Energy Policy 159 (2021) 112620

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Examining existing policy to inform a comprehensive legal framework for agrivoltaics in the U.S.

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ARTICLE INFO

Keywords:
Agrivoltaics
Legal analysis
Legal framework
Multi-level governance
Solar energy
Land use policy

ABSTRACT

Advances in solar photovoltaic applications demonstrate the viability of combining agriculture and solar energy production in a system known as agrivoltaics. Because scarce consideration has been given to the socio-political context of development, this study applies Legal Framework Analysis to identify barriers and opportunities for a comprehensive legal infrastructure to enable agrivoltaics in the U.S. The State of Massachusetts is used as a case study to understand what elements of their regulatory regime contribute to their novel agrivoltaic policy program, while also considering the surrounding federal and local government dynamics in which this state program is embedded. Based on the analysis results, a comprehensive legal framework for agrivoltaics should arguably include a combination of federal and state energy financing mechanisms coupled with favorable state and local land use policies. Specifically, a state-level feed-in tariff and local government allowances for mixed land use between solar and agriculture will be the key features of an enabling legal framework. The results demonstrate that multi-level, multi-sector policy integration is imperative for advancing agrivoltaics and that strategic measures to align solar energy and agricultural land use regimes can catalyze the diffusion of this promising technology in the U.S.

1. Introduction

Advances in solar photovoltaic (PV) applications (e.g., Riaz, 2019; Thompson et al., 2020) allow the combination of agricultural and solar energy production in a manner that increases global land productivity (Dupraz et al., 2011), improves crop yield and resilience (Marrou et al., 2013; Amaducci et al., 2018; Barron-Gafford et al., 2019), reduces environmental impacts (Macknick, 2019; Pascaris et al., 2021a), and provides rural economic opportunities (Dinesh and Pearce, 2016; Proctor et al., 2021). These strategically combined systems, known as agrivoltaics, have been demonstrated as a viable approach to solar development that can alleviate growing demands for both food and renewable energy (Weselek et al., 2019) while minimizing 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, 2021b, 2021c; Pascaris et al., 2020, 2021b, 2021c) and therefore it is critical that the relevant legal framework adapts along with state-of-the-art technologies appearing on the market to support their advancement. For the case of agrivoltaics in the U.S., development occurs at a nexus that is governed by different levels of government and sectors, which suggests that an intentionally comprehensive legal framework that aligns laws on energy and agricultural land use will be instrumental to 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 barriers and opportunities in the multi-level, multi-sector governance regimes that have implications on solar development and agricultural land use.

Given both the dearth and nascence of policy designed to advance agrivoltaic development in the U.S., it is unclear whether multi-level, multi-sector governance interactions play a significant catalyzing or inhibiting role. Because multiple layers of policy overlap and intersect, it is maintained that multi-level, multi-sector governance characterized by policy integration can produce synergies that address conflicts or fragmentation in legal frameworks (e.g., Leck and Simon, 2012; Harker et al., 2017; Schelly and Banerjee, 2018). As agrivoltaics transcend the traditional policy niches of the U.S. government, the development of an integrated multi-level and multi-sector legal infrastructure will be requisite to support this technology.

The purpose of this study is to analyze the extent to which existing U.S. laws and regulations allow, encourage, constrain, or prevent the diffusion of agrivoltaics and to identify the necessary features of a

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https://doi.org/10.1016/j.enpol.2021.112620
Received 24 March 2021; Received in revised form 17 September 2021; Accepted 22 September 2021
Available online 29 September 2021
0301-4215/

comprehensive legal framework that enables increased deployment. Energy researchers that recognize misalignment in policy as a critical barrier for energy investment and technological diffusion apply Legal Framework Analysis to contribute findings that create a more supportive regulatory environment (e.g., Müller, 2015; Kuiken and 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 assess what elements of their regulatory regime contribute to their novel agrivoltaic policy program, while also considering surrounding federal and local government dynamics. The results bring potential legal barriers and opportunities into full view so that forthcoming efforts to advance agrivoltaics may proactively account for the realities of the U.S. legal framework.

2. Background

Agrivoltaic systems have become recognized as a viable solution to make significant progress towards energy sector decarbonization (Mavani et al., 2019; Proctor et al., 2021) and increase crop resilience in the face of climate change (Barron-Gafford et al., 2019). To realize this potential, it is necessary to consider the socio-political context in which the technology exists, which sets the foundation for its success, as the 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 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., Malu et al., 2017; Elamri et al., 2018; Sekiyama and Nagashima, 2019), fish in aquavoltaics (Pringle et al., 2017), and green roofs (Bousselot et al., 2017). Researchers have demonstrated in diverse contexts and climates that agrivoltaics are an advantageous approach to solar development that provides an adaptation method to conventional agricultural production that guards against drought and heat stress (Hassanpour Adeh et al., 2018; Barron-Gafford et al., 2019; Ott et al., 2020) and an opportunity to increase local level acceptance of solar (Pascaris et al., 2021b). From an environmental perspective, life cycle 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., 2021a). 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 social factors play a deciding role in realization, which advises that socio-political considerations will have implications on the increased development of agrivoltaics. Empirical research that places agrivoltaic technology in a social context remains limited (e.g., Ketzer et al., 2019; Pascaris et al., 2020, 2021b; 2021c; Li et al., 2021), leaving questions about the role of key stakeholders, legal frameworks, and host communities in the diffusion of agrivoltaics unanswered. Advancing the current state of agrivoltaic development will require a multidimensional, interdisciplinary assessment of the barriers and opportunities for 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 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 deployment 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; ; Altenburg and Engelmeier, 2013; Shrimali and Jenner, 2013; Chowdhury et al., 2014; Crago and Chernyakhovskiy, 2017).

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) and the Rural Energy for America Program (REAP) Loan Guarantees and Grants issued by the U.S. Department of Agriculture (USDA) supply financial support to install solar PV. While these federal-level incentives are pertinent to agrivoltaics, authority over land use is constitutionally deferred to subnational governments as police power rights (Zoning in the United States, 2020). This subnational jurisdiction over solar energy siting (Klass and Wiseman, 2017) and agricultural land use creates a varied and complicated development landscape for agrivoltaics in the U.S. The implications of these multi-level, multi-sector governance interactions are further considered in Section 4.

Despite their agricultural function, agrivoltaic systems are subject to the permitting and regulatory process of a conventional solar PV installation, with the added condition of placement on agricultural land. Therefore, this study analyzes the U.S. legal framework from a solar PV policy perspective. The goal is to analyze solar PV regimes within the context of agricultural land use policy to identify if there are barriers or opportunities 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 incentivize agrivoltaic development. This state-level initiative is novel and unparalleled, representing a logical case study for understanding the laws and regulations that are relevant to its enactment. An analysis of the State of Massachusetts' ASTGU provision through the embedded, multi-level policy regimes at play allows an assessment of barriers or opportunities 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 to inform forthcoming initiatives.

3. Literature review

The development of combined solar energy and agriculture systems presents a multi-level, multi-sector policy integration challenge, which suggests that a proactively strategic 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 features of a comprehensive legal framework to enable widespread deployment. Positioning the advancement of agrivoltaics within broader discussions of policy integration provides opportunity to conceptualize development as a multidimensional process that can be strengthened through coordination of relevant policy efforts, both between levels of government as well as agriculture and energy sectors.

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 and Perotti, 1999), disjointed government (Pollitt, 2003), departmentalism (Christensen and Lægreid, 2007), sectorization (Verbji, 2008), and siloisation (Schelly and 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 and Meijers, 2004), joined-up government (Bogdanor, 2005), policy coherence (May et al., 2006), polycentric governance (Berardo and Lubell, 2016), and policy integration (Lafferty and Hovden, 2003; Nilsson and Persson, 2003; Persson, 2004; Candel and 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, 2018; Cejudo and Michel, 2017; Biesbroek and Candel, 2019). These governance approaches forge inter-dependencies between policy domains to overcome siloisation, eliminate contradictions, and ultimately make policy goals more realizable (Briassoulis, 2005).

Cejudo and 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 and 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 and 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 for 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 and 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 and Volkery, 2004; Peters, 2018). The traditional approach to decentralized or specialized government units was originally pursued to increase effectiveness and accountability (Cejudo and Michel, 2017) but has become a hindrance to the realization of synergies borne of horizontal coordination, such an enhanced coherence and policy outcomes (Peters, 2018). 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 and 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, which requires administrative coordination and presents significant institutional obstacles (Jordan and Lenschow, 2010; Howlett and 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 and Lenschow, 2010). Peters (2018) 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 assess the regulations and legal acts relevant to the diffusion of agrivoltaics in the U.S. (FAO Legal Office, 2000). Legal Framework Analysis was used to discern potential barriers and opportunities for agrivoltaics present in the legal nexus between solar energy and agricultural land use and to outline an ideal legal framework to enable the advancement of the technology. 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 and 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), which is particularly applicable to agrivoltaics, as such projects are tied to rural and agricultural development. The guidelines offer a straight-forward approach in comparison to a traditional legal framework study (e.g., Olujobi, 2020). The analysis presented herein follows three key steps: (1) compile applicable legal texts, (2) analyze the substance of the laws and regulations, and (3) identify barriers or opportunities within the laws and regulations under study and assess the feasibility of addressing legal constraints (FAO, 2000). This study followed the FAO guidelines to analyze the multi-level, multi-sector legal framework associated with solar PV and agricultural land use in the U.S., using the Massachusetts' SMART program agrivoltaic provisions as a state-level case study.

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 agricultural land use 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 excluded those that do not exactly pertain to the nexus of solar PV and agricultural land use. The refined sample of 7 legal documents presented in this analysis (Table 1) is presumed to be

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 renewable energy technologies	Corporate tax credit
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/Smart Energy Toolkit	Local	Massachusetts Executive Office of Energy and Environmental Affairs	To serve as a resource for model bylaws and case studies for smart growth and smart energy strategies	N/A

sufficient as it accounts for solar energy regimes within the context of agricultural land use at all three levels of U.S. government that are directly relevant to agrivoltaics.

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 barriers or opportunities 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 be proposed by outlining what type of government action or change in regulation is required to mitigate the identified barriers. For this study, potential inhibitors to agrivoltaic development were identified and empirically-based recommendations were proposed. The resulting recommendations reflect an objective assessment of multi-level, multi-sector regime interactions and aim to contribute to an enabling legal framework for agrivoltaics in the U.S.

5. Results & discussion

Results reveal no evidence of consequential conflicts embedded within solar energy support mechanisms as related to agricultural land use at the national level. 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 land use policy 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 a comprehensive legal framework. Additionally, effective legal framework analysis requires identification of feasible options for improvement (FAO, 2000) and therefore recommendations for modifying Massachusetts' SMART program's agrivoltaic provisions are discussed. The results demonstrate that multi-level, multi-sector policy integration is imperative for advancing agrivoltaics and that strategic measures to align solar energy and agricultural land use regimes can catalyze the diffusion of this promising technology in the U.S.

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. To be eligible to receive the ITC, developers must be for-profit or otherwise pay taxes, which limits nonprofit developers or otherwise low-income, small scale firms from taking advantage of the credit. Further, while the ITC acts as a catalyst for solar development, it is limited temporally by 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 posing limitations on eligibility and temporal constraints, 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 simultaneously. Given there are no stipulations around developments on certain land types, this federal subsidy allows for agrivoltaics.

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. 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 considerable assistance for parties interested in agrivoltaics. Under this program, solar PV technology is not accompanied by any restrictions pertaining to specific design parameters, making the REAP a 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 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 concurrently. The acquisition of compounded financial support could reduce economic barriers to development, notwithstanding impending expiry of the ITC. Because subnational agrivoltaic initiatives are not constrained by these federal regimes, this analysis maintains that these incentives from both sectors are ng features of the U.S. legal framework for agrivoltaics.

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, 2021). RPS can be used 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, 2021). At least 21 U.S. states and Washington D.C. have solar carve-out provisions in their RPS policies (Shields, 2021). The presence, magnitude, and structure of RPS vary across the U.S.; currently 29 states and Washington D.C. 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 3,200 MW declining block incentive that 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.

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. Implementing a feed-in tariff designed to support developers pursuing agrivoltaic applications specifically could be a direct way to incentivize development, as demonstrated by the Massachusetts' ASTGU initiative.

5.2.1. Agriculture Solar Tariff Generation Units

Pursuant to the SMART program, the Massachusetts Department of Energy Resources (MDOER), in consultation with the Massachusetts Department of Agricultural Resources (MDAR), enacted guidelines to stimulate the desired installation of solar systems that provide dual-use benefits on agricultural lands. 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 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. 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 than a conventional installation. Leveraging both the compounding Compensation Rate Adders and the avoidance of the Greenfield Subtractor, the ASTGU is a key incentivizing mechanism for agrivoltaics at the state-level.

This policy is among the first designed specifically for agrivoltaics in the U.S. and it demonstrates that alignment of land use considerations (system parameters) and energy policy (feed-in tariff) are the necessary features of a state-level legal framework. The ASTGU provides a model for forthcoming initiatives to advance both agricultural and solar energy production in a manner that is environmentally and economically sustainable. Other states interested in incentivizing agrivoltaics could adopt the key components of the ASTGU provision while considering the recommended modifications (Table 2).

Despite the ASTGU's intention 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 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. While the ASTGU allows for developers to seek a waiver to the design criteria set forth by the provision, it creates an upfront barrier to the solar industry and therefore such parameters could be imposed only when deemed necessary 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 MDOER and 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 stimulate agrivoltaic development.

Table 2 below outlines the major features of the ASTGU provision and highlights potential inhibitors to 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

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 - "Greenfield Subtractor"	C	Retain
Raised racking system requirements	I	Revise[a,b]
Panel spacing and shading parameters	I	Revise[c,d]
Regulatory complexity	I	Revise

[a] 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.

[b] 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.

[c] 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.

[d] 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.

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 feature of an enabling legal framework for agrivoltaics in the U.S. is dependent on its ability to appeal to developers, both in terms of financial gains and in terms of regulatory simplicity (Pascaris et al., 2021b).

Recommendations for revision of the raised racking and panel spacing/shading requirements are based on recent innovations in solar PV 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 and Pearce, 2012; Wittbrodt and Pearce, 2017). Second, research shows that patterned panel designs with smaller modules as well as east-west tracking configurations create more optimal 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 accommodate these technological advances 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., 2021b) and farmer adoption (Pascaris et al., 2020).

5.3. State zoning laws

In the U.S., authority over 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 enabling laws (Zoning in the United States, 2020). The General Laws of Massachusetts, 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, which have direct implication on land use 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, the state of Massachusetts has established an enabling legal framework for agrivoltaics, which exemplifies the effect of deliberate policy integration.

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 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 enabling it, this study maintains that they are a supportive mechanism for state governments pursuing increased deployment. 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 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 advance agrivoltaics without disempowering local communities in agricultural land use decision-making and employ policy incentive mechanisms that are not underscored by land use controls. Because this analysis seeks to identify barriers and opportunities for agrivoltaics rather than question the soundness of existing laws and regulations, the zoning enabling and Right to Farm laws which support agrivoltaic systems are maintained as key features of a state-level 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 use 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 such land use 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). 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 in deciding whether, where, and how agrivoltaic projects fit into their community. Zoning ordinance silence can either mean the land use is permitted or prohibited (Light et al., 2020), and this silence creates uncertainty for developers, as its meaning varies across the map.

The presence of strict land use policy related to solar energy siting on farmland is a critical barrier for agrivoltaics. However, an absence of zoning regulations presents an opportunity to develop local bylaws that specify the implementation of solar energy systems on farmland and signal receptivity to developers. Local governments interested in advancing agrivoltaics can draw insight from existing solar permissive model ordinances (e.g., Becker, 2019) and 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 may be a preferential path because they entail conditional or special permit uses that are permissive of solar in certain zones (Gravin, 2001), which gives local governments opportunity for strategic siting of agrivoltaics in their jurisdiction. 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 and granted a reduced set of land use standards, given that they are intended to allow agricultural production and provide immediate income diversification for farmers. Local governments may consider making permanent installations subject to a more extensive set of long-term land use standards. Lastly, given the steady rate of innovations in energy technology, local governments with established renewable energy zoning schemes that are interested in advancing agrivoltaics should reconsider whether their ordinances explicitly allow for these systems or if some well-intentioned regulations (e.g., perennial groundcover) may be unintentionally preventing agrivoltaic development. The above options to amend or adopt zoning ordinances that are permissive of solar infrastructure on farmland are key approaches to establish 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 and 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 protect natural resources (Executive Office of Energy and 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 and 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 farmland.

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, state-level zoning enabling laws and "Right-to-Farm" bylaws create an opportunity to vertically align local initiatives in a manner that eliminates contradictions in land use policy. The goal of increased deployment of agrivoltaics may be more realizable in the presence of vertical policy alignment between state and local land use regimes.

5.5. *Implications for a multi-level governance framework*

Overall, the legal framework in the U.S. has significant potential to enable the advancement of agrivoltaics. Federal subsidies provide uniform incentive to states for developing solar energy facilities without restriction regarding agricultural land use, while placing the authority of development permitting under the jurisdiction of subnational governments. Given that the horizontally aligned federal-level incentives are complementary and permit agrivoltaics, state and local level governments are the critical actors shaping the socio-political context in which the technology may diffuse. While there are currently no explicit efforts for policy integration between levels or sectors of government to support agrivoltaic development, this analysis has found no major inhibitors to alignment of initiatives, indicating that proactive coordination could produce policy synergies. 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 advancing agrivoltaics, 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 could be reconsidered include: imposed system parameters such as raised racking, panel spacing, and shading requirements, and regulatory complexity for developers.

Local land use policy was identified as the key leverage point for enabling solar development on farmland, 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. Local level allowances for mixed land use will be a necessary feature of a comprehensive legal framework for agrivoltaics.

6. Conclusion and policy implications

This study applied Legal Framework Analysis to analyze the policy environment relevant to the diffusion of agrivoltaics in the U.S. Findings indicate that an enabling legal framework for agrivoltaics must be characterized by multi-level, multi-sector alignment. Results reveal no

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

Level of Government	Policy Tool	Recommendation
Federal	IRS ITC USDA REAP	Congressional extension of ITC expiration dates 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"[a]
	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[b]
	Zoning enabling laws	Explicit exemption of commercial agricultural land and solar energy systems from unreasonable county or municipal zoning regulation[c]
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

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

[b] Model from State of Massachusetts' SMART Program ASTGU provision (Table 2).

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

evidence of consequential conflicts embedded within solar energy support mechanisms as related to agricultural land use at the national level. 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 land use policy as the most significant barrier or opportunity for agrivoltaic development. The findings of this study demonstrate that proactive measures to align solar energy and agricultural land use regimes are feasible and can catalyze the diffusion of agrivoltaics in the U. S.

Based on the analysis results, a comprehensive legal framework for agrivoltaics should arguably include a combination of federal and state energy financing mechanisms coupled with favorable state and local land use policies. Specifically, a state-level feed-in tariff and local government allowances for mixed land use between solar and agriculture will be the necessary features of an enabling legal framework. The variability in local land use policy across the U.S. suggests that the subnational legal framework for agrivoltaics will differ spatially 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, the findings can speak broadly to U.S. states and local governments interested in advancing agrivoltaics. As an exemplary initiative, the State of Massachusetts' SMART program ASTGU provision may serve as a template for other states adopting strategies to incentivize agrivoltaic deployment. Because the legal framework in the U.S. is 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.

To build upon this initial Legal Framework Analysis, future research needs to consider the potential justice concerns related to states pre-empting local zoning decisions to advance agrivoltaics. Finding a just solution that advances agrivoltaics without harming or disempowering agricultural communities will be critical. Given the limited technical capacity of local governments, future research could assess if state-level zoning enabling laws are more well-suited to guide agrivoltaic development in comparison to local land use policy. 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.

The insights derived from this study highlight that continued efforts for policy integration across levels and sectors of government will be imperative to enable 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. These results may serve as a framework for future legal analysis or agrivoltaic policy development, as key regulatory barriers and opportunities have been identified.

Meeting growing demands for both renewable energy and food 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, multi-sector governance approach characterized by horizontal and vertical alignment of solar energy and agriculture land use regimes will be necessary. Ultimately, combined federal and state energy financing mechanisms coupled with favorable state and local land use policies are the key features of the comprehensive legal framework needed for agrivoltaics to prevail.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Alexis S. Pascaris: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The author would like to acknowledge Dr. Roman Sidortsov, Dr. Chelsea Schelly, and Dr. Richelle Winkler for their support throughout the development of this work.

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