming?

9.Do you have suggestions of other experienced solar professionals I should speak with?

Figure 1: United States Regions (source: National Geographic Society)

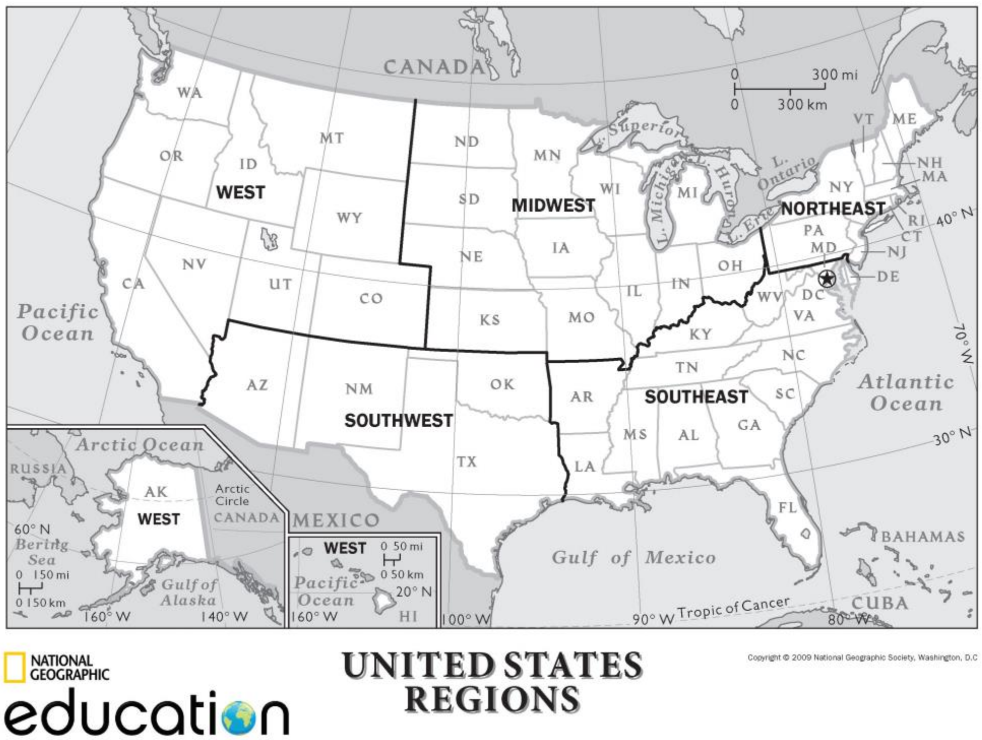

Table 3: Significant themes and participant quotes

Dimension	Theme	Barrier	Opportunity
Market (4.1)	Complexity	1. The nature of it right now, it is pretty complicated. We take on a lot of risk and complexity operating projects like this. 2. For me it's a complexity and a headache and I don't want to deal with it. 3. I think when you start to do mixed use projects you create a lot more complications. 4. We attempted to see if we could make that happen, but the sheep farmer requirements were- there was a lot of effort and costs involved to make that happen, so we weren't able to do that.	1. Adding another layer is just going to increase complications. But you know, if it is something the client wants, we don't really care. 2. We're kind of becoming more familiar and aware of having to add this into our daily process, especially if we're going to be doing more ground mounted systems.
	Economic profitability	1. The point of building solar right now is to drive the price down such that it's cheaper than fossil fuel, and you want to build more of it. So, to me, you want a big square site with nothing else on it and no complications and you want to drive the cost as low as possible to get it built. 2. We're not moving forward with agrivoltaics in that particular area due to multiple cost constraints. 3. There is some upfront capital, the first couple of years are upfront costs- you want to be able to know that those costs are going to die down with time and you'll be able to see some long-term savings from a vegetation management perspective. 4. Economics is first and foremost, because	1. If we were to bring in somebody like that, we would probably not be looking for a share of revenue per se, but maybe a payment to help defray some of our own lease costs. 2. Farmers, particularly small farmers, are struggling in many areas. So, the attractiveness of another revenue stream, even if that means sacrificing some land to grow, they could potentially make more money off of the solar revenue than they could off of the broccoli or whatever. 3. I don’t think we would be in this because we wanted to collect revenue from the farmer, like I don’t want a portion of his revenue or profit. 4. The increase in revenue, that's huge. I think having those components- you have solar, which is going to save money as far as electricity rates or energy savings, and then you have an increased revenue maybe with the [livestock] as well. 5. The cost is really a wash and more and more it's about

		ultimately, you're not going to be able to get buy-in from all of the teams internally from the development side if it doesn't pencil financially.	competition and it's about big players in the market that know how to do beautiful projects, and know how to promote them, and that's moving other companies. 6. Things like planting a different seed mix or grazing or using a different type of vegetation management, are kind of like a drop in the bucket in terms of overall project costs. But ultimately you want to be able to pencil that into your project to be able to see a long-term savings. 7. Watering the crops could be somehow combined with cleaning the solar arrays as part of the same process that makes the cost of doing the two less than if they were done individually or something. 8. We could show people that, "Hey this can be on a piece of land and we can grow a high value crop and bring a lease payment to the farmers. It's a double value to them and therefore, we should do more of this." 9. If this does work out, and we do have these sites and this is a cash positive crop like it could be, this could have a financial business portion of it.
	Operations & Maintenance	1. If that state naturally has very low vegetative maintenance average costs, like the cost to mow and herbicide and things like that are already super low, you're going to have a really tough time convincing an O&M provider that having animals on site is going to be cheaper and more cost effective because ultimately, unfortunately, it always comes down to cost. 2. So it's really finding a dual use that has little cost impact and little maintenance impact or somehow reduces maintenance. 3. Many times, you're still paying just as much to have a farmer graze sheep as you are on just	1. It should reduce with time, those vegetation management costs, because you're not going to have to go out there with mechanical mowers every so often. 2. Most likely in any given scenario with whatever type of alternative vegetation management you're working with, the first couple of years are probably going to be a bit of a higher cost. And then those costs typically reduce with time once the upfront equipment and stuff it is covered. 3. When those O&M providers are having to travel a bunch, have higher costs, different sizes of sites, just the whole list factors, then that's where you're probably going to have a better chance of having some type of alternative vegetation management, A.K.A. an animal.

		somebody using the mower. 4. Sheep aren't always...they're not really interested in the weeds. They're interested in the grass. So, weeds still become a problem. You still need some kind of manual mechanical maintenance of sites, even when you do have grazing animals.	4. The fact that you could figure something out that can be a saving, you know, a $500 a month check to mow- that money could be spent on something else that puts money in somebody’s pocket. 5. It would be less expense for grounds maintenance and hopefully some benefit to the farmer.
	Risk, Safety, Liability	1. Safety would be one of the potential barriers that whoever was going to use the site would be able to do so in a safe manner without getting hurt. 2. We definitely have looked into all that and tried to get our investors to consider those ideas and we have not been successful. Mostly for those liability reasons. 3. What I know is that today, there's no banker or insurance company that's going to ensure or finance a project where there's a combine driving around under solar panels. 4. Basically, the idea here is someone gets in there, damages the array or gets hurt because they've touched something- making this huge investment that folks acquired something that is now an issue. 5. I just think there is too much potential for damage if you got big equipment going down those isles. 6. Safety would be a big concern for us as well as the high voltage that those projects operate at, making sure that people are safe. 7. If you want to do it with animals and livestock, you have to worry about them eating wires or	1. We can provide information to the farmer about what is necessary to keep the solar panels safe, but also get information from him on what is necessary for [livestock] to kind of thrive in that environment. 2. If somebody were to propose some kind of co-use, it would have to have those things taken into consideration including security at the site and the integrity of the site. 3. I think if the system is designed electrically correct, it's grounded, I don't think you're going to see a lot of animals get electrocuted or shocked in any way. 4. I know that we have had talks about plants, and I could see our investors getting some comfort level with that.

		getting into somewhere that could kill them, which is really bad for everyone.	
Community (4.2)	Community Acceptance	1. It's getting people to understand the exact purpose, that solar does not take land out of agricultural use. And it needs to be proven and shown that it does not, and it's a decent use of space.	1. Where I think it would be most helpful though, is in community acceptance. 2. I see agrivoltaics, the various streams, whether its growing vegetables or farm animals, as potentially accretive or helpful to the growth and acceptance of solar. I think it’s positive. 3. I think this type of project or projects in general, whether it be pollinators or livestock, are really cool. I think they kind of reinvigorate what people want to see with renewable energy and kind of a green future.
	Community Resistance	1. We started getting calls from farms, from just local people- people don’t want things in their backyard, as well- really concerned about our farmland being taken up by solar development. So, the food versus fuel argument, “we’re losing valuable land.” 2. If you're coming into an area that's really unfamiliar with these types of technologies, I think that it's going to increase pushback. 3. People were calling us saying, "What are you doing? You can't just let these developments just start taking food away and putting solar in!”	1. If you're in more of the rural area that has livestock, then yeah, I think it could probably reduce the pushback. 2. It really comes down to the developer. Do they want to be a good neighbor, or do they want to push the project through?
	Local interests and values	1. There have been instances where we want to develop on land they’re using and that they valued, and they didn't want to see it. 2. Even if the farmer is totally on board and the developer is totally on board, the community gets to say, “this is not in keeping with our community goals.”	1. If you are in an area, maybe that already has an existing livestock history, maybe it's better to kind of mix those uses together there. If there's other space, that maybe it requires more of the plants, flowers, the fauna, flora, et cetera…. that it might make more sense. I really just think it's a context dependent kind of thing. 2. Local expertise is a huge factor. If there's a farmer next door that has a flock of sheep, it's going to be pretty affordable and economic to have sheep graze the solar farm. If a state has an abundance of

			expertise in planting and establishing pollinator habitat, it'll be way more cost competitive compared to other states that don't have this expertise. 3. The general public, who might live adjacent to farms and know farmers and want to support farmers, they would certainly want to be involved in the vetting and design of any dual-use program.
	Development "selling-point"	1. We're going to grow from 300,000 acres to 3,000,000 acres in the next 10 years. And it's not going to be bare ground, it's not going to be turf grass, you know? 2. They are realizing, "Crap, I don't want to be the next Blockbuster," and Blockbuster is turf grass solar.	1. It was a good selling point because we sold the project and the competitor didn't. 2. I imagine a situation like this for a company like us doesn't help us at all in terms of revenue, it helps us in terms of the development. 3. That would be a great thing to be able to go to the communities and describe an offer in conjunction with the PV. 4. In those areas where there are mixed-use opportunities, I think maybe you present them with an opportunity to kill two birds with one stone, for lack of a better phrase. 5. I think it is a great idea and it might be the only way for ground mount PV to survive or continue at least in some regions.
	Local Partnerships	1. We're not going to get to all of our climate action goals, especially state renewable energy portfolio goals and things like that, without some consensus and comradery between both the solar industry and agriculture industry. 2. The solar industry itself, are they interested and willing to work hand in-hand with farmers on what are more expensive almost across the board, and complex installations?	1. I think that's where the main benefit is, in kind of a partnership to help the development phase. 2. So as an electric utility, if we were to think about co-use, we would be open to it but we would probably not do it ourselves because it's not a core part of our business, so we would happily partner with somebody to do it on our site. 3. If you're partnering with somebody else that has more local roots…that might be a different story because the local story gets broken down there. 4. Really understanding the land that you're working with, and the community you're working with, and maybe the landowners you're working with, to kind of work what's best for them. And just getting a sense from them what the best use would be in conjunction with the solar.

			5. When we go to develop a solar facility, we are there to provide clean energy to that community. And we work with that local community to get to know them, what their needs are, provide as much information as we can about renewable energy, specifically solar and what benefits that will provide to their community. And not only from a clean and renewable energy future, but also the economic benefits for their community.
Socio-Political (4.3)	Policy	1. Things related to land-use have started to change five years ago and now especially, the conditions and restrictions are much tighter. It is at the point where you cannot- there are ways- but it is very difficult to put a large solar array on a parcel that is, has been, or currently is being used for agriculture purposes. 2. We have a lot of people that are anti-renewable, in particular solar, and have tried to legislate it off the farms. They changed the zoning and the requirements such that it's been really hard to help a farmer out and put a small array on a farm to do a community-based solar program. 3. Policy-wise, the fact that we are not developing ground mount right now is driven by the policy changes. 5. There's definitely a local regulatory process that kicks in and has led to projects not being successful.	1. It just keeps ramping itself up and to the point where we now actually have an incentive to put dual use in through a state solar program, which is the first time we are able to do that. 2. I only see a very few solar developers who are going in and saying, "I'm going to do agrivoltaics, I'm going to do crops under the panels, I'm going to do grazing.” It's usually they've gotten there because they've been forced to by government requirement or they've been forced to because of the preference of one of their customers. 3. A customer expressing a preference is a way to get that outcome with a carrot, a government requiring it is a way to get to that outcome with a stick. And both are really effective policy tools. 4. The bees or the sheep are examples of, “If you allow us to zone this project, we will do this mixed-use thing to benefit the community.”

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Chapter 4: Examining Existing Policy to Inform A Comprehensive Legal Framework for Agrivoltaics in the U.S.

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Abstract

Technological advances in solar photovoltaics (PV) show great potential to combine agriculture and solar energy production in a system known as agrivoltaics. Yet legal frameworks need to adapt to support the advancement of this technological innovation. This study applies Legal Framework Analysis to identify opportunities and barriers to a comprehensive legal infrastructure for enabling agrivoltaic development. Using regulatory documents as the primary data source, the State of Massachusetts is used as a case study to understand what elements of their regulatory regime contribute to their novel agrivoltaic policy, while also considering the surrounding federal and local government dynamics in which this state program is embedded. Based on the analysis results, a supportive policy framework for agrivoltaics should arguably include a combination of federal-level subsidies from both the energy and agriculture sectors; a state-level renewable portfolio standard with solar carve-out provisions and a feed-in tariff specifically for agrivoltaics; and local government application of zoning techniques that allow for mixed land use between solar and agriculture. Specific local zoning strategies for increased agrivoltaic development include the establishment of overlay districts; agrivoltaic land use provisions; context-specific site requirements; and adoption of Smart Growth principles. Findings indicate that proactive measures to align solar energy and agricultural land use regimes are legally feasible and can catalyze the diffusion of emerging agrivoltaic technology.

Keywords: agrivoltaics; legal analysis; legal framework; multi-level governance; solar energy; zoning

1. Introduction

Recent technological advances in solar photovoltaic (PV) technology (e.g., Riaz, 2019; Thompson et al., 2020) show great potential to combine agriculture and solar energy production in a manner that increases global land productivity (Dupraz et al., 2011), improves crop yields and resilience (Marrou et al., 2013; Amaducci et al., 2018; Barron-Gafford et al., 2019), reduces environmental impacts (Pascaris et al., n.d.), and provides rural economic opportunities (Dinesh & Pearce, 2016; Mavani et al., 2019; Proctor et al., 2021). These strategically combined systems, known as agrivoltaics (Dupraz et al., 2011), have been demonstrated as an effective approach to development that can alleviate growing demands for both food and renewable energy (Weselek et al., 2019) and minimize land use constraints (Adeh et al., 2019). Yet the diffusion of a technological innovation is underpinned by the socio-political context in which it exists (Grübler, 1996; Pascaris et al., 2020; 2021) and therefore it is critical that the relevant legal and regulatory framework adapts along with state-of-the-art technologies appearing on the market to support their advancement. For the case of the emerging agrivoltaic innovation in the U.S., development occurs at a nexus that is inherently governed by different levels of government and sectors, which suggests that an intentionally comprehensive legal framework that harmonizes laws on energy, land use, and agriculture will be instrumental to its diffusion (Ketzer et al., 2019). Based on the viability of and necessity for innovative solar PV applications, an assessment of the U.S.

legal framework is needed to identify contradictions and opportunities in the multi-level governance regimes that shape solar development on agricultural land.

Given both the dearth and nascence of policy designed to deliberately support agrivoltaic development, it is unclear whether multi-level governance interactions play a significant catalyzing or inhibiting role. As multiple layers of policy overlap, intersect, and exhibit trade-offs, support from all levels of government are essential to effectively overcome gaps in resources, regulation, and legislation (Hsu et al., 2017). The challenges of climate change present policy problems at scales that no single level of government or sector acting alone can effectively manage themselves (e.g., Leck & Simon, 2012; Harker et al., 2017; Schelly & Banerjee, 2018), suggesting that multi-level, multi-sectoral governance characterized by policy integration can produce synergies that address conflicts or fragmentation in legal frameworks. As agrivoltaic technology transcends the traditional policy niches of the U.S. government, the development of an integrated multi-level and multi-sectoral legal infrastructure will be requisite to support this technology.

The purpose of this study is to analyze the extent to which existing laws and regulations allow, encourage, constrain, or prevent the diffusion of agrivoltaics in the U.S. and to identify the necessary components of a comprehensive legal framework for supporting agrivoltaic development. Energy research that recognizes misalignment in policy as a critical barrier for energy investment and technological diffusion apply Legal Framework Analysis to contribute to a more enabling regulatory environment (e.g., Müller, 2015; Kuiken & Más, 2019; Sunila et al., 2019; Schumacher, 2019). This study outlines an ideal legal framework for agrivoltaics by studying an existing state-level policy program within the broader U.S. context. Using regulatory documents as the primary data source, the State of Massachusetts is used as a case study to understand what elements of their regulatory regime contribute to a supportive agrivoltaic policy program while also considering surrounding federal and local government dynamics. The results bring potential legal constraints and opportunities into full view so that forthcoming attempts to advance agrivoltaic development may proactively account for the realities of the U.S. legal framework.

The remainder of this paper is structured as follows. Section 2 provides a background on the agrivoltaic technology, a general overview of related policy, and a description of the case study under consideration. Section 3 presents a literature review that conceptualizes agrivoltaic development as a multidimensional policy integration process. Section 4 details the Legal Framework Analysis methodology employed and the rationale behind the approach. Lastly, Section 5 presents the results of the analysis and a discussion of recommendations aimed at developing a supportive legal framework for agrivoltaics in the U.S.

2. Background

The agrivoltaic innovation has become recognized as a practical and viable solution to make significant progress toward energy sector decarbonization (Mavani et al., 2019; Proctor et al., 2021) and increase crop resilience in the face of climate change (Amaducci et al., 2018; Barron-Gafford et al., 2019). To realize this potential, it is critical to consider the socio-political context in which the technology exists, which sets the foundation for its success, as the regulations and policies that create an institutional framework for its deployment can be constraining or stimulating (Wüstenhagen et al., 2007; Chowdhury et al., 2014). This section provides a background on the agrivoltaic technology, a general overview of related policy, and a description of the case study under consideration.

2.1 Developments in Agrivoltaics

Empirical research has investigated various agrivoltaic applications, ranging from co-location with livestock (e.g., Andrew, 2020; Lytle, 2020), crops (e.g., Dupraz et al., 2011; Elamri et al., 2018; Amaducci et al., 2018; Sekiyama & Nagashima, 2019), fish in aquavoltaics (Pringle et al., 2017), and green roofs (Bousselot et al., 2017). Researchers have demonstrated in various contexts and climates that agrivoltaic systems are a practical innovation that not only reduces reliance on fossil energy but provides an adaptation method to conventional agricultural production that guards against drought and heat stress (Hassanpour Adeh et al., 2018; Elamri et al., 2018; Barron-Gafford et al., 2019; Ott et al., 2020). From an environmental perspective, lifecycle assessments show that agrivoltaic systems have similar environmental performance in comparison to traditional PV installations but provide valuable auxiliary benefits of crop production stabilization, reduced land occupation, and greenhouse gas emission mitigation (Agostini et al., 2021; Pascaris et al., n.d.). Not only have the tested applications been diverse and regionally appropriate, but the PV module technology itself has evolved to support integration with agricultural production (Riaz et al., 2019; Perna et al., 2019; Thompson et al., 2020). Cumulatively, these technological advances exhibit the viability of the agrivoltaic innovation, yet scarce consideration has been given to the socio-political context of development.

Scholars who have studied the diffusion of technology (e.g., Rogers, 1962; Grübler, 1996; Guerin, 2001; Karayaka et al., 2014) emphasize that no matter how innovative a technology may be, social factors play a deciding role in its realization. Empirical research that places agrivoltaic technology in a social context remains sparse (e.g., Ketzer et al., 2019; Pascaris et al., 2020, 2021; Li et al., 2021), leaving questions about the role of key stakeholders, policy, and legal frameworks in the diffusion of agrivoltaics unanswered. A recent study by Pascaris et al. (2021) suggests that the potential for agrivoltaic systems to increase community acceptance of solar development by retaining agricultural interests is a key opportunity for this technology, as social resistance can hinder renewable energy projects (Ribeiro, 2001; Sovacool & Ratan, 2012; Carlisle et al., 2015; Carlisle et al., 2016; Swain, 2019). Continued investigation of agrivoltaics from a social science perspective will be critical for a comprehensive identification of the opportunities and barriers to the diffusion of this innovation.

2.2 The Function of Policy in Technology Diffusion: A Brief Overview

Because technology transfer and adoption occur within a legal context (Guerin, 2001), policy makers and related stakeholders can play a central role in shaping a supportive regulatory environment for the diffusion of an innovation. Currently, there is a modest legal infrastructure in place to support solar development in the U.S. at both federal and state levels of government. A combination of federal subsidies and state renewable portfolio standards have driven an increase in solar PV generating capacity in the U.S. (Wiser et al., 2008), which exemplifies the function of government in technological diffusion. Incentives and regulations can facilitate the diffusion of renewable energy technologies (Jarach, 1989; Karakaya et al., 2014), and more specifically, empirical research shows that energy policy support schemes have had a significant impact on the diffusion process of solar PV (Jarach, 1989; Chowdhury et al., 2014).

When considering existing regulatory mechanisms for solar energy in the U.S., two federal level financial instruments are of most relevance for agrivoltaics. Administered independent of one another, the Business Energy Investment Tax Credit (ITC) provided by the Internal Revenue Service (IRS) (IRS, 2014) and the Rural Energy for America Program (REAP) Loan Guarantees and Grants issued by the U.S. Department of Agriculture (USDA, 2011) supply financial support to install renewable energy systems, including solar PV. While these federal level incentives are considerable and pertinent to agrivoltaic development, authority over private property and land use are constitutionally deferred to subnational governments as police power rights (Zoning in the United States, 2020). This subnational jurisdiction over solar energy development (Klass & Wiseman, 2017) leads to variations in state and localized zoning schemes and can complicate the realization of energy projects. The implications of these multi-level governance interactions are further considered in Section 4.

Despite their agricultural function, agrivoltaics are classified as energy systems and therefore are subject to the permitting and regulatory process of a conventional solar PV installation. This means dual use developments are legally managed as energy infrastructure, with the added condition of placement on designated agricultural land. Therefore, this study analyzes the U.S. legal framework from a solar PV policy perspective. The goal is to analyze solar PV siting regimes within the context of agricultural land development to identify if there are contradictions or restrictions at various levels of government.

2.3 A Case Study

The State of Massachusetts is currently the only state in the U.S. that has a policy program designed specifically for agrivoltaics. The Solar Massachusetts Renewable Target (SMART) program (MDOER, 2018a) establishes regulations in the form of an Agriculture Solar Tariff Generation Unit (ASTGU) (MDOER, 2018b) to explicitly incentivize agrivoltaic development. This state level initiative to financially support innovative solar projects on farmland is novel and unparalleled, representing a logical case study for the purpose of understanding the relevant legal framework involved in its execution. An analysis of the State of Massachusetts' ASTGU provision provides an opportunity to empirically examine solar policy and governance in the U.S. through the embedded, multi-level policy regimes at play to assess any conflict or shortcomings within the U.S. legal framework more broadly. The SMART program represents the most complete set of data in terms of legal documents, and therefore can provide early insight about the laws and regulations that are directly connected to its enactment, which can inform forthcoming initiatives.

3. Literature Review

The development of combined solar energy and agriculture systems presents a multi-level, multi-sectoral policy challenge, which suggests that a proactive and integrated approach to governing their diffusion will be necessary. Recognizing the complex nature of the governance regimes in which agrivoltaic systems are embedded, this study represents an early effort to identify the needed components for a comprehensive legal framework to support this technology. Positioning this effort within broader discussions of policy integration provides opportunity to conceptualize agrivoltaic development as a multidimensional process that can be strengthened through consistency and coordination of relevant policy efforts, both horizontally and vertically.

3.1 Policy Integration

There are many concepts used among policy scholars to describe the challenge of systematically aligning governance regimes towards mutual and reinforcing goals, including: policy fragmentation (Kontopoulos & Perotti, 1999), disjointed government (Pollitt, 2003), departmentalism (Christensen and Lægreid 2007), sectorization (Verbji, 2008), and siloisation (Schelly & Banerjee, 2018). There are also different expressions of concepts to describe possible solutions to such challenges, which are often used interchangeably, such as: policy coordination (Stead & Meijers, 2004), joined-up government (Bogdanor, 2005), policy coherence (May et al., 2006), polycentric governance (Berardo & Lubell, 2016), and policy integration (Lafferty & Hovden, 2003; Nilsson & Persson, 2003; Persson, 2004; Candel & Biesbroek, 2016). Despite slight variations in definitions, these concepts all seek to achieve compatibility among the objectives of different policy domains and ultimately establish a holistic, networked form of governance that creates synergies or at least reduces conflict (Peters, 2015; Cejudo & Michel, 2017; Biesbroek & Candel, 2019). These approaches forge inter-dependencies between policy domains to overcome siloisation, eliminate contradictions, and ultimately make policy goals more realizable (Briassoulis, 2005).

Cejudo & Michel (2017) define policy integration and coherence as the outcome of coordination, suggesting that attempts to deal with crosscutting policy problems will require the involvement of multiple levels and sectors of government. Policy integration is the product of intentional efforts to create an overarching regulatory framework that accounts for the complexity of multi-regime interactions and the multidimensional nature of policy (Howlett & Del Rio, 2015). While there is no standardized method to approach policy integration because policy problems are often context dependent (Peters, 2015), opportunities to mitigate contradictions in regulatory frameworks and generate synergies exist at both horizontal and vertical levels of government (Howlett & Del Rio, 2015).

Horizontal and vertical policy integration act as conduits to fill gaps within or across domains, facilitate information sharing, enhance capacity building functions, and ultimately support subnational climate action (Hsu et al., 2017). Based on these insights, this study maintains that horizontal and vertical policy integration efforts early in the development of a legal framework that supports agrivoltaics will be fundamental for diffusion, as these systems crosscut both government levels and policy domains.

3.2 Horizontal Alignment

Horizontal alignment within the context of policy integration concerns interactions between policies, instruments, and goals in a single level of government or sector of policy making (Howlett & Del Rio, 2015). Policy integration at the horizontal level involves government agencies either intentionally avoiding conflict (negative coordination), or actively pursuing common objectives that overcome policy gaps (positive coordination) (Jacob & Volkery, 2004; Peters, 2015). The traditional approach to decentralized or specialized government units was originally pursued to increase effectiveness and accountability (Cejudo & Michel, 2017) but has become an evident hinderance to the realization of synergies borne of horizontal coordination, such an enhanced coherence and policy outcomes (Peters, 2015). There are various approaches to horizontal alignment, including: other sectors may be asked or encouraged to adopt policies that support a particular objective of another sector; mutual attainment of the objectives of different sectors through pursuing a specific policy measure; or systematic cooperation where actors from one sector openly make their expertise available to another (Tosun & Lang, 2017). Horizontal alignment provides a means to address policy problems that are interconnected and transcend domains (such as agriculture and energy in this case), highlighting a necessary feature of a comprehensive legal framework for agrivoltaics.

3.3 Vertical Alignment

Vertical alignment is characterized by the coordinating of policies between levels of government (Hsu et al., 2017). The vertical dimension of policy integration involves different levels of goals, policies, and sectors, requiring administrative coordination and presenting significant institutional obstacles (Jordan & Lenschow, 2010; Howlett & Del Rio, 2015). In instances of synergistic vertical alignment, subnational governments draw upon top-down policy support and garner financing from the federal government (Hsu et al., 2017). This vertical alignment and the subsequent leveraging of federal resources can support the autonomy of subnational governments in pursuing policy goals that would otherwise be arduous without multi-level support mechanisms (Jordan & Lenschow, 2010). Peters (2015) asserts that vertical policy integration is an effective feature of federal regimes where sovereignty is granted to subnational governments, as central governments can steer the system in a coordinated fashion. Given the necessity and benefits of vertical policy integration, the development of a legal framework that is conducive to agrivoltaic development will require both multi-level and multi-sectoral coordination efforts.

4. Methodology

This study applied Legal Framework Analysis to delineate and interpret the relevant regulations and legal acts influencing adoption of agrivoltaics and to identify barriers embedded in governance frameworks as a whole (FAO Legal Office, 2000). Legal Framework Analysis was used to discern potential contradictions or opportunities for agrivoltaics present in the legal nexus between energy and agriculture in the U.S. This analysis tool supports inquiries about legal coherence and is typically used by scholars to support the design of a comprehensive legal infrastructure (e.g., Von Bogdandy et al., 2010; Müller, 2015; Rytova et al., 2016; Kuiken & Más, 2019; Sunila et al., 2019; Schumacher, 2019). The validity of this methodology is further demonstrated by similar applications in energy policy research (e.g., Müller, 2015; Sunila et al., 2019; Schumacher, 2019).

The Food and Agriculture Organization (FAO) of the United Nations Legal Office presents a set of guidelines for conducting Legal Framework Analysis for rural and agricultural investment projects (FAO Legal Office, 2000). Using the FAO guidelines to study agrivoltaics is particularly applicable, as such projects are tied to rural and agricultural development. The guidelines offer a straight-forward approach in comparison to a traditional legal analysis study (e.g., Olujobi, 2020). The analysis follows three key steps: (1) compile applicable legal texts, (2) analyze the substance of applicable laws and regulations, and (3) identify shortcomings or contradictions within the laws and regulations under study and assess the feasibility of addressing legal constraints (FAO

2000). This study follows the FAO guidelines to analyze the multilevel legal framework associated with solar PV siting on agricultural land and the Massachusetts' SMART program agrivoltaic provisions.

The first step of this analysis entailed compiling a body of applicable legal texts. The Database of State Incentives for Renewables & Efficiency (DSIRE, 2021) and the National Archives and Records Administration (NARA, 2021) were used to screen documents and search for government agencies to determine their relevance to the nexus of renewable energy development and agriculture at three levels of government in the U.S. (federal, state, local). An initial survey of existing laws and regulations resulted in collection of 9 legal documents, which an iterative process refined to exclude those that do not exactly pertain to the nexus of solar PV and agricultural land development. The condensed sample of 7 legal documents presented in this analysis (table 1) is presumed to be sufficient as it accounts for renewable energy regimes within the context of agricultural land development at all three levels of U.S. government that are directly relevant to agrivoltaics.

Table 1: Legal documents included in analysis

Policy	**Level of Government**	**Legal Authority**	**Core Purpose**	**Means of Implementation**
Investment Tax Credit	Federal	U.S. Internal Revenue Service	To provide an economically valuable tax incentive to taxable business entities that invest in	Corporate tax credit

			renewable energy technologies	
Rural Energy for America Program	Federal	U.S. Department of Agriculture	To provide financial assistance to rural small businesses and agricultural producers to purchase, install, and construct renewable energy systems	Loan or grant
Solar Massachusetts Renewable Target (SMART) Program	State	Massachusetts Department of Energy Resources	To establish a statewide solar incentive program that promotes long-term, cost-effective solar development	Incentive
Agriculture Solar Tariff Generation Units (ASTGU) provision	State	Massachusetts Department of Energy Resources; Massachusetts Department of Agricultural Resources	To incentivize the development of diverse solar installations that provide unique dual-use benefits	Tariff-based incentive
Massachusetts Zoning Act (Chapter 40A, Section 3)	State	The General Court of the Commonwealth of Massachusetts	To outline subjects which local zoning ordinance or by-law may not regulate	Zoning enabling law
Massachusetts Actions for Private Nuisances (Chapter 243, Section 6)	State	The General Court of the Commonwealth of Massachusetts	To declare limitations on actions against farming operations	"Right to Farm" bylaw
Smart Growth/Smar	Local	Massachusetts Executive Office of Energy and	To serve as a resource for model bylaws	N/A

t Energy Toolkit	Environmental Affairs	and case studies for smart growth and smart energy strategies

The second step of this analysis involved analyzing the substance of the relevant laws and regulations (FAO, 2000). By investigating the clarity of institutional mandates, looking for contradictory provisions within sectoral legislation, and identifying the allocation of legal authority, the legal framework associated with agrivoltaics was defined. An in-depth review of the policy documents that were found to have direct implications for solar energy development on agricultural land (table 1) was undertaken.

The final step in this analysis was to identify any shortcomings or contradictions within the laws and regulations under study and assess the feasibility of addressing the present legal constraints (FAO, 2000). After determining the inhibiting features of the legal framework, this method maintains that opportunities to modify those features to mitigate their impact be proposed by outlining what type of government action or change in regulation is required to address the identified barriers. For this study, potential inhibitors to agrivoltaic development were identified and practical, empirically based recommendations for modifying an existing state level agrivoltaic policy initiative were proposed. The resulting recommendations reflect an objective assessment of multi-level regime interactions and aim to contribute to an enabling legal framework for agrivoltaics in the U.S.

5. Results & Discussion

Results reveal that there is no evidence of consequential conflicts embedded within renewable energy support mechanisms as related to agricultural land development at the national level. Because there is no variance in the way federal law is applied throughout the U.S., it is assumed that this discussion will be of relevance to any state pursuing agrivoltaics that may wish to modify their regulatory approach accordingly. Subnational regulatory environments in the U.S. differ spatially but generally state-level energy policy allows for agrivoltaic development, given the relevant local authority is in accord. Results further identify local level zoning as the most significant catalyst or inhibitor for agrivoltaic development. The following discussion considers in more detail how the current legal system sets the stage for agrivoltaics in the U.S., outlining relevant regulations, their interactions, and their position within an enabling legal framework. Further, effective legal analysis requires the identification of feasible options for improving the relevant legal framework (FAO, 2000), and therefore recommendations for modifying the Massachusetts' SMART program agrivoltaic policy model are provided. These findings highlight that an effective legal framework for agrivoltaics will need to align energy and agricultural land use regimes at all levels of government and reflect recent advances in solar PV technology.

5.1 Federal Level Solar Energy Incentives

The Business Energy Investment Tax Credit (ITC) administered by the U.S. Internal Revenue Service (IRS) is a federal financial incentive that serves as the sole corporate tax credit available for solar technologies (IRS, 2014). To be eligible to receive the ITC, developers must be for-profit or otherwise pay taxes, which limits nonprofit developers or relatively low-income, small scale firms from taking advantage of the credit. Further, while the ITC acts as an effective catalyst for solar development, it is limited temporally by established expiration dates, which creates investment uncertainty and may prove to stall the construction of new facilities absent of Congressional action to continue the credits. Despite the limitations on eligibility and potential inhibitor to new agrivoltaic developments, there are no restrictions related to where eligible facilities may be established nor on power generators seeking to receive both the ITC and other financial support. Given there are no stipulations around developments on certain land types and the potential to compound financial incentives allowed by the ITC, this federal subsidy allows for agrivoltaics notwithstanding its impending expiry.

Administered by the U.S. Department of Agriculture (USDA), the Rural Energy for America Program (REAP) Grants & Loan Guarantees offer financial assistance for the construction of eligible solar energy systems by agricultural producers and small rural businesses (USDA, 2011). The Food, Conservation, and Energy Act of 2008 established the REAP to promote renewable energy for agricultural producers, inadvertently serving as a subsidy for agrivoltaic systems. The REAP grant is designed to cover up to 25% of a proposed project cost, which can be combined with a loan guarantee not to exceed $25 million. This opportunity for agricultural producers to unify grants and loans represents significant assistance for interested parties. Under this program, solar PV technology is not accompanied by any restrictions pertaining to specific design parameters, making the REAP a substantial financial opportunity for agrivoltaic development.

Together, the IRS ITC and USDA REAP form a functional federal regulatory environment that allows solar development on agricultural land. These federal energy policy mechanisms interact complementary rather than in conflict for agrivoltaics, demonstrating horizontal alignment of these regimes is an enabling feature of the national legal framework. Considering this, no recommendations are made pertaining to legal barriers, but rather to capitalize on opportunities provided by these horizontally aligned energy regimes. Based on the potential for joint ownership of an agrivoltaic system between both a solar company and an agricultural producer, it is possible to receive both the ITC and the REAP grant & loan guarantee in tandem. The acquisition of compounded financial support could significantly reduce economic barriers to development for interested parties and effectively catalyze the development of agrivoltaic systems, notwithstanding impending expiry of the ITC. Vertical alignment of subnational agrivoltaic initiatives are not constrained by these federal regimes, therefore these incentives from both sectors at the federal level are supporting features of the U.S. legal framework for combined solar energy and food systems.

5.2 State Level Legal Framework for Agrivoltaics

Renewable portfolio standards (RPS) are a state level regulatory mechanism that mandate utilities to derive a certain percentage of their electricity from renewable energy sources (NREL). RPS can be used strategically to encourage the deployment of a particular technology using “carve-out” provisions, which is commonly used to drive an increase in solar energy generation (NREL). At least 21 U.S. states and Washington D.C. have solar carve-out provisions in their RPS policies (Shields, 2021). The magnitude, structure, and presence of RPS vary across the U.S.; currently the District of Columbia and 29 states have adopted RPS, including the State of Massachusetts.

Massachusetts’ RPS features a Class II Solar Carve-out to support new PV installations, which has progressively evolved into the launch of the Solar Massachusetts Renewable Target (SMART) program (MDOER, 2018a). The SMART program is a 3,200MW declining block incentive, which includes provisions for Agriculture Solar Tariff Generation Units (ASTGU) (i.e., agrivoltaic systems). These regulations are discussed in depth in subsection 5.2.1. The presence of the RPS and the embedded solar incentive form an enabling regulatory environment for solar development at the state level that is not constrained by surrounding vertical policy dimensions, highlighting key elements of a legal framework that will allow agrivoltaics. The following subsections detail the state level framework associated with the Massachusetts ASTGU provision and identify opportunities to modify constraining features.

5.2.1 Agriculture Solar Tariff Generation Units

Pursuant to the SMART program, MDOER enacted guidelines establishing Agricultural Solar Tariff Generation Units (ASTGU) (MDOER, 2018b). To stimulate the desired installation of solar systems that provide dual-use benefits on agricultural lands, the ASTGU incentive was developed in consultation with the Massachusetts Department of Agricultural Resources (MDAR). This provision defines an ASTGU as a solar generation unit that is located on farmland and intentionally allows for the continued use of the land underneath the array for agriculture purposes. To qualify as an ASTGU and receive the associated Compensation Rate Adder (tariff) of $0.06/kWh, solar generation units are expected to optimize a balance between agricultural production and electricity generation. The provision limits maximum capacity to no more than 2MW and establishes system design parameters such as raised racking requirements and direct sunlight specifications to ensure the agricultural function of the land beneath the array is maintained. Aimed at maximizing innovation, the ASTGU offers compounding Compensation Rate Adders in which a developer is incrementally rewarded for incorporating energy storage into the system, utilizing solar tracking technology, or off-taking. The potential for solar developers to accumulate greater compensation based on their ability to design innovative agrivoltaic systems acts as a significant support for development. Further, solar generation units proposing to qualify as an ASTGU may be exempt from the SMART program's "Greenfield Subtractor" that is otherwise deducted from the Base Compensation Rate. This exemption effectively rewards development that foregoes new land disturbance and allows ASTGUs to receive higher compensation. Leveraging both the compounding Compensation Rate Adders and the avoidance of the Greenfield Subtractor, the ASTGU is a strong supporting mechanism for agrivoltaic development at the state level.

The ASTGU incentive program both outlines system parameters (capacity, design) to protect the agricultural function of the land and provides solar developers compensation for pursuing agrivoltaic projects. This policy is among the first designed specifically for agrivoltaics, and it provides evidence that the system parameters and developer compensation are necessary features of a state level legal framework as they uphold agricultural interests while stimulating an increase in solar generating capacity. Other states interested in increasing the deployment of dual use systems could adopt these key components of the Massachusetts' ASTGU provision and consider the recommended modifications (table 2) to support agrivoltaics, as they provide a foundation for forthcoming initiatives to advance both agricultural and solar energy production in a manner that is environmentally and economically sustainable. Along with outlining the strong features of the ASTGU provision, this analysis has identified potentially constraining features.

Despite the ASTGU's ability to stimulate agrivoltaic development, the program itself is marked by system design requirements and regulatory hurdles that may discourage interested parties. Solar facilities seeking to qualify for the ASTGU incentive must conform to specific system parameters including a raised racking system to elevate the array to a height that can accommodate agricultural machinery and labor (minimum height of lowest panel to be 8 feet above ground). This provision imposes heavily on hardware costs and may in effect nullify the financial gain provided by the Compensation Rate Adder. In addition, ASTGUs must achieve maximum direct sunlight requirements for the land underneath the panels by adhering to panel spacing and shading parameters. Such spacing and shading parameters may compromise the productive capacity of the array and deter solar developers who are intrinsically interested in prioritizing power generation to obtain output that satisfies their Power Purchase Agreement. Common agrivoltaic applications such as integration with specialty crops (Barron-Gafford et al., 2019) or small-statured livestock (Mow, 2018) have proven successful without requiring alterations to panel height or spacing, suggesting that the need to elevate and reconfigure the array is context-dependent. Modified system design is contingent on the agricultural function of the land, therefore such parameters could be imposed only when deemed appropriate or alternative methods for maintaining PV area while allowing crop growth could be considered (Perna et al., 2019). Further, surrounding these system design parameters are regulatory burdens such as annual reporting to both Massachusetts Department of Energy Resources (MDOER) and Massachusetts Department of Agricultural Resources (MDAR), performance guarantee deposits, performance standards certificates, as well as the need to obtain federal qualifying facility status from the Federal Energy Regulatory Commission (FERC). Together, these program requirements are constraining features of the state level framework that may counter the intention to catalyze agrivoltaic development.

Table 2 below outlines the major features of the ASTGU provision and highlights potential constraints that may inhibit agrivoltaic development. Based on this analysis, recommendations are made for other U.S. states considering a similar policy program to either retain or revise the features of the ASTGU provision. For the stimulus provided by the ASTGU incentive to overcome its embedded challenges will require Compensation Rates to be continuously adjusted to exceed the sum of hardware and labor costs involved in system design and installation. The potential for this program to be a key component of an enabling legal framework for agrivoltaics is dependent on its ability to appeal to developers, both in terms of financial gains and in terms of regulatory simplicity. This state level initiative can serve as a model regulation to other states and can potentially be the most effective element of a comprehensive legal framework for agrivoltaics in the U.S., given the identified constraints are further considered and addressed.

Table 2: SMART program ASTGU provision features

Major Feature	**Catalyst or Inhibitor**	**Recommendation**
Compounding Compensation Rate Adders	C	Retain
Exemption from new land disturbance deductions	C	Retain
Raised racking system requirements	I	Revise[1,2]

[1] See alternative panel types and configurations: Riaz, M.H.; Younas, R.; Imran, H.; Alam, M.A.; Butt, N.Z. Module Technology for Agrivoltaics: Vertical Bifacial vs. Tilted Monofacial Farms. arXiv 2019, arXiv:1910.01076.
[2] See flexible open-source racking systems: Buitenhuis, A.J.; Pearce, J.M. Open-source development of solar photovoltaic technology. *Energy Sustain. Dev.* 2012, 16, 379–388;
Wittbrodt, B.; Pearce, J.M. 3-D printing solar photovoltaic racking in developing world. *Energy Sustain. Dev.* 2017, 36, 1–5.

Panel spacing and shading parameters	I	Revise[3,4]
Regulatory complexity	I	Revise

[3] See options for spacing optimization: Perna, E. K. Grubbs, R. Agrawal and P. Bermel, "Design Considerations for Agrophotovoltaic Systems: Maintaining PV Area with Increased Crop Yield," 2019 IEEE 46th Photovoltaic Specialists Conference (PVSC), Chicago, IL, USA, 2019, pp. 0668-0672, doi: 10.1109/PVSC40753.2019.8981324.

[4] See alternative modules for shading optimization: Thompson, E. P., Bombelli, E. L., Shubham, S., Watson, H., Everard, A., D'Ardes, V., ... & Bombelli, P. (2020). Tinted Semi-Transparent Solar Panels Allow Concurrent Production of Crops and Electricity on the Same Cropland. *Advanced Energy Materials*, 10(35), 2001189.

Recommendations for revision of the raised racking and panel spacing/shading requirements are based on recent innovations in solar PV hardware designed specifically for agrivoltaics (e.g., Riaz et al., 2019; Perna et al., 2019; Thompson et al., 2020). First, vertical bifacial modules (Riaz et al., 2019) and arrays with racking systems that can be manually adjusted to be either perpendicular or parallel to the ground can overcome concerns about accommodating farming equipment and long-term land use (Buitenhuis & Pearce, 2012; Wittbrodt & Pearce, 2017). Second, research shows that patterned panel designs with smaller modules as well as east-west tracking configurations create more optional conditions for plant growth while maintaining the same area of PV (Perna et al., 2019). These innovations demonstrate that it is feasible to address potential impacts of panel packing density on solar radiation received by the land beneath the array and therefore can reduce concern about compromised agricultural productivity, which the ASTGU system parameters were designed to protect. In addition, studies show that tinted or semitransparent modules improve the photosynthetic use of solar radiation; semitransparent modules selectively utilize different light wavelengths for energy and crop production, thus allowing optimization of the solar resources available on a single plot of land (Thompson et al., 2020). Forthcoming agrivoltaic policy should reflect the emergence of these innovations and allow for more flexibility in system design that upholds agricultural productivity yet does not compromise the generating capacity of the solar array. Minimizing complexity and the added costs to solar developers by allowing for more flexibility in system design will be important to stimulate development (Pascaris et al., 2021).

5.2.1.1 State Level Feed-in Tariff

The SMART program was developed in 2018 by the Massachusetts Department of Energy Resources (MDOER) to create a long-term sustainable solar incentive program by supporting diverse solar PV installation types through use of a RPS and feed-in tariff (MDOER, 2018a). A feed-in tariff is a regulatory instrument intended to provide long-term investment security in renewable energy development by mandating retail electric providers to establish contracts with premium rates over a fixed period with generating facilities (Thibault, 2014). However, state level decision-making and feed-in tariff implementation is vertically constrained and complicated by federal level regulatory structure, highlighting a conflict in vertical alignment of energy regimes. Split between federal and state governments, the nature of public utility regulation in the U.S. is not conducive for successful feed-in tariff implementation (Thibault, 2014). Further, feed-in tariffs need continuous price adjustments to properly respond to cost reductions in renewable energy technology. Considering the complexity of state level feed-in tariff implementation in the U.S. imposed by vertical challenges and their growing obsolescence in light of declining solar technology prices, it is unclear whether this policy tool can serve to support solar development effectively.

Given the vertically complicated energy regulatory structure and low solar technology prices in the U.S., the suitability of the SMART program's feed-in tariff is questionable yet innovative in terms of the agrivoltaic component. The ASTGU provision (detailed in subsection 5.2.1.) is unique in the sense that it mandates a raised racking system and spacing requirements, which imposes increased capital costs on solar developers that may be unattractive absent of the premium price guarantee provided by the tariff. The relatively aggressive rate of $0.06/kWh is an effective way to ensure investment security in agrivoltaic systems, which are subject to higher hard costs compared to conventional PV facilities, as per the system design parameters of the ASTGU provision. Seeking maximum deployment of agrivoltaic systems, the use of a feed-in tariff may prove effective for this innovation specifically. Implementing a feed-in tariff designed discretely to support developers pursuing agrivoltaic applications could facilitate agrivoltaic adoption.

5.3 State Zoning Laws

Authority over private property and land use is constitutionally deferred to subnational governments (Zoning in the United States, 2020). State governments can exercise this power by determining the nature of zoning schemes with zoning enable laws (Zoning in the United States, 2020). Looking at Massachusetts as a case study, their General Laws establish a permanent legal foundation for the state. Part 1 Administration of the Government Title VII Cities, Towns, and Districts Chapter 40A *Zoning* (Massachusetts Zoning Act) (MGL, 2019a) details the regulations associated with zoning ordinances and by-laws, having direct implication on land and energy development. Section 3 of Chapter 40A *Zoning* concerns subjects which zoning may not regulate, maintaining that:

> …Nor shall any such ordinance or by-law prohibit, unreasonably regulate, or require a special permit for the use of land for the primary purpose of commercial agriculture…Nor prohibit, unreasonably regulate, or require a special permit for the use, expansion, reconstruction, or construction of structures thereon for the primary purpose of commercial agriculture…
>
> No zoning ordinance or by-law shall prohibit or unreasonably regulate the installation of solar energy systems or the building of structures that facilitate the collection of solar energy, except where necessary to protect the public health, safety or welfare.

In horizontal alignment with these laws, agrivoltaic systems were defined by the MDOER as solar systems that provide maximum dual output of both solar power and agricultural products. This framing effectively preserves the primary agricultural purpose of land and exempts dual-use systems from unreasonable regulation by ordinance or by-law, which demonstrates a development advantage resulting from horizontal alignment. Through the establishment of supportive zoning enabling laws for commercial agricultural land and solar energy development, the State of Massachusetts has virtually disallowed county and municipal jurisdictions from restricting agrivoltaics, except in instances that it is demonstrated as necessary to do so for public health, safety, or welfare. By horizontally aligning the ASTGU provision to be compatible with state level zoning laws that are designed to impose vertical restrictions on local government, the state of Massachusetts has established an enabling legal framework for agrivoltaics, which demonstrates the consequence of deliberate policy integration in both directions.

Further, Section 6 of Chapter 243 *Actions for Private Nuisances* (MGL, 2019b) declares limitations on actions against farming operations, stating that:

> No action in nuisance may be maintained against any person or entity resulting from the operation of a farm or any ancillary or related activities thereof, if said operation is an ordinary aspect of said farming operation or ancillary or related activity; provided, however, that said farm shall have been in operation for more than one year.

Such limitations on actions for private nuisances are known as “Right to Farm Bylaws” (Tovar, 2019). The objective of these state restrictions is to simultaneously protect and encourage the development of farm-related businesses by guarding farmers against nuisance lawsuits (Pioneer Valley Planning Commission, 2021). The Right to Farm language embedded in state statutes as presented above is intended to promote agriculture-based economic opportunities by allowing agricultural uses and related activities to function with minimal conflict from town agencies. Within the State of Massachusetts, local communities can adopt their own Right to Farm bylaws to further emphasize interest in protecting local farming operations and related activities (Pioneer Valley Planning Commission, 2021).

These state-level zoning enabling laws related to commercial agricultural land, solar energy development, and limitations on actions against farming operations establish a favorable regulatory environment to deploy solar energy systems on farmland. Because these zoning enabling laws are not inhibiting agrivoltaic development, but are rather catalyzing it, this study maintains that they are a supportive mechanism for state governments pursuing increased deployment of combined solar and agriculture systems. While these laws are strong features of a state-level legal framework for agrivoltaics, preempting local zoning control of agricultural land development has potential justice implications, therefore modifying these features to mitigate their impact on rural communities must be considered. It is suggested that states interested in advancing agrivoltaics by modeling these Massachusetts zoning enabling and Right to Farm laws grapple with justice concerns related to state lawmakers superseding the decisions of local leaders. To avoid such challenges and their potential negative externalities, states may consider alternative approaches to support agrivoltaics without disempowering local communities in agricultural development decision-making and employ policy incentive mechanisms that are not underscored by state land use controls. Because this analysis seeks to identify opportunities and barriers to agrivoltaic development rather than question the soundness of existing laws and regulations, the zoning enabling and Right to

Farm laws which support dual-use systems are maintained as key features of a comprehensive enabling legal framework.

5.4 Legal Framework at the Local Level

In the U.S., state and local governments have "police power" rights, which grant authority over the development of land use laws (Zoning in the United States, 2020). Additionally, the Tenth Amendment of the U.S. Constitution makes the structure and degree of power granted to local governments a matter of state law than federal law (U.S. Const. amend. X). These various forces have resulted in a diverse range of local government systems that have different levels of authority over land use (Local Government in the United States, 2021). Most U.S. states have two tiers of local government: county and municipality, which are further broken down into different types of municipal level jurisdictions such as cities, villages, and towns (Local Government in the United States, 2021). Identification of which level of government holds the authority over land use is therefore convoluted and context-specific across the nation. This high variability in local level governance over land development and zoning suggests that a subnational legal framework for agrivoltaics will differ spatially and will need to be adapted by each county or municipality according to local circumstance.

Local governments have discretion over the design of zoning regulations and use them to reflect the long-term visions of the community. In theory, the primary intent of zoning is to segregate land uses that are deemed incompatible, but in practice zoning is a permitting system that can direct and restrict patterns of development from threatening existing interests (Zoning in the United States, 2020). In the context of renewable energy development, a feasible strategy is to position these land uses to serve existing community goals such as economic growth, diversification of tax base, job creation, localization of energy generation, or farmland preservation (Light et al., 2020). Zoning regulations are among the primary considerations impacting a developer's ability to site a renewable energy project (Light et al., 2020). Light et al. (2020) explain that when it comes to renewable energy development, if zoning regulations do not explicitly allow for such land use then it is likely prohibited. Because renewable energy is a relatively new land use, not all jurisdictions have incorporated plans to accommodate such facilities. For example, only 19% of zoning ordinances in the State of Michigan explicitly address the siting of utility scale solar projects (EGLE, 2020), suggesting that there is opportunity for municipalities to be proactive, thoughtful, and strategic in deciding whether, where, and how agrivoltaic projects fit into their community.

The absence of explicit zoning schemes or presence of strict regulations for renewable energy is a barrier for agrivoltaics. However, an absence of zoning regulations presents an opportunity to proactively and strategically develop comprehensive plans that specify implementation of solar energy systems on agricultural land and signal receptivity to developers. Local governments interested in supporting agrivoltaic system deployment can draw insight from existing solar permissive model ordinances (e.g., Becker, 2019) as well as leverage a range of zoning regulation techniques (e.g., Horner et al., 2018). First, zoning for agrivoltaics can be accomplished by designating certain districts as eligible for siting by use of overlay districts. An overlay district to support agrivoltaics would entail conditional or special permit uses that are permissive of solar in certain zones (Gravin, 2001). Local governments pursuing this approach could, for example, designate certain regions of farmland that receive abundant solar insolation relative to other areas of the state as an eligible overlay district for agrivoltaics. To utilize such an overlay district, a developer would have to apply to have the land rezoned to accommodate solar infrastructure on farmland. Second, zoning regulations may be designed to impose land use standards upon solar developers, requiring the submission of decommissioning plans that outline removal procedures and site restoration. Requiring financial guarantees or surety bonds for decommissioning is common practice among municipalities to further the effectiveness of such land use standards. Third, local governments may consider outlining different zoning requirements based on the scale and type (i.e., temporary versus permanent) of solar installation. Site requirements for temporary installations on farmland may assessed differently, given that they are intended to allow land use in the future and provide opportunistic income diversification for farmers. Lastly, given the steady rate of innovations in energy technology, local governments with established renewable energy zoning schemes that are interested in increasing agrivoltaic development should reconsider whether their ordinances explicitly allow for these systems. The above options to amend or adopt zoning ordinances that are permissive of solar infrastructure on farmland are proactive and powerful approaches to establishing a favorable regulatory environment for agrivoltaics at the local level.

Further, as urban sprawl and its associated high electric infrastructure costs and loss of green space become growing challenges faced by local governments (Nechyba & Walsh, 2004), there has been a shift towards mixing land uses rather than segregating them (Michigan Townships Association, 2021). "Smart Growth" is considered a principle of land development that prioritizes innovative mixing of land uses and compact design, aimed to enhance quality of life and protection of natural resources (Executive Office of Energy & Environmental Affairs, 2020). Smart Growth can support a community in crafting bylaws to protect their unique interests and to implement zoning ordinances in pursuit of a specific objective (Executive Office of Energy & Environmental Affairs, 2020). Given the opportunity to apply Smart Growth principles for innovative land uses, a supportive regulatory environment at the local level for agrivoltaics must feature allowances for mixed land use, specifically solar infrastructure on agricultural land.

The results of this analysis suggest that states with zoning enabling laws and "Right-to-Farm" bylaws similar to Massachusetts more readily allow vertical alignment of solar permissive zoning regulations at the local level. By constraining what local governments can control through zoning, zoning enabling laws and "Right-to-Farm" bylaws create an opportunity to vertically align local initiatives in a manner that reduces conflict and eliminates contradictions in land use regulation. These findings demonstrate that the goal of increased deployment of agrivoltaic systems is more realizable in the presence of vertical policy alignment between state and local land use regimes.

5.6 Implications for a Multi-level Governance Framework

Overall, the legal framework in the U.S. has potential to significantly support the advancement of agrivoltaic technology. Federal subsidies provide uniform incentive for developing solar energy facilities without restriction regarding agricultural lands, while placing the authority of development permitting under the jurisdiction of subnational governments. Given that existing federal level incentives are horizontally aligned and create a permissive legal framework for agrivoltaics, state and local level governments are key actors in shaping the socio-political context in which the technology may diffuse. While there are currently no explicit efforts for policy integration between levels of government to support agrivoltaic development, this analysis has found no major inhibitors to vertical alignment of initiatives, indicating that intentional coordination could produce policy synergies to advance dual-use systems. Table 3 below outlines an ideal legal framework for agrivoltaics in the U.S. based on the findings derived from this analysis. In pursuit of increasing dual use development, recommendations are made for policy makers, land use planners, and related stakeholders.

To capitalize on the novel agrivoltaic policy program designed by the State of Massachusetts, other U.S. states may replicate aspects of their model and consider amending other components by considering the shortcomings identified in this analysis (see Table 2). Specific features of this policy to be retained in the development of other state-level agrivoltaic incentive programs include: compounding compensation rate adders, and exemption from new land disturbance deductions. Features of this policy that should be reconsidered or revised include: imposed system parameters such as raised racking, panel spacing, and shading requirements; regulatory complexity for developers.

Local-level land management and zoning strategies remain critical components of an enabling legal infrastructure for solar development on agricultural land, therefore future agrivoltaic initiatives should prioritize establishing a supportive regulatory environment at this level of government. Zoning strategies available to local governments pursuing increased agrivoltaic development include the establishment of overlay districts; agrivoltaic land use provisions; context-specific site requirements; and adoption of Smart Growth principles. Being proactive in planning for and accommodating innovative mixing of land uses will be a vital feature of a comprehensive legal framework for agrivoltaics.

Table 3: Legal framework for agrivoltaics in the U.S.

Level of Government	**Policy Tool**	**Recommendation**
Federal	IRS ITC	Congressional extension of ITC expiration dates
	USDA REAP	Joint ownership of project between solar developer and farmer so both subsidies can be obtained
State	RPS	Mandate utilities to obtain set percent of electricity from solar energy, specifically by use of a “solar carve-out”[5]
	Feed-in tariff specifically for agrivoltaics	Set cap on MW of PV financed to protect long term agricultural interests
		Continuous price adjustments to ensure compensation exceeds added hardware costs to incentivize solar developers
		Flexible system parameters including allowed capacity size, panel height, spacing, and level of transparency[6]
	Zoning enabling laws	Explicit exemption of commercial agricultural land and solar energy systems from unreasonable county or municipal zoning regulation[7]

[5] For best RPS design practices see: NREL https://www.nrel.gov/state-local-tribal/basics-portfolio-standards.html#:~:text=A%20renewable%20portfolio%20standard%20

[6] Model from State of Massachusetts’ SMART Program ASTGU provision (Table 2)

[7] Refer to: General Laws of Massachusetts Part 1 *Administration of the Government* Title VII *Cities, Towns, and Districts* Chapter 40A *Zoning*

Local	Zoning techniques	Designation of certain zones as eligible for siting by use of overlay districts
		Land use provisions that specify regulations such as system duration, decommissioning requirements, and surety bonds
		Requirements based on the scale and type (i.e., temporary versus permanent) of solar installation
	'Smart Growth'	Shift away from land use segregation towards allowing mixed use development, explicitly solar PV infrastructure on agricultural land

6. Conclusions and Policy Implications

This study applies Legal Framework Analysis to analyze the policy environment for the diffusion of agrivoltaic systems in the U.S. Findings indicate that an enabling legal framework for agrivoltaics will need to align energy and agricultural land use regimes at all levels of government. While there are currently no explicit efforts for policy integration between levels of government to support agrivoltaic development, this analysis has found no major inhibitors to vertical alignment of initiatives. The findings indicate that proactive measures to align solar energy and agricultural land use regimes are legally feasible and can catalyze the diffusion of emerging agrivoltaic technology.

Results reveal that there is no evidence of consequential conflicts embedded within renewable energy support mechanisms as related to agricultural land development at the national level. Because there is no variance in the way federal law is applied throughout the U.S., it is assumed that these findings will be of relevance to any state pursuing agrivoltaics that may wish to modify their regulatory approach accordingly. Subnational regulatory environments in the U.S. differ spatially but generally state-level energy policy allows for agrivoltaic development, given the relevant local authority is in accord. Results further identify local level zoning as the most significant catalyst or inhibitor for agrivoltaic development.

Based on the results of this analysis, a supportive framework for agrivoltaics should arguably include a combination of federal-level subsidies from both the energy and agriculture sectors; a state-level renewable portfolio standard with solar crave-out provisions and a feed-in tariff specifically for agrivoltaic systems; and local government application of zoning techniques that allow for mixed land use between solar and agriculture. Specific zoning strategies available to local governments pursuing increased agrivoltaic development include the establishment of overlay districts; agrivoltaic land use provisions; context-specific site requirements; and adoption of Smart Growth principles. The variability in local government strategies to zoning and land development suggests that the subnational legal framework for agrivoltaics will differ spatially within the U.S. and will need to be adapted by each county or municipality according to local circumstance.

While the Legal Framework Analysis methodology was applied to the case of Massachusetts, these findings can speak broadly to U.S. states and local governments interested in agrivoltaic development. As a novel and exemplary initiative to incentivize agrivoltaics, the State of Massachusetts' SMART program ASTGU provision may serve as a template for other states adopting strategies to support increased deployment of the technology. Considering the regulatory framework in the U.S. is supportive and invariable at the federal level, the horizonal diffusion of the SMART program ASTGU provision among states may expedite agrivoltaic development and therefore an in-depth analysis has been provided to outline the catalyzing and inhibiting features of this policy (subsection 5.2.1). While increasingly obsolete as the costs of solar PV technologies plummet, a state-level feed-in tariff established specifically for agrivoltaic systems may be key in stimulating this unique energy application.

This study suggests that continued efforts for policy integration across levels and sectors of government will be critical to the establishment of an enabling legal framework for agrivoltaics in the U.S. Forthcoming agrivoltaic policy initiatives need to adapt to contemporary multi-level government complexity and consider the interaction between existing policies when formulating new ones. The results of this study may serve as a framework for future legal analysis or agrivoltaic policy development, as key regulatory opportunities and barriers to have been identified.

This study acknowledges that a multi-regime perspective to agrivoltaics must also consider fossil fuel subsidies as well as large agribusiness subsidies. Fossil fuel subsides are inconsistent with energy sector decarbonization and represent a conflicting agenda at the national level, given the existence of concurrent subsidies to encourage renewable energy production. This study recognizes this contradiction and its implications on a coherent energy policy framework but maintains that fossil fuel subsidies do not exactly impinge on the development of agrivoltaic systems and therefore have been excluded from this analysis. Fossil fuel and agribusiness subsidies are the substrate of federal level energy and agriculture regimes but this study undertakes a solar PV policy perspective to consider only renewable energy mechanisms and potential farmland development implications, therefore future work may overcome this limitation by considering these underlying multi-regime conflicts and potential impacts on agrivoltaics.

To build upon this initial Legal Framework Analysis, future research needs to consider the potential justice concerns related to states preempting local zoning decisions to advance agrivoltaics. Finding an agreeable and just solution that supports this technology without harming or disempowering agricultural communities will be critical and could support the horizontal diffusion of the Massachusetts' agrivoltaic policy to other states with similar development objectives. As agrivoltaic development becomes more commonplace, justice implications such as threats to existing agricultural interests or effects on rural electrification must be considered in full. Also, states and municipalities interested in legislative reform to facilitate agrivoltaic development will need to assess the potential impact on long-term agricultural productivity and energy portfolio diversification.

Meeting both growing renewable energy and food demands sustainably implies that agrivoltaics must become the conventional ground-mounted solar PV development practice if the U.S. is to simultaneously preserve arable land while increasing renewable energy generating capacity. To realize the synergies provided by agrivoltaic systems, a multi-level government approach characterized by horizontal and vertical alignment of solar and agriculture land use regimes will be imperative. Ultimately, combined federal and state financial mechanisms coupled with favorable local level zoning bylaws will create a comprehensive legal framework for the agrivoltaic technology to prevail.

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Chapter 5: Conclusion: Technology, Society, and Policy

1. Introduction

This thesis explores the social dimensions of the agrivoltaic innovation to identify opportunities and barriers to its diffusion. Combining theoretical frameworks on technology diffusion and social acceptance of renewable energy with expert perspectives, this work sets the foundation for understanding, addressing, and accommodating the role of society and policy in agrivoltaic development. The socio-political opportunities and barriers for agrivoltaics identified by these empirical studies can ultimately inform decision making, solar development practices, land use management, and policy making in a way that supports the furtherance of the renewable energy transition, conserves arable land, and utilizes innovative solar PV technologies.

Chapter 2 investigates the perspectives of the agriculture sector in terms of barriers to adoption of the agrivoltaic technology. Participants raised the importance of land productivity and integration with current practice, identifying opportunities to refine the agrivoltaic development process in a way that accommodates agriculturalists concerns and upholds their long-term interests. This paper demonstrates the importance of the adopter’s perspective in technology diffusion and emphasizes the need to bridge solar developers with farmers meaningfully for agrivoltaics. Rather than approaching agrivoltaic development as a one-way dissemination, the findings of this study suggest an iterative process between both energy and agriculture sectors can support a mutually beneficial refinement of the technology.

Chapter 3 engages solar industry professionals to explore their perceptions about agrivoltaic development and the associated opportunities and barriers. Participant responses centered on public perception issues and potentially advantageous community relations, highlighting the importance of the local social context of development and the role of social acceptance in agrivoltaics. By retaining agricultural interests rather than threatening them, agrivoltaic systems may be a key strategy for continued large-scale PV deployment in the face of community resistance to energy infrastructure on arable land. This study highlights the function of solar developers in the diffusion of this technology is to cultivate deliberate local partnerships and to engage stakeholders early in the development process to foster a supportive community and regulatory environment for agrivoltaics.

Chapter 4 presents a Legal Framework Analysis that evaluates to what extent the existing regulatory framework in the U.S. allows, encourages, constrains, or prevents the diffusion of agrivoltaics. By outlining an ideal comprehensive legal framework for agrivoltaics, this paper identifies policy tools that can catalyze and support the agrivoltaic technology at multiple levels of government. Given the localized variability in energy development permitting and land use management, this study advocates for subnational government efforts focused on incentivizing solar PV and easing the regulatory burdens associated with development restrictions on agricultural land. This work recognizes how the diffusion of an energy innovation is contingent on its socio-political context and argues that legal and regulatory frameworks must adapt along with state-of-the-art technologies appearing on the market to support their advancement.

2. Implications & Policy Recommendations

As the world increasingly struggles to manage finite energy and land resources, the need for renewable energy transitions coupled with land optimization techniques is imperative and unavoidable. The findings developed in this thesis can directly contribute to relieving these coupled challenges by illuminating socio-political opportunities and barriers to agrivoltaic development and offering directions for improvement. Pioneering beyond technical and economic considerations of agrivoltaics, this thesis is a testament to the significance of the social dimensions of technological innovations. A socially relevant understanding of agrivoltaics entails appreciating what is important to stakeholders, identifying complications to the development process, and accounting for the legal and regulatory environment in which the technology will operate. The insights drawn from this research effectively serve as a comprehensive manual for agrivoltaic development as the most relevant barriers that may challenge the path of diffusion have been brought to light. Solar developers, land use planners, subnational governments, and policy makers that understand energy development is a social matter with technical components rather than a technical matter with social components will find this work relevant to their attempts to pursue agrivoltaics. Ultimately, moving agrivoltaics from the laboratory to the field will require acknowledging and accommodating the social dimensions of this innovation.

Future agrivoltaic developments can be enhanced if they reflect and address the concerns raised by the agriculture sector identified in Chapter 2 of this thesis. Based on the need for long-term land productivity and system flexibility, it is recommended that solar developers engage farmers early in the development process to understand their farming practice, accommodate their technical needs, and establish liability for potential damages as well as a contract for the decommissioning of the array. This will provide farmers with the certainty of future land use and give solar developers a means to proactively build a system that is less vulnerable to opposition as it reflects local values. Farmers may also consider stipulating the use of a raised racking system or semitransparent modules to minimize impacts on land productivity and allow for changes in farming practice over the lifetime of the system. Should system design parameters by mandated, it is recommended that solar developers receive compensation in the form of a financial incentive from state or local governments to mitigate increased hardware costs, ensure profitable return on investment, and ease the burden of added development complexity.

The findings of Chapter 3 imply that solar developers need tangible benefits to encourage the development of agrivoltaic systems, as they are perceived as complex comparative to traditional PV projects. Together with enhanced community relations, advantages such as an expedited permitting process or a tax holiday may incentivize developers to pursue agrivoltaics. To ensure that the dual-revenue stream generated by agrivoltaic projects is not compromised, it is recommended that land developed for dual-use is not taxed commercially, as a typical energy development would be. Considering the agricultural function of the land is still preserved in agrivoltaics, the agricultural tax bracket should be maintained.

The Legal Framework Analysis presented in Chapter 4 highlights numerous opportunities for multi-level governance to support increased agrivoltaic deployment. Based on the success of the initiative enacted in the State of Massachusetts, it is recommended that both an RPS and a state-level feed-in tariff be implemented to financially promote agrivoltaic development. Such a feed-in tariff should include a cap on the MW of PV financed to limit the potential development footprint and therefore minimize threats to long-term agricultural productivity. Further, states that seek to support agrivoltaics may consider revising their zoning enabling laws to directly control the nature of zoning schemes surrounding solar development on agricultural land, which in effect could preempt local government restrictions of agrivoltaic projects. Lastly, it is recommended that governments with zoning authority shift away from land use segregation towards allowing mixed use development that can reconcile land conflicts and provide synergistic benefits. Such a shift would entail amending local zoning ordinances to explicitly allow solar infrastructure on farmlands and may even include setting standards for such infrastructure that mandates the agricultural function of the land is maintained.

These recommendations are based on insight drawn from the empirical studies presented in this thesis and comprehensively consider the socio-political dynamics related to energy development, land use, and policy making. This thesis does not argue that agrivoltaic systems are a panacea to all social and environmental problems but rather advocates for purposeful, prudent, and innovative means of producing both food and energy in a way that leverages existing enterprises and maximizes resource efficiency. The recommendations above consider the production of both food and solar energy as equally important and therefore seek to preserve the agricultural interests and values of communities while rewarding solar developers for innovative and locally appropriate land use. Ultimately, the agrivoltaic innovation provides opportunity to revitalize solar development practice, conserve arable land, and increase the generation of solar PV electricity, all of which contribute to a sustainable future.

3. Limitations

It is necessary to consider the implications of research design on the findings presented in this thesis. First, because the findings of chapters 2 and 3 are based on interview data, the participant characteristics such as geographic location and profession influenced the results. For example, the insights drawn from interviews with solar industry professionals may have been different if only developers with experience in agrivoltaics were engaged or if samples were drawn intentionally from specific regions in the U.S. with particular climatic conditions. The snowball and theoretical sampling methods employed, and the consequent composition of the interview samples, shaped the findings of these two studies. While not a detrimental limitation, the potential influence of these methodological choices suggests that if I were to have been more deliberate in obtaining equal representation across geographic regions and professions, the results of these interview studies may have been different as they would reflect different perspectives.

Second, the Legal Framework Analysis presented in Chapter 4 analyzes an intentionally limited set of regulatory documents. Laws and regulations that did not explicitly pertain to the nexus of renewable energy and agricultural land development were not included in the analysis, which may have limited the scope of the study or have overlooked policy that has indirect implications on agrivoltaic development. Also, this paper focuses on a single state level case study, which eschewed consideration of state level variations in energy and agricultural regimes. While the purpose of this methodological choice was to examine an existing agrivoltaic policy in the broader U.S. context, this study may have produced alternative insights if it involved an in-depth, horizontal comparison of state legal frameworks. I believe these limitations are noteworthy but not detrimental to the significance and validity of this study.

Lastly, this research is limited spatially and is only logically representative of the United States, both in terms of expert perspectives and in terms of the nature of the legal system. Efforts to assess the global potential of agrivoltaics need to explore variations in solar system siting practice and account for structural differences in regulation and control of energy development in other countries. Although these findings are directly relevant to agrivoltaics in the U.S., they provide broad insight into the potential socio-political opportunities and barriers to diffusion that other countries may face.

4. Future Work

The empirical studies presented here are merely a prelude for more extensive investigations of the social dimensions of the agrivoltaic innovation and provide a logical point of departure for future research. Considering agrivoltaic systems were commended by both the agriculture sector and solar industry, this innovation is ripe for diffusion yet needs a few supporting mechanisms to increase deployment. Of most immediate utility would be a template that outlines zoning techniques and land use bylaws that when implemented together could create a supportive local regulatory environment for solar development on farmland. Such a template would have to account for variance in subnational government systems and offer locally appropriate policy tools to accelerate and ease the development of agrivoltaic systems. An important extension of such work would be to consider the implications of land value taxes on agrivoltaic development, investigate the eligibility for dual use systems to retain agricultural tax bracket status, and identify the means to establish this potential. Further, solar developers pursuing agrivoltaics may find value in an interactive map that depicts how and where zoning authority is delegated within a state, ranks the degree of regulatory support for solar deployment, and identifies optimal locations for development that considers present agricultural practices. A map that displays these localized variations and catalogues potential sites could ease the regulatory process, circumvent land use conflicts, and expedite the diffusion of agrivoltaics.

5. Reflections

My experience as a graduate student in the Environmental and Energy Policy program and as a research assistant has significantly shaped me as a professional, a researcher, and as an individual. I prepare for graduation feeling both capable and eager to be of service at the nexus of energy, policy, and society, specifically the renewable energy transition. Not only have I learned the craft of scientific exploration, enhanced my written and oral communication skills, and expanded my problem-solving capabilities, but I have also cultivated an appreciation for the vast and meaningful world of research. My social science research endeavors have nurtured my ability to listen deeply, consider alternative perspectives, raise the voices of others, and to think globally but act locally. I feel intellectually agile and prepared to apply my learned skills to solve our world's pressing environmental and societal challenges. This research experience against the backdrop of a global pandemic has prompted me to take personal initiative and accountability for my success and I intend to carry this with me as I transition into a career in renewable energy, sustainability, and policy, which demands perseverance and optimism. With a heightened understanding about the U.S. energy system, an expertise in agrivoltaic and solar development, and a personal vocation to preserve and heal the planet, I am ready to navigate the world outside of academia and turn my energy into action.