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Abstract

In this contribution, we explore the dynamics of emerging agrivoltaics systems in Germany. Agrivoltaics combine solar energy panels and agricultural production on a single plot and are commonly promoted as a win-win solution which addresses energy needs and upholds food security whilst being land-efficient. Existing work tends to treat agrivoltaics from a purely empirical or techno-economic perspective which gives limited recognition to its origin from two pre-existing socio-technical systems which come with established structures. Instead, we characterise it as a new, combined system, emerging from the combination of the pre-existing solar energy and agriculture systems. We therefore adopt a multi-system interaction (MSI) perspective and focus on the institutional dimension since we find the institutionalisation process highly relevant for enabling the integration of the systems. We adopt Scott's (2009) institutional pillars (the normative, the cultural-cognitive, and the regulative pillar) and suggest that their interaction affects the process of institutionalisation of combined systems. The empirical analysis of agrivoltaics in Germany highlights the important role of a shared understanding of the combined system (cultural-cognitive pillar). Motivations and values, in combination with normative framings about agrivoltaics (normative pillar) impact the decision-making of stakeholders regarding investments but also regarding their engagement in the definition of shared rules (regulative pillar). These dynamics shape the process of institutionalisation guiding the development prospects of agrivoltaics.

Keywords

Agrivoltaics, multisystem interaction, institutions, solar energy, agriculture

1 Introduction

Despite progress in the deployment of renewable energy, further efforts to intensify decarbonization across sectors are needed to reach climate goals, such as net-zero emissions by 2050 (International Energy Agency, 2021). Among renewable energy sources, production from solar photovoltaic (PV) systems is instrumental to meet these goals, as it can be deployed decentralised and at relatively low cost. Recent evidence found that most new solar installations are developed on croplands (Kruitwagen et al., 2021) and that, in Germany, 1.5% to 2% of croplands will need to be converted to solar PV to achieve energy transition targets (Die Bundesregierung, 2024). Solar PV adds to the existing pressure on the agricultural sector to supply food to a growing world population, and ensure farmers' incomes, while also preserving landscapes and biodiversity to protect the ecosystems that underlie the global food system (European Union, 2021). The recent decision, in response to farmers' protests, to relax the requirement that farms devote at least 4% of arable land to non-productive areas shows how difficult it is to combine all goals within the available land in Europe (European Parliament, 2024). In addition, geopolitical tensions call for upholding national and European capacities both in energy and food production. Against this complex context of tensions surrounding land use, options for multiplying uses on single plots of land are commonly promoted (Khanna and Miao, 2022).

Agrivoltaics, defined as "approaches to use agricultural areas simultaneously to produce food and to generate photovoltaic (PV) electricity" (Schindele, 2021) is often depicted as a technical 'win-win solution', solving the conflict on use of land for food or energy (Vezzoni, 2025). Not only can energy production and agricultural production be integrated on the same plot of land, thereby providing a much-needed additional source of income for farms, but the installations may also create synergies, for example protecting crops from weather impact, thereby substituting other measures such as plastic tunnels (Gerhards et al., 2022). At the same time, the technical integration presents new challenges, for example when large amounts of water concentrate with an impact on the ground, or dust and plant protection products collect on panels, impacting their capacity. Despite the current relative readiness of the technology for mainstream markets (Pascaris et al., 2023), adoption rates of agrivoltaics remain rather low, at 21 agrivoltaics facilities with a total capacity of 81.67 MWp as of March 2023 in Germany, which mainly concentrate in the South of the country (Pump et al., 2024). Whilst there is a significant amount of research on the techno-economic aspects of agrivoltaics, a comprehensive perspective at the level of the socio-technical systems (i.e. the energy system on the one hand, and the agricultural system on the other) and their integration is missing. The emerging literature on multi-system interaction (MSI - Andersen et al. 2019) offers insights on the challenges that arise when previously relatively unconnected sectors are combined. The centrality of land as a resource in agriculture and in other key sectors involved in sustainability transitions calls for more research on MSI surrounding agriculture (Bengochea Paz et al., 2020). In the case of agrivoltaics, Moore et al. (2022) identify a lack of knowledge about agriculture by the involved energy actors and suggest that deep, upfront mutual learning is necessary to make agrivoltaics work. We therefore conceptualize agrivoltaics as a case of MSI where the (solar) energy system and the agricultural system are to be integrated. Adopting an MSI lens allows us to spotlight relevant dynamics arising from the energy and agricultural systems when they integrate in a combined system.

The role of institutions for MSI has been relatively less explored (as compared to the actor and technology dimensions) despite their relevance in the provision of stable conditions for deeper system integration and the diffusion of the novel combined arrangement (cf. Chlebna and Mattes, 2020; Geels, 2025). In the case of agrivoltaics, Pascaris et al. (2020) express that concerns about the long-term productivity of agrivoltaics and its consequence for agricultural land can be alleviated with contracts and arrangements that clarify obligations and compensations between stakeholders. This reflects a need for clearer rules of engagement. In a review on the willingness to adopt agrivoltaics, Wagner et al. (2024) show how farmers' 'subjective norms' come just second to technology factors. This highlights the relevance of informal institutions such as framings and attitudes. Beyond the individual level, community and societal acceptance (Ketzer et al., 2020) is also key, as agrivoltaics may help address normative concerns about a 'fair share' of the created value going to the community (Torma and Aschemann-Witzel, 2023), about what kind of agricultural value is desired (Plumhans, 2025) or about agricultural activity being displaced by energy production (Pascaris et al., 2021). Acceptance can be facilitated with local participation processes and supportive local regulatory environments that determine local authorizations. Existing studies highlight the absence of mature regulatory oversight in many contexts, which creates challenges for local stakeholders and the inability to integrate the dynamics between the two sectors in governance frameworks (Carrausse and Arnauld De Sartre, 2023). It can also lead to poor procedural and distributive justice and low social acceptance (Taylor et al., 2025), or lacking and misleading incentives (Williams et al., 2025), all generating barriers to adoption. Overall, there transpires from prior studies a need to understand better the complex process of institutionalization of agrivoltaics. A structured consideration of this process is so far missing.

This work builds on prior studies of the role of institutions for MSI (Andersen et al., 2023; Andersen and Geels, 2023; Käsbohrer et al., 2024) but proposes a more nuanced approach by adopting Scott's (2009) distinction between a regulative, a normative, and a cultural-cognitive pillar of institutions. We therefore pose the following research question:

How do the dynamics between the normative, the cultural-cognitive, and the regulative institutional pillars affect the institutionalisation of combined systems?

To provide context, we identify key actors and discuss the technological compatibility between solar installations and agriculture. Our institutional analysis shows how core attitudes by farmers (normative pillar) affect their willingness to engage with agrivoltaics by investing or getting involved in norming and other processes which ultimately shape regulations (regulative pillar). We point to the relevance of arriving at a shared and accepted definition of agrivoltaics (cultural-cognitive pillar). This is reflected in the contested process around developing technical specifications that were adopted in several subsequent regulations (regulative pillar). In combination, these dynamics affect how agrivoltaics is understood, presented, and enshrined in rules and regulations, which will ultimately influence its diffusion as an industry and on the fields in Germany.

The remainder of this paper is structured as follows: In the following chapter, we lay out the conceptual foundations for this contribution and present our own approach. In chapter 3 we introduce the research design and methodology. Chapter 4 presents the narrative analysis of our empirical material and key findings. We discuss our findings and their implications both in practical and in theoretical terms and conclude with a reflection on limitations and avenues for further research in chapter 5.

2 Theoretical Background

2.1 Multi System Interaction (MSI)

The energy transition ('Energiewende' in German) now promotes electrification across sectors to accelerate decarbonization. This implies stronger connections with other socio-technical systems, which may be understood conceptually as multi system interactions (MSI), a context which is claimed to carry greater complexity and interactions across dimensions than transition theories have suggested so far (Löhr et al., 2024; Markard and Rosenbloom, 2023; Ohlendorf et al., 2023).

Early contributions in this context have mostly drawn on the nomenclature of the multi-level perspective (MLP) referring to niches, regimes and landscapes (Geels, 2002; Konrad et al., 2008; Papachristos et al., 2013; Raven and Verbong, 2007, 2009; Sutherland et al., 2015). Raven and Verbong (2007) suggest a typology of regime interaction which distinguishes between four types which are relevant for the development and diffusion of innovations. First, 'competition' occurs where "actors from different regimes compete for the same resources [...], compete for access to infrastructures, produce products for similar markets or compete for institutional arrangements" (p. 502). Second, 'symbiosis' refers to a situation where two regimes benefit from collaboration or may even enter a co-dependent state. Third, 'integration' occurs "when previously separated regimes more or less become one" (p. 503). Fourth, 'spill-over' occurs when rules are transferred from one regime to another. The case of agrivoltaics constitutes a situation where an initially competitive situation (for land) between agricultural activity and energy generation is ideally resolved through integration. For integration Raven and Verbong point to the importance of policies that encourage alignment between regimes and state a need for further research on this (Raven and Verbong, 2009). We therefore highlight how different kinds of institutions and the dynamics between them affect MSI and, further down the line, the diffusion of combined systems.

Authors of a more recent surge in this literature seek to understand the drivers and barriers that underlie MSI (Andersen and Geels, 2023; Rosenbloom, 2020). They tend to move away from the MLP nomenclature and typically study MSI in the dimensions of actors, technologies, and institutions (Andersen et al., 2023; Andersen and Geels, 2023; Finstad and Andersen, 2023; Löhr and Chlebna, 2023). The *agentic dimension* received particular attention in recent work on MSI. Musiolik et al (2020) identify the role of system builders and their differing strategies depending on the availability and distribution of resources. They arrive at three modes of system building: A single mode where system builders independently create system structures, often because they control key resources; a partner mode where system builders partner with other actors and co-create structures; and an intermediary mode where system builders coordinate activities in a network to develop new, intermediate organisations which will work on developing system structures. Building on this, system entanglers have been defined as those actors that pro-actively create links between systems through different activities (Kanger et al., 2021; van der Vleuten, 2019). In the context of sector coupling, Löhr and Chlebna (2023) emphasise the importance of developing cross-sectoral competencies and mutual learning as well as building networks across systems (see also Finstad and Andersen, 2023). Similarly, Andersen et al (2023) point to the important role of external pressures, a sense of urgency, power imbalances and different degrees of interest which may lead to suboptimal workaround solutions. Along with a heightened attention to incumbents in MSI (Magnusson et al., 2025), Ohlendorf et al (2023) study how their interests in a particular combination affect their discursive strategies and thus potential outcomes, whilst Löhr et al (2024) show how previous experiences with respective counterparts may support unusual actor coalitions. In the *technological dimension* authors tend to focus on the relevant technologies in either system and their compatibility with each other. This includes an interest in the maturity and readiness of the respective technologies for combination, and in adjustments that need to be made in either system (Andersen et al., 2023; Magnusson et al., 2025). It also concerns the knowledge required to support the combined system (Finstad and Andersen, 2023). Existent treatment of the *institutional dimension* points to legal and regulative misalignments between the interacting systems (Werner-Torgersen, 2024). Andersen and Geels (2023) assert that institutional mismatches lead to uncertainty for actors which hampers cross-system collaboration. Actors therefore need to engage in institutional work to align institutions to enable collaboration and exchange between systems (cf. Käsbohrer et al., 2024). A distinction in formal and informal institutions has become common, thus recognising the role of unwritten aspects such as institutional logics and cultural differences between the systems to be integrated (e.g. Andersen et al., 2023). We argue that more nuance in this regard including on the interdependency between formal and informal institutions would contribute to our understanding of the process of institutionalisation and associated stabilisation of the combined system (cf. Genus and Mafekheri 2014).

2.2 Agrivoltaics as MSI: Interactions between the energy and agricultural sectors

The energy sector has long used agricultural inputs to generate multiple forms of energy, creating varying types and depth of interactions between the two sectors (Acosta-Silva et al., 2019; Chel and Kaushik, 2011). At the lowest level of integration, farmers typically rent out small parts of their land to energy developers for the installation of wind turbines and receive a compensation in return (e.g. Sutherland et al., 2015). Slightly more involved, larger parts of land can be devoted to the installation of open field solar panels. Activities of energy and agricultural production remain segregated, and land is repurposed from agricultural to energy production (Battersby, 2023; Dias et al., 2019). Next, the production of biogas from biomass coming directly from energy crop grown for this purpose or from agricultural waste generates a higher integration of the two activities. Also, the digestate, a by-product resulting from the fermentation process, is used back by the farmers as an organic fertilizer to grow their crops (Blades et al., 2017). In this setting, activities of biomass production and energy production are integrated in a circular process, where each activity relies on the other to supply inputs (Parikh, 1985). Farmers often operate biogas plants themselves or in cooperatives (Burg et al., 2021).

Finally, agrivoltaics present another form of integration with the generation of both agricultural and energy production simultaneously. Although they remain separate production processes, they integrate more deeply than other models as each activity shapes and influences the other constantly (Trommsdorff et al., 2021; Weselek et al., 2019). Farmers must adapt their crop or produce to the presence of solar panels on the fields, which may benefit the agricultural output by protecting from winds, drought, and hail but may lower beneficial radiation from reaching the crops. The energy production is affected by structural components (height and spacing of the panels) to allow for the agricultural activity, and by situational aspects (e.g., dust, damages) generated by the farming activity. This greater technical and economic integration is a source of additional relational challenges between the stakeholders, as reported by Agir et al. (2023), in particular because of added interdependence, differing priorities given to food and energy, as well as conflicts over access to resources (land, water, sunlight), which further highlights the importance of the institutional context to regulate and stabilise these relations.

2.3 Policy context of agrivoltaics in Germany

Agriculture and energy are some of the most regulated and supported industries in Germany, but they differ significantly in how they are governed and subsidized: agriculture is primarily regulated at the EU level with substantial subsidies and common policies, while energy is largely shaped by national legislation, market-based mechanisms, and targeted transition incentives.

From the current Common Agricultural Policy (CAP, 2023-2027), farmers receive direct payments based on their farm size, amounting to 30% of farm income on average (Weber et al., 2024), and payments for voluntary actions taken to protect climate, landscape and the environment (Runge et al., 2022). Germany (together with only Italy, the Netherlands, and Slovenia) explicitly mentions 'agri-photovoltaics' in its CAP plan only since 2023 (Chatzipanagi et al. 2023), allowing agricultural land to remain eligible for CAP support as long as energy-generating installations occupy no more than 15% of the land. The EEG ('Erneuerbare Energiengesetz') has been the main driver of the energy transition in Germany since 2000. It provides generous financial support (through feed-in-tariffs and market premiums) and a regulative framework (priority grid connection and priority purchase of the generated electricity) to produce electricity from renewable energy. Specifics for agrivoltaics have started to appear in the regulation, showing the political will to address and integrate these installations to the energy supply, but apparent inconsistencies, for example between the cost surplus for elevation and the technology bonus available to compensate it, show that the regulation is still nascent (Vollprecht and Trommsdorff, 2024). In addition to these two regulative frameworks, agrivoltaic projects must abide by the federal building code (BauGB) to obtain a building permit, which is awarded by the municipality considering local development plans.

Different arrangements of dual land use exist. The DIN SPEC for agrivoltaics was developed in 2021 when representatives from agriculture, the PV sector, research, and certification bodies agreed on a preliminary technical specification under the DIN PAS process to define shared criteria and requirements for combining solar power and agricultural use, aiming to reduce risks and support wider deployment of agrivoltaics (DIN Deutsches Institut für Normung e. V., 2021). DIN SPEC only needs the participation of a minimum of three partners and does not require consensual decisions (Gesellschaft für Qualitätsprüfung mbH, 2025). Although it is already widely cited, it does not yet have the status of a norm but rather amounts to a formalised agreement amongst the industry partners that participated in the process. DIN SPEC 91434 now defines three variations as types of agrivoltaics. Category I foresees elevated PV panels at 2.10 meters minimum where agricultural activity continues underneath the panels which may either be fixed or track the sun to optimise radiation. Category II foresees near ground elevation of PV panels where agricultural activity continues between panels. This category recognises variations with either standard tracked or fixed panels, or bifacial panels, vertically arranged in a fence-like manner (DIN Deutsches Institut für Normung e. V., 2021). They allow for bigger machinery to pass between rows of panels but may also influence wind patterns. Technically, closed installations such as the use of solar panels on glasshouses are also agrivoltaics. In Germany, however, glasshouses are legally considered buildings and therefore are regulated under the building law and respective rules for rooftop solar apply (Fraunhofer ISE, 2022). These definitions are still contested as we will discuss in section 4.2.2.

2.4 Conceptual Framework

To study the institutional dimension of an MSI, we go beyond current approaches within the MSI debate that distinguish between formal and informal institutions and draw on the sociologist W. Richard Scott's institutional pillars. Generally, institutions may be interpreted as the 'rules of the game' and thereby distinguished from actors (incl. organisations) as the 'players of the game' (North, 1996). Based on their stabilizing and meaning-making properties, institutions may guide behaviour and resist change, which makes them durable over time (Scott, 2009) but may also lead to path dependency and lock-in effects (Setterfield, 1993). There is wide agreement across the literature that institutional structures must evolve alongside industrial development, providing stability whilst also allowing for variation and innovation (Nelson, 1994; North, 1996; Perez, 1983). In this contribution we argue that, just as for industrial development in general, institutions need to co-evolve and align between the systems to allow for synergies to be exploited and MSI to occur. This implies a process of institutionalisation of the MSI. The distinction between formal and informal institutions in existent work has produced some insights but more nuance is required. Scott (2009) usefully distinguishes three pillars of institutions:

First, the normative pillar holds aspects such as values and norms of social behaviour, akin to informal institutions (cf. North, 1990). They circumscribe informal conceptions of the desirable and understandings as to "how things should be" (Scott, 2009, p. 64). The normative pillar therefore rests very much on a sense of appropriateness vis-à-vis explicit and implicit common understandings. It includes expectations of actors' behaviour which are experienced in the first instance as external pressures but may be internalised over time. (Non)conforming comes with a sense of respect/shame, which rests on self-evaluation rather than a formal authority. We add to that a sense of belonging to a certain group. In the MSI context we here particularly subsume the sense of shared values, identities and belonging of stakeholders and their understanding of what they do and why as this will shape how they engage with the MSI process.

Second, in the cultural-cognitive pillar, the shared meanings attributed to objects and activities are negotiated. It therefore demands attention to the subjective interpretations that actors hold rather than just objective conditions (Scott, 2009, p. 67). These subjective interpretations are socialised into cultural understandings. This involves framings and patterns of belief or organisational logics that structure behaviour. The key mechanism is one of “orthodoxy, the perceived correctness and soundness of the ideas underlying action” (ibid, p. 68). Feelings associated with this pillar are a sense of certainty versus confusion, competence versus cluelessness or even craziness. In the MSI context we here subsume the very basic struggle for a common understanding of what exactly is the combined system, which includes how it is represented in the media, but also in emerging definitions. This plays an essential role since it will be the basis of subsidies and other regulative measures.

Third, the regulative pillar circumscribes what is commonly understood as institutions, namely formalised, written down rules and regulations (cf. North, 1990). The mechanism of compliance is coercion by a legitimated authority that is legally sanctioned. (Non)conforming is therefore seen to come with a sense of innocence or guilt. Behaviours and efforts of rulemaking are oftentimes (especially in the economic tradition) associated with own best interests. Studies focused on this pillar tend to come with an “interest in the role of the state: as rule maker, referee, and enforcer” (Scott, 2009, p. 62). For the MSI context, we here subsume not only laws but also the rules and regulations that accompany economic subsidies relevant to both systems and eventually the combined system.

Scott’s three pillars provide more detail on influential informal institutions, with the distinction between behavioural norms and attitudes, and shared understandings and framings. Despite the distinction, the three pillars are understood to work in concert, although one might dominate over others depending on the context of the setting under study. Scott (2009) points to the constituting role of the cultural-cognitive dimension, which includes the power of definition and impacts dynamics in both other pillars. Scott’s institutional framework has been applied to add nuance to the institutional debate on the energy transition. Genus & Mafakheri (2014) observe a preoccupation with formal rules when it comes to institutional analysis in the context of the energy transition and argue that adopting a neo-institutionalist perspective would put other driving factors such as norms, culture and cognition more in focus. They conceptualise the emerging UK bioenergy industry for electricity and heat generation as organisational field and demonstrate key dynamics across the three institutional pillars. Genus (2014) also argues for combining neo-institutionalism with discourse analysis since language reinforces social practice and is thus instrumental in the creation and maintenance of institutions. In a similar vein, König (2020) draws on the pillars to show how energy efficiency related decision making is structured by more than just regulation in German industrial SMEs. Chlebna & Mattes (2024) also adopt a field approach and conceptualise regional transition fields within which dynamics of adaptation and delimitation shape conflicts over regional energy transition in each of the three pillars of institutions. Similarly, Schnell & Mattes (2026) show how dynamics of legitimation and illegitimation result in legitimacy gaps across the three pillars.

Our study aims at building a deeper understanding of the interactions between the three pillars, which is so far marginal, with findings drawn from the case of agrivoltaics. In the context of MSI, a further dimension of this work refers to the dynamics between the two pre-existing systems within each pillar, and how the established institutions and logics of each originating system align or conflict with each other. Figure 1 illustrates our conceptual framework.

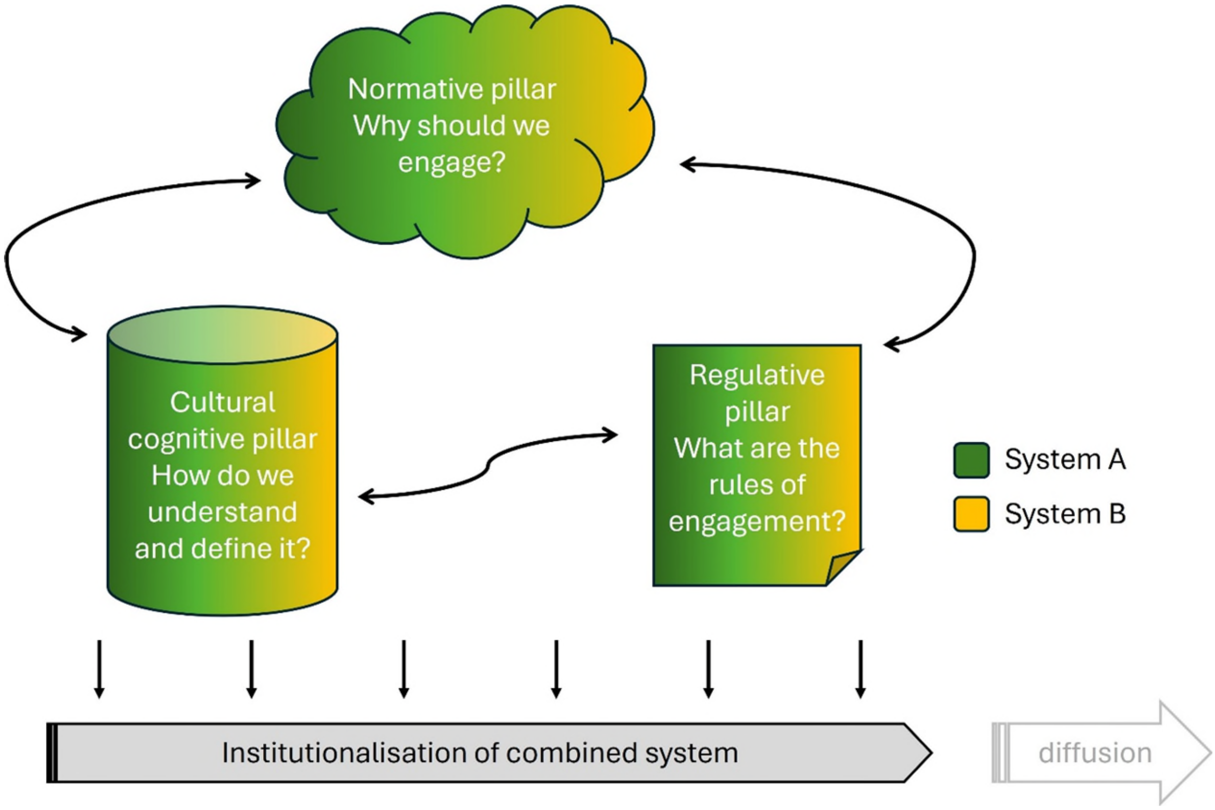

Figure 1: Conceptual Framework, authors' own

3 Research Design

The aim of this study is to examine in detail the institutionalisation process of MSI through the study of agrivoltaics in Germany. Given the emergent stage of agrivoltaics and its so far restricted adoption, the case study follows an exploratory research design (Bryman, 2016). We combine 100 newspaper articles with nine semi-structured expert interviews with key stakeholders in agrivoltaics in Germany. A summary of the material can be found in Appendix I.

The newspaper articles were extracted from the LexisNexis database. The search was restricted to newspaper articles from Germany, in German or English language, and to articles of a length of more than 200 words. Search terms were inclusive of all variants used in German and English to describe agrivoltaics projects[1]. The date range was set from January 2022 to March 2024, accounting for the period of intense discussions that followed the first formalisation effort with the DIN SPEC (May 2021) and covering key policy changes, such as amendments to the EEG (2022 and 2023) and the CAP (2023). The search returned more than 1600 results which were sorted according to the relevancy score provided by LexisNexis[2]. The first 100 articles were downloaded and imported to MaxQDA. Newspaper articles must be understood in their context since local editors commonly adopt press releases by companies with few changes. Evidence for this was found in the numerous text duplicates across different news outlets (deleted and not included). They still serve to highlight what key benefits are typically presented of a new technology and what reasons are given to engage with it (cf. Kriesch and Losacker, 2026). Information presented as facts, however, must not be taken at face-value, but needs to be double-checked and ideally cross-referenced. The newspaper articles served to identify the key stakeholders in agrivoltaics in Germany and their relative importance. They also gave an early indication of potentially contentious issues.

A total of 9 interviews were conducted during and after the collection and analysis of the newspaper articles. Interviewees were selected to cover a broad range of stakeholders (see list in the Appendix I). The relatively small number of interviews results from the emergent state of agrivoltaics in Germany (Forbes and Kirsch, 2011). They were experts on agrivoltaics in their organisations or representatives of companies active in this field. The interview guide primarily covered a general overview of the agrivoltaics innovation system (key stakeholders, development hotspots) and the framework elements (normative, cultural-cognitive, and regulative institutions) as well as further aspects that the interviewees brought in. Interviews lasted between 35 and 63 minutes and were carried out online, recorded and transcribed. The transcripts were then imported into the MaxQDA project and underwent qualitative content analysis together with the newspaper articles. Policy documents and position papers complemented and further informed the analysis.

Our approach to the qualitative content analysis of the material combines both a theory-derived, deductive stage and a more open and flexible inductive stage (cf. combination of theory-generating expert interview and problem-centred interview - Döringer, 2021). First-tier codes were derived deductively from the framework (institutions: cultural-cognitive pillar, normative pillar, regulative pillar). In the initial stages of the process, further codes that alluded to the dynamics between the pillars were developed

[1] LexisNexis search string: (agrisolar or agrosolar or agripv or agrivoltaic or agrivoltaik or agrovoltaic or agrovoltaik or agriphotovoltaik or agrophotovoltaik or agri-solar or agro-solar or agri-pv or agro-pv or agropv or agri-voltaic or agri-voltaik or agro-voltaic or agro-voltaik or agri-photovoltaik or agro-photovoltaik) and length > 200

[2] "SmartIndexing terms are followed by a relevance score between 50% and 99%. The score measures the relevance of the discussion of an index term within a given document based on criteria such as term frequency, weight, and location." (Lexis Nexis Help)

inductively from information in the textual material. We therefore introduced a second tier of codes (technical variations / deep system integration, definition of agrivoltaics, weather protection/climate adaptation, securing longer term economic futures, farmers' attitudes, CAP/EEG funding rules, other regulation). Thus, a comprehensive code tree was developed and used to code the rest of the articles (Appendix II). To increase reliability the authors co-coded sections of the material and discussed attributions in-depth. The information thus gained was summarised in overviews, and illustrative quotes were chosen and translated to be used in the analysis chapter.

4 Analysis

This section presents the insights of our analysis on the emergence of agrivoltaics in Germany. We start by briefly introducing key stakeholders and technological aspects of agrivoltaics in Germany before diving deeper into the institutional dimension.

4.1 Actors and technologies in agrivoltaics in Germany

4.1.1 Various but co-dependent stakeholders

The following list of key stakeholders is based on the agentic analysis of the emerging agrivoltaics industry in Germany. It is not meant as an exhaustive list for agrivoltaics, or for MSI but displays the variety of stakeholders involved and their (economic) interests.

First, **research institutes** were found to be the most relevant stakeholder group in the still emergent field of agrivoltaics in the newspaper analysis (mentioned in 78 segments in 44 documents[3]). The most prominent is Fraunhofer ISE (Institute for Solar Energy Systems) who has developed several research projects around different crops and has been driving the process of gathering stakeholders to define standards and norms for agrivoltaics. Research institutes deliberately position themselves as intermediaries to encourage MSI (N7, N4, I06_farmer). **Farmers** were found to be the second-most relevant stakeholder group (53 segments in 38 documents). Subject to climatic variations, the instability of farming incomes is a primary concern for farmers (I04_developer, I06_farmer). To stabilize their income, farmers attempt to diversify their income sources, e.g. by leasing land to open-field PV, which delivers very high, stable, and long-term revenues (N2, I01, I03_farmers rep). Agrivoltaics, too, are perceived as a way to secure farm operations through diversification (N44, N38, N83). Farmers' investments are prominently driven by economic feasibility and investment costs, protection against climate risks but also a sense of responsibility towards sustainability (N9, N76). **Developers** were found to be the third most relevant stakeholder group in the newspaper analysis (47 segments in 31 documents). A first key group consists of smaller firms that have entered agrivoltaics early on and consider themselves pioneers. Not only have they

[3] 'Segments' here refers to coded items whereas 'documents' describes the number out of 100 articles where this code was used.

gathered experience over time, they also commonly have an agricultural background. They might be seen as system builders/entanglers that are situated between systems. A second group of firms stem from PV developers and are new entrants to agrivoltaics. They often place agrivoltaics prominently in their online communication but are usually considerably less experienced. They constitute system entanglers that are situated firmly within one system but pro-actively seek MSI as they see a business opportunity. Finally, stakeholders that may be easily overlooked but hold considerable influence are **local and regional authorities,** as they make planning decisions and deliver authorizations for agrivoltaics projects (N50). They are external to the projects but represent the public interest (I08_research). They manage a balance between agriculture and energy and are confronted with the frequent perception that "we have enough PV already" by residents, which works in favor of authorization for agrivoltaics project compared to open-field PV (I04_developer). Reflecting on the brief overview of key stakeholders, we see that the different groups hold very diverse motivations.

4.1.2 A mature yet friction-laden technological combination

In agrivoltaics, adjustments in both systems are needed to allow for the respective other system to work, affecting the performances. Stakeholders accept these constraints because they also bring synergies. The protection of crops from impacts of weather and other climatic conditions such as strong heat has been by far the most common argument for agrivoltaics in the newspaper analysis (101 segments in 61 documents).

"Rising temperatures and changes of amount and distribution of rain are signs of progressing climate change. Especially the availability of water decreases drastically in many regions of the world – with significant impacts for the food security of an increasing population." (N13)

Aside the crop protection effect, the panels might also have some negative impacts, however. For example, prolonged rain might lead to the collection of abundant water on small space and lead to wash-out and erosion. Shading may negatively impact crop growth (e.g. maize, broad beans, soy, lupin – N19). Not all agricultural machinery can be used near solar panels, implying a need for smaller machinery and a potential advantage for organic farmers who often have smaller operations already (I03_farmers rep, I04_developer, I05_agrivoltaics rep). Solar installations are a source of danger for farm operations but are also in danger of being damaged by them (I03_farmers rep). Dust and plant protectants may collect on panels and diminish their performance, thus requiring more regular cleaning and pushing up costs (I03_farmers rep). Integrating the two systems has positive as well as negative effects on the output of each system, and the balance depends on the conditions of implementation and use (I08_research).

A good understanding of agricultural operations is required to achieve a mutually beneficial integration. Interviewees commonly pointed to the high complexity of both agrivoltaics itself and farm operations (I06_farmer, I08_research). Achieving synergies with agrivoltaics depends on the compatibility between crop choice, farming practice and chosen technology, under the constraints of local growing conditions. A significant lack of willingness to engage with such knowledge by PV developers is commonly lamented among stakeholders. The sheer complexity of agrivoltaics explains a tendency for PV developers to lobby for open field PV installations (producing only energy), allowing them to stick to what they know best (I02_public sector, I08_research). However, the complexity provides a safe ground for differentiation for the smaller developers that focused their operation purely on developing agrivoltaics from a very early stage. They often have their own research sites or a background in farming and therefore possess essential knowledge advantages vis-à-vis new entrants, particularly those that enter from PV development (I07_developer, I09_developer).

4.2 The institutional dimension

We structure this institutional section according to our framework and first lay out observations in the normative pillar, then turn to the cultural-cognitive pillar, and finally to the regulative pillar. The following discussion section explores their interdependencies.

4.2.1 The normative pillar: Why should farmers engage with agrivoltaics?

In the normative pillar, the fundamental motivation for becoming a farmer and for doing farming is addressed. Farmers are very heterogeneous and have diverse approaches toward farming and towards environmental concerns. Interviewees explained that farmers' motivations for agrivoltaics range on a spectrum starting with an idealistic type, that feels a strong connection to the land and considers themself somewhat of a guardian of nature and the environment (I09_developer). On the other end of this spectrum, we find a primarily economic motivation where the intention is to maximise profits. Alternatively, given deteriorating land quality and climate-induced volatility in yields, some focus on the reliable income from selling electricity, which might help stabilise the farm economically (I08_research). Securing the long-term future of the farm arose from the news analysis as the second most important rationale for engaging with agrivoltaics (42 segments in 33 documents) after adaptation to climate change (weather protection). This often came along with an alleged added value creation in rural areas through farm income diversification (N36, N38, N61, N71, N76, N83).

> *"We hear from farmers who have milk cows and they can make the same amount of money with one agrivoltaics installation as with all their cows. With a fraction of the work." (I01_developer)*

Selling electricity to the grid represents income that is much more stable than income from crop yield or animal husbandry and comes with a significantly reduced physical effort too (I02_public sector, I03_farmers rep), yet adoption of solar energy in general is uneven. A 'preference for farming' underlying farmers' decisions (Wilson, 2025) could explain why farmers do not engage more fully with solar energy production, even though higher incomes are expected. Linked with these different motivations and identities, we find different approaches to agrivoltaics. Farmers nearer to the 'guardian of nature and environment' end might also view the installation itself as a feature that protects the environment and encourages biodiversity (I09_developer). For example, crop protection in form of plastic tunnels could be replaced by PV panels, with the additional electricity output and associated income. For them, agrivoltaics provides an opportunity to transition their operations towards more sustainability while keeping farming at the heart of their identity. Further, agrivoltaics is viewed as means to stabilize farm income and protect crops. These farmers' motivations remain rooted in agriculture: they value agrivoltaics for their support to production by reducing climate risks such as drought, while addressing economic vulnerabilities through an additional, diversified income stream from electricity sales. Agrivoltaics is framed as a mean to sustain agricultural activity and insure against farming risks. Finally, farmers that are nearer the profit maximising end of the spectrum are exposed to significant financial incentives to orient towards the more cost-efficient open field PV (I05_agrivoltaics rep) and have less barriers to shift land use from food to energy production only.

"In Germany open field PV is just more relevant. There is a lot of experience, it just works, and you can earn good money." (I08_research)

Naturally, these basic attitudes in combination with the rationales given by media and other stakeholders influence whether and how stakeholders engage both with agrivoltaics and with the creation of respective rules and regulation. They also shape how agrivoltaics is understood.

4.2.2 The cultural-cognitive pillar: How do stakeholders understand and define agrivoltaics?

It transpires that a shared understanding of what constitutes agrivoltaics is still emerging (I09_developer). Ideas range from a simple co-existence between agricultural activity and energy production on a single plot, thereby increasing land efficiency, to the creation of mutual benefits such as crop or animal protection, up to a deeper integration where the produced electricity is used on-site for farm operations (N7, N13, N21, N28, N36, I03, I05_agrivoltaics rep, I07_developer). Some even foresee the reduction of virgin materials use with the substitution of the steel constructions by biomaterials such as flax, wood fibre or carbon, making production more sustainable and more independent of the international steel market (N56, I04_developer). This vision of a deeper integration has not materialised so far. The various possible intensities of the integration between agriculture and solar fuel a discussion as to what can legitimately be called agrivoltaics.

As a dual system, a further initial confusion related to whether such a system would be considered an industrial or an agricultural investment. This explains initial reluctance of farmers to some extent, as an industrial development would mean losing the agricultural status of the land and receipt of CAP subsidies, and to forfeit the lower tax rate on agricultural assets under the inheritance law. Efforts to standardise minimal requirements and create norms have been made and agricultural benefits are now guaranteed for projects that fulfil the specifications of the DIN SPEC 91434, a first outcome of the norming process. Reflecting the variety of possible agrivoltaics concepts, the DIN SPEC recognizes three variants as eligible (see section 2.3). Among them, the concept most beneficial for agriculture (with the installation of PV modules mounted at a height of ≥ 2.1 m providing weather protection) is also the most expensive due to its higher steel support structure. Interviewees criticise that this cost difference creates incentives for profit-maximizing investors to adopt the other, lower-cost designs that involve minimal agricultural integration. The fear is that agriculture-minded projects would not be able to compete and would eventually disappear (I04_developer). This resonates with a perception that agricultural stakeholders were not sufficiently heard and that PV interests prevailed.

"We were part of this norming consortium, and you could really observe how [PV] developers worked to simplify framework conditions to get as much PV development on a plot as possible, thereby undermining our principle of 'agriculture first, energy second'." (I02_public sector)

To counteract this, some promote a particularly narrow definition which would only recognise agrivoltaics where an actual synergy between the panels and the crops underneath (e.g. protection from weather) is achieved (I06_farmer), thus promoting agricultural production. Such an extremely narrow definition would exclude most crops and put a distinct focus on specialty crops such as apple or wine production where crop protection is particularly relevant. Given the narrow application and higher installation costs, the counterargument is that we would thus unnecessarily subsidise a more expensive way of producing electricity.

"Shouldn't the fruit be able to pay for its own roof?" (I09_developer)

Others criticise DIN Spec 91434 as overly narrow and restrictive towards certain developers' own business case and interests (I09_developer), which do not maximise land efficiency. The current specification raises costs on both the energy and agricultural sides, as taller structures and wider spacing make electricity generation more expensive, while farming becomes more costly due to additional field passes, narrower working widths, higher fuel use, and increased labour time.

Efforts to protect agricultural interests by requiring the submission of an agricultural utilisation concept, which needs to be reviewed every three years, are met with scepticism overall. Farming stakeholders perceive it as a rigid requirement that prevents them from flexibly adapting their farming activities to market fluctuations and climate conditions. The required renewal every three years by the federal network agency (Bundesnetzagentur) and likely individuals who lack agricultural training is problematic or even unnecessary (I09_developer), and an additional source of risk and uncertainty, for the potential loss of the EEG bonus after the investment is completed (N26).

The first attempt at defining what can be a legitimate agrivoltaics project has brought some clarity for stakeholders, but it remains imperfect and disputed, while criteria for how agriculture will be maintained are considered inadequate.

4.2.3 The regulative pillar: What are the rules of engagement for stakeholders?

The regulative pillar is fundamental in the institutionalisation process since it circumscribes how ideas and visions about emerging systems are eventually formalised in rules and regulations. For agrivoltaics, the DIN spec 91434 provides a first orientation and serves as the technical basis for defining agrivoltaics in the regulations that determine subsidy regimes and entitlements. The regulative pillar is where conflicts between the stakeholder groups are most visible, since regulations determine how various combinations of agriculture and energy are valued, and thus affect how benefits will be distributed among stakeholders.

In 2022, a clear definition of the CAP Direct Payments Regulation (§ 12(5)) secured eligibility to the CAP subsidies, if the system "reduces the agriculturally usable area by a maximum of 15 percent based on DIN SPEC 91434:2021-051" (Vollprecht and Trommsdorff, 2024). Together with the classification of agrivoltaics installations as agricultural assets for inheritance tax purposes (contrary to open field PV which are considered land assets) (N31, N11), this has boosted confidence for farmers that agrivoltaics installations will not harm their agricultural status and revenues. Accordingly, farmers derive a sense of security for their agricultural activities, income and intergenerational succession (I04_developer).

A further support for agriculture was the removal in 2022 of the EEG surcharges that discouraged own consumption of the electricity produced directly onsite for large producers.

"Farmers would constrain the size of their installations to below 30 kW even though their electricity need for airing stables, cooling milk, milking machines, or water treatment was much higher." (N6)

However, higher installation costs for agrivoltaics compared to open-field PV are not compensated by the CAP payments received for the agriculture (N5). This explains the need for special arrangements under the EEG to make these investments attractive for the energy sector to develop. Participation of agrivoltaic installations was possible for the first time in 2022 within the so-called 'innovation tender' (N8), which only applied to installations above 1 MW initially. Smaller farms were structurally excluded from this funding opportunity, an issue that was addressed through the most recent EEG 2023 (Eisel and Heintze, 2022). Under the EEG 2023, agrivoltaic installations are integrated into open-space tenders as “first-segment solar installations”, guaranteeing a long-term perspective on access to competitive remuneration through the auction scheme. In addition, certain agrivoltaic installations receive a bonus to compensate their significantly higher costs, creating favourable conditions (ibid, I03_farmers rep). Further, the amendment promotes highly ambitious renewable energy targets, requiring an increase of solar capacity to 215 GW by 2030 (N31). This is expected to add pressure on agricultural land given limited land availability (I03_farmers rep) and to provide a significant push for agrivoltaics, together with an emphasis on large systems (>1 MW). In comparison, the payments received under the CAP appear unable to compete with the incentives created by the EEG. For example, interviewees report of farmers achieving financial stability with an energy production system, and with significantly less work (I01_developer). In addition, elements of the EEG may place liability and risk related to the joint system on the farmers (I09_developer). Together, the conditions favor constellations where energy takes a dominant position (higher returns, lower farmer workload and risk), shifting incentives.

PV developers who prefer conventional PV are seen to move into the better paid agrivoltaics tender despite limited experience in the joint system or no agricultural intentions beyond that of meeting the minimum requirement to qualify as agrivoltaics, leading to substandard projects regarding the agricultural quality (I01_developer). A commonly cited goal is therefore to tighten definitions in such a way that pure PV developers are kept out but genuine agrivoltaics projects are kept and have sufficient room to manoeuvre in their agricultural activities (I01_developer), raising again the question of which projects and agents can be legitimately called ‘agrivoltaics’. This shows the complexity of the matter but points to the crucial importance for fair process and participation in the creation of the respective norms which will be drawn upon in numerous regulations.

Table 1 **Fehler! Verweisquelle konnte nicht gefunden werden.** summarises the key sources of conflict in the normative, the cultural-cognitive, and the regulative institutional pillar for the case of agrivoltaics. We also allude to observed dynamic interactions between the pillars which we will turn to in the following chapter.

Institutional dimension	Source of conflict in agrivoltaics	Dynamic interaction and effect on MSI
Normative pillar	'Guardian of nature' vs. viability of agriculture vs. economic motivation	Identities and motivations affect investment decisions, as well as engagement with creation of definition and regulation
Cultural cognitive pillar	Narrow vs. wide definition; purpose of agrivoltaics	Shared understanding and definitions affect how and to whom regulations will apply and who can get subsidies
Regulative pillar	Misaligned incentives of funding schemes	Lends stability to engagement with the combined system through security of investments and confidence

Table 1: Analysis summary of the sources of conflict found in the agrivoltaics context in the regulative, normative, and cultural-cognitive pillar of institutions, and their dynamic interaction and effect on MSI; author's own following Scott (2009)

5 Discussion and conclusion: Conflicting objectives and interaction between pillars

The empirical analysis suggests ongoing interactions between the normative, cultural cognitive and regulative pillars with theoretical implications. An institutional analysis based on a distinction between formal and informal institutions may have identified the aspect of regulative misalignments (regulative pillar) and differing motivations (normative pillar). Widening the analysis to a third pillar (cultural-cognitive) has enabled us to uncover the important role of defining the boundaries of a combined system. We additionally theorise how the interaction between the pillars affects the institutionalisation of the combined system. While we agree with Scott on the constitutive role of the cultural-cognitive pillar, we also attribute an important role to the normative pillar. Core attitudes and beliefs combine with framings of the combined system and influence fundamentally how it is interpreted and how actors feel about emerging standards and associated incentives and benefits. This eventually dictates if they find it worthwhile to engage with the combined system, which materialises in their investment decision and their contributions to policy formation. These interactions shape the institutionalisation process of combined systems, which in turn has implications for a potential deeper integration and for the diffusion of such combined systems.

Despite being unachieved so far, we empirically observe developments within and across the institutional pillars that point toward more integrated regulations, standards, and shared understandings. We assert a potential virtuous cycle: stakeholders committed to improving land-use efficiency have advanced the issue within the normative pillar, raising questions on the alignment between motivations for agrivoltaics and the actual applications emerging from the regulatory frameworks.This stimulates dialogue and highlights the need for clearer conceptualization and formalization of agrivoltaics within the cultural-cognitive pillar. Although the resulting policy design remains contested, it reduces uncertainty and increases clarity at an early stage, which may increase attractiveness. As new actors enter with different priorities and values, they may propose alternative definitions for the combined system, generating new pressure for regulatory adjustment.

Our study has of course limitations which point to avenues for further research. We only analyse agrivoltaics within the context of one country. Results must therefore be interpreted in this territorial and sectoral context. A comparative qualitative case study approach might add to the transferability of the results on the role of institutions for MSI. We also only interviewed a relatively small sample of respondents. This is somewhat offset by the newspaper analysis but as agrivoltaics mature in Germany, future research should complement our work with further conversations. In a mixed methods design, quantitative spatial analysis may examine the spatial distribution of combined systems, followed by qualitative work which unpacks how territorial factors can be drivers or hinderers of MSI. This would introduce spatial sensitivity to MSI studies, an entirely understudied area thus far. Likewise, the wide range of institutional logics that determine each pre-existing system and create friction in MSI also deserve more research. From a political science perspective, it might be productive to dive deeper into the policy process, including the negotiation of shared norms and standards which plays such a substantial role in this case. Surely, significant learnings could be derived for the design of future norming processes, considering their wide-reaching influence. Further agro-economic research is required regarding a better alignment of CAP and EEG regulations and subsidy design, to best balance energy and agricultural production within the land available.

As regards the subject in focus, there is evidently a disconnect between land efficiency and economic efficiency, and this fuels the tensions between stakeholders across all pillars. Agrivoltaics suggest land efficiency, understood as a higher output of the combined energy and agriculture activities, compared to each activity being conducted on separate fields. However, given how the respective products are monetized, agrivoltaics most likely do not ensure economic efficiency. With the recent changes within the regulative pillar concerning agriculture, the systems may be profitable enough to be adopted by farmers whose norms center on preserving agricultural activities and land efficiency. With agrivoltaics, they can then benefit from weather protection and other technical synergies, generate energy for own consumption, or stabilize incomes from the sale of extra electricity to the grid (notwithstanding high investment costs), all of which contribute to the viability of farms. On the other hand, farmers or developers whose norms center on economic rationality or on climate goals can extract higher economic value and renewable energy from open-field PV without agriculture. The current regulative pillar shifts adoption of these actors toward PV concepts with just enough agriculture to qualify as agrivoltaics. Given the low relative value of agricultural production compared to renewable energy production under current regulative conditions (even accounting for possible synergies) and that the value of each production system is not only determined by the regulative pillar, but also by supply and demand, production costs of alternatives, and complex established regulative contexts, it is so far difficult for the current regulative pillar to reconcile economic efficiency and land efficiency. From this perspective, the current DIN SPEC (cognitive pillar) is essential and, in fact, represents the minimum level of agriculture that will be implemented by these stakeholders to secure additional land for PV installations and/or access additional remuneration granted for agrivoltaics, but it does not guarantee land efficiency. Setting stricter conditions (nearer the 'narrow' definition) for energy installations promotes more farming-centered systems, whose purpose is to support agricultural activities. Setting a wider definition encourages the large-scale production of renewable electricity necessary to reach climate goals, but at the likely expense of agricultural production. Solving this puzzle requires policymakers with a firm view of the longer term public good.

The key question with a view to policy design is whether the joint system is intended primarily to support agriculture or energy production, as each objective requires a different policy framework. Supporting climate goals would favor large-scale installations, located near existing grid infrastructure. In this context, the EEG special bonus for agrivoltaics may not be adequate or even necessary. On the other hand, supporting farm economic resilience to economic and climate fluctuations with agrivoltaics may be better achieved with agriculture-specific policy instruments, e.g. measures that alleviate the high initial investment cost and avoid pitting agricultural projects against energy-driven projects, as with the current DIN SPEC. At present, the conditions under which both goals can be achieved simultaneously remain unclear in Germany. Some stakeholders demand a special subsidy segment for the higher-up panel variant to rebalance incentives towards the system with greater land efficiency. However, deployed at large scale, this would be a more costly energy transition for the public. Many studies report that social acceptance is an essential driver of agrivoltaics projects, as a bypass to public fears of losing agricultural landscape to the energy transition. However, it is not clear yet that the public is aware of the associated costs. There remains the question of whether the anticipated synergies could help alleviate these trade-offs. They played little role in the discussion of economic incentives by interviewees, as they have not materialized or been researched enough yet. A specific policy design to define and attach an appropriate value to them is still needed. Overall, the institutional alignment remains incomplete. The current policy landscape reflects a dissent between the stated objective of creating a synergistic, land-efficient combined system and regulatory incentives that favor energy-driven projects. Reservations remain regarding future deployment, particularly whether recent reforms are sufficient to address difficult technological and operational implementation.

Declarations

Availability of data and material: Due to the sensitive nature of the interviews with stakeholders and the ethical commitments made to ensure participant anonymity and confidentiality, the raw data (transcripts and field notes) supporting the findings of this study are not publicly available.

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Appendix I: Source material for qualitative analysis – newspaper articles and interviews

Code	Material background
N01 - N100	Newspaper articles mentioning agrivoltaics from local and regional newspapers, LexisNexis database, length > 200 words, date range: 1st January 2022 – 28th March 2024
I01 – I09	Semi-structured online interviews, based on desk research and snowballing, 36 to 63 minutes, 13th March 2024 to 21st March 2025
▪ I01_developer	Proprietor of an agrivoltaics development company (specialised)
▪ I02_public sector	Experts from a public sector organisation that provides expertise on the energy transition in rural areas
▪ I03_farmers rep	Agrivoltaics expert from a farmers' representative body
▪ I04_developer	Project developer in a leading agrivoltaics development company (specialised)
▪ I05_agrivoltaics rep	Speaker of the newly founded agrivoltaics representative body
▪ I06_farmer	Farmer engaged in agrivoltaics research project
▪ I07_developer	Research and development expert in agrivoltaics development company (specialised)
▪ I08_research	Senior researcher in a research institute with focus on agrivoltaics
▪ I09_developer	Research and development expert in agrivoltaics development company (specialised)

Appendix II: Code System for qualitative analysis

- Normative institutions (rationale, framings)
  - Farmers' attitudes
  - Securing long term economic future
- Cultural cognitive institutions (shared understanding)
  - Deep system integration
  - Definition of agrivoltaics // DIN 91434
- Regulative institutions
  - Funding rules (EEG, CAP)
  - Other regulation (e.g. planning regulation)