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Agrivoltaics and artificial intelligence. New geographies of power

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Abstract. This paper explores the integration of Artificial Intelligence (AI) in agrivoltaic systems as a critical lens for understanding the socio-territorial implications of digital innovation in rural landscapes. Agrivoltaics, which combine agricultural production and solar energy generation on the same land, have emerged as a promising solution to the crises of energy transition and food security. However, their implementation raises significant questions about land use, community participation, and environmental justice. Through a series of case studies – including the European SYMBIOSYST project and two geospatial monitoring experiments using GIS and UAV technologies – the study investigates how AI-based tools such as predictive modelling, 3D digital twins, and sensor-integrated agritech platforms are reshaping the planning, governance, and visual representation of rural energy landscapes. While AI enhances the operational efficiency of agrivoltaic infrastructures and supports site-specific optimisation, it also introduces new spatial asymmetries, risks of algorithmic land grabbing, and challenges to data sovereignty. The analysis draws on critical geography to argue that AI should not be viewed merely as a technical enhancer but as a socio-technical actor that reconfigures power relations and decision-making in energy transitions. The cases discussed illustrate both the risks of centralised and extractive AI models and the opportunities for participatory and place-sensitive technological governance. The paper advocates for a geography-informed framework of AI adoption in the energy sector that promotes equity, transparency, and territorial justice.

Keywords: agrivoltaic, Artificial intelligence, geography of power, socio-territorial implications, AI governance.

1. INTRODUCTION

The energy sector is forecasting a substantial rise in global consumption. In fact, it is estimated that by 2050, energy demand could exceed the current level by 70% (Enerdata 2023; IEA, 2024). As a result, while it is difficult to accurately predict the timing and the amounts of greenhouse gas emissions released into the atmosphere in the future, a transition from fossil fuels to zero-carbon impact sources can no longer be delayed (BloombergNEF, 2025).

Among the various sustainable and carbon-neutral energy sources, solar power stands out as the most relevant, not only due to its ease of use but also due to its huge energy potential. Forecasts indicate that just one hour of sunlight delivers more energy than what is consumed by all human activities over a year (US Department of Energy, n.d.). In this context, the agrivoltaic system represents a noteworthy innovation by integrating agriculture with clean energy production on the same land. However, the implementation of agrivoltaic systems has generated contrasting opinions (Weselek et al., 2019). While it offers potential benefits for agriculture and the fight against climate change, some experts warn about its impacts on biodiversity and on potential microclimatic changes due to the use of solar panels, as well the risk of reducing vital agricultural space. These challenges could be mitigated through advanced digitalization of the agro-energy sector, particularly by leveraging Artificial Intelligence (AI), which can enhance operational efficiency and environmental monitoring while also transforming land planning.

Through the lens of these considerations, the first section of the paper aims to shed light on agrivoltaics, a topic that has sparked diverse opinions within the scientific community.

The following paragraph will delve into the opportunities and challenges associated with the application of AI in the management of agrivoltaic systems, seeking to ascertain whether advanced technologies can foster a synergy between economic growth and environmental and social sustainability. Finally, two experimental methodologies, along with a project analysis case, will be introduced to demonstrate how AI can enhance agricultural productivity and renewable energy generation. By means of the analysis of these results, valuable insights are expected to emerge on how to tackle both current and future challenges in the sector, encouraging a development model that merges energy efficiency with social responsibility.

2. AGRIVOLTAICS: AI AS FACILITATOR OF DIVERGENT OPINIONS

Agrivoltaics, developed in the 1980s by Adolf Goetzberger and Armin Zastrow (1981), represents an innovative approach that consists of elevating solar panels above crops, strategically spaced to minimize the land used for agricultural activities, unlike traditional ground-mounted installations. After some small-scale installations in Germany (Trommsdorff et al., 2021) and Japan (Sekiyama and Nagashima, 2019), the first significant agrivoltaic system was tested in France (Dinesh and Pierce, 2016), followed by larger projects in Germany and Italy (Agostini et al., 2021). However, it is in China that agrivoltaic has seen considerable development since 2010 (Hu, 2023).

Scholars hold radically opposing views on the impacts of agrivoltaics. Some argue that the introduction of this system diversifies income sources since the energy produced can be marketed, providing farmers with greater earning opportunities and increasing land productivity. This assertion is supported by a metric developed by agronomists known as the Land Equivalent Ratio (LER), used to assess soil productivity in conjunction with energy production (Toledo et al., 2021). Simulations suggest that integrating agriculture and energy production could boost overall land productivity by up to 70% (Dupraz et al., 2011; Amaducci et al., 2018; Dupraz, 2024). Furthermore, some experts agree that agrivoltaics plays a crucial role in combating the effects of the climate crisis by optimizing land and water resource use, reducing land degradation, and ensuring sustainability in terms of environmental protection and biodiversity (Colantoni et al., 2021; Trommsdorff et al., 2022; Schweiger & Pataczek, 2023; Taylor et al., 2025).

Skeptical scholars, rather, highlight potential negative effects associated with agrivoltaics, particularly how this practice may influence various microclimatic factors, such as air temperature, shading, and humidity. For instance, they point to the increase in thermal levels beneath solar panels on hot and poorly ventilated days, which can severely impact crop yields and the nutritional quality of agricultural products (Magarelli, Mazzeo, and Ferrara, 2025). Furthermore, critics of agrivoltaic emphasize its adverse effects on the landscape, including visual impact, loss of traditions, and destabilization of farming communities – risks that have sparked opposition movements within civil society and environmental organizations.

The contrasting opinions of scholars, which span from emphasizing the positive to the drawbacks of integrating agricultural crops and energy production on the same land, may find a common ground in the advanced digitalization of the agro-energy sector. This evolution proves how the adverse effects of agrivoltaics can be mitigated through AI and machine learning models. These technologies are becoming essential tools for analyzing complex data, enabling a comprehensive evaluation by assessing environmental, agronomic, and infrastructural variables.

The integration of AI with IoT technologies enhances the efficiency of agrivoltaic systems by allowing for real-time monitoring of critical parameters such as humidity and temperature. This, in turn, improves resource management and optimizes both agricultural and energy yields (Morkūnas et al., 2023; Issa et al., 2024; Assimakopoulos et al., 2025). Numerous case studies, including one from Maharashtra in India, illustrate AI's potential to boost agricultural productivity and enhance water resource management. Notably, this study reported a 30% reduction in water consumption, a significant achievement given the growing issue of water scarcity in India (Medonna and Ghosh, 2025). Other initiatives in Indonesia, where chili cultivation occurs in an off-grid area, highlight how technology can enable remote management through mobile devices. Projects in Kenya and Niger show the application of AI in analyzing agronomic data and planning crop practices, reducing the use of chemicals and enhancing food security. These are examples of successful applications of AI capabilities that have allowed the agrivoltaic system to adapt to a variety of climates and geographic contexts, from arid regions to temperate and tropical areas (Satria & Rosnelly, 2025), offering innovative solutions to better address the challenges of food security for a continuously growing global population and the fight against climate change.

This framework characterized by challenges and expectations, requires tools that can incorporate territorial, environmental, and social variables. This is where algorithmic geography becomes an essential analytical tool for decision-making.

3. THE ALGORITHMIC GEOGRAPHY OF AGRIVOLTAICS: TWO METHODOLOGICAL EXPERIMENTS

In this study, GIS and UAV case studies are methodological experiments, purposely selected to demonstrate site-specific optimisation and national-scale spatial effects, serving an illustrative – rather than statistically generalisable – role in analysing AI-territory coproduction.

In the current discourse debate surrounding agrivoltaics and its territorial implications, it is valuable to focus on examples of methodological experiments that, although not tied to a specific local context, clearly reveal the potential and challenges posed by the digital infrastructure of rural landscapes. Two recent studies stand out as exemplary cases of how geospatial technologies and advanced monitoring systems can redefine the design, management, and oversight of coexistence between agricultural production and energy generation.

The first significant contribution is a national-scale analysis that employed a Geographic Information System (GIS) approach based on multiple criteria to assess agrivoltaic potential in Italy. This study developed a spatial model capable of integrating various layers of information – such as land use, solar availability, regulatory constraints, and landscape sensitivity – to identify the most geographically suitable areas for the installation of agrivoltaic systems (Fattorusso et al., 2024).The methodology not only quantifies the extent of potentially installable areas but also highlights the deep territorial asymmetries that emerge when overlapping energy priorities, agricultural logics, and environmental protection demands. What makes this approach particularly significant is its ability to cartographically and reveals through modelling the political and selective nature of the energy transition. The maps generated through these tools do not simply represent neutral data about the territory; they reflect decision-making hierarchies, constraints imposed by existing regulations, and the infrastructural choices of public and private entities.

In essence, the geography of agrivoltaics is a constructed reality rather than a mere observation shaped by computational choices and algorithmic filters that determine what is visible and what remains outside the realm of possibilities (Fattorusso et al., 2024). This methodology aligns with the growing affirmation of territorial intelligence as a key component of spatial governance, emphasizing the integrated use of data and technologies to guide environmental transformations consistent with systemic goals (Lu, 2024).

A second complementary example involves an experiment utilizing UAV (Unmanned Aerial Vehicle) surveys and three-dimensional photogrammetry, to monitor the interaction between the shading effect of photovoltaic panels and crop growth (Cuaran & Leon, 2021). The study demonstrated that by leveraging high-resolution three-dimensional models, it is possible to optimize the placement of modules and assess the microclimatic impact of the installations on the agricultural ecosystem in real time. The data collected from this type of monitoring also helps inform dynamic predictive models that can adapt to the specific climatic and agronomic conditions of the site, transforming the agrivoltaic installation into an adaptive system rather than a static one.

This experimentation prompts important reflections on the role of algorithmic monitoring in rural areas. By employing drones, sensors, photogrammetric models, and digital simulations as everyday management tools for agricultural land, we are witnessing a radical redefinition of the relationship between agriculture, landscape, and control. On one hand, these tools enhance efficiency, reduce uncertainty, and enable highly specialized management of crops and energy yields. On the other hand, they raise significant questions regarding data sovereignty, ownership of the generated information, and the decision-making asymmetries between large technological operators and local communities (Jobin et al., 2019; Reasoner & Ghosh, 2022).

Together, these two practical experiences confirm that the synergy between agrivoltaics and AI should not be seen merely as a process of innovation; rather it must be understood in the context of geopolitical and territorial transformation. In this framework technologies such as GIS, AI, UAVs, predictive models – function as essential tools for spatial selection, priority definition, and resource reorganization. Consequently, the agricultural landscape becomes a subject of coding, interpretation, and transformation guided by computational logics. Thus, the challenge extends beyond technical aspects; it holds deep political implications. It revolves around the potential to direct these tools towards fostering territorial justice, transparency, and participation, rather than perpetuate centralized and opaque models of digital value extraction (Moser, 2023; TRUST-PV, 2024).

3.1. The SYMBIOSYST project: the potential of AI

In a context marked by the previously mentioned challenges, AI can be effectively applied by taking into account the unique characteristics of the territory and actively engaging administrations and local communities this approach is exemplified by the SYMBIOSYST project (SYMBIOSYST of Photovoltaic Systems with Agriculture for Smart Land Use). Funded by the Horizon 2020 program with a total budget of €5 million, the project is coordinated by the Eurac Research center in Bolzano, in collaboration with ENEA, the Laimburg Experimental Center, and various stakeholders from the agricultural and industrial sectors. Its goal is to develop advanced technological solutions to enhance the sustainable competitiveness of agrivoltaic systems in Europe through the adoption of artificial intelligence techniques and site-specific predictive models.

The project's methodological foundation relies on multi-objective models that integrate agricultural and energy production simultaneously. In particular, the modeling of crop yields and photovoltaic output utilizes deep learning algorithms, data imputation to manage incomplete climatic data, and three-dimensional digital twins of landscape systems. In this context, AI serves not only as a tool for operational optimization but also as a mechanism for territorial configuration, influencing the design, monitoring, and governance of agrivoltaic systems (Reasoner & Ghosh, 2022; Moser, 2023).

The methodological basis of the project is the use of multi-objective models capable of simultaneously integrating agricultural and energy production. In particular, the modeling of crop yields and photovoltaic output employs deep learning algorithms, data imputation for managing incomplete climatic data, and three-dimensional digital twins of landscape systems. In such a case, AI not only serves as a tool for operational optimization but also acts as a territorial configuration device, influencing the design, monitoring, and governance of agrivoltaic systems (Reasoner & Ghosh, 2022; Moser, 2023).

A particularly noteworthy aspect of the project is the development of a decision support system that integrates predictive algorithms and agronomic indicators into complex decision-making processes. As demonstrated in the related experience of TRUST-PV, these tools can effectively guide energy planning through innovative metrics that identify environmental challenges and optimize interventions in real time. This enhances the alignment between digital inputs and the ecological characteristics of territories (Moser, 2023). Furthermore, the SYMBIOSYST project utilizes drones to create 3D models, allowing for construction of a digital twin. This twin is instrumental not only during the design phase but also for continuous monitoring of the site's energy and agricultural performance.

What makes SYMBIOSYST particularly relevant to discussion in geography is its ability to blend technical innovation with sensitivity to landscape. This combination fosters reflective dialogue on the necessity for transparent and participatory algorithmic governance.

These operational outcomes demonstrate that the success of this transition relies heavily on how we incorporate digital tools into territorial governance, a theme that will be explored in the conclusions.

4. CONCLUSION

The findings of the study suggest that the synergy between agrivoltaics and artificial intelligence represents not just a technological advancement, but a radical change in geopolitical and territorial relations. Technologies, as tools for spatial organization and resource management, possess the power to transform rural landscapes by reshaping usage dynamics and foster enhancement. However, this evolution comes with serious risks. The integration of AI in agrivoltaics could exacerbate existing inequality and a concentration of power, as platforms and algorithms are often controlled by external actors who may overlook local specificities. There is a growing concern that these technologies might evolve into instruments of algorithmic extraction, draining value from territories and jeopardizing their integrity.

Digital platforms and predictive algorithms are frequently developed by industrial and technological actors external to the local context, who control data collection, analysis infrastructures and decision-making framework (Lu, 2024; Jobin et al., 2019). As a result, AI-driven agrivoltaic technologies risk becoming mechanisms for extracting data, resources and value from local communities, channeling them into centralized and opaque valorization circuits.

A responsible evaluation of AI adoption in the agrivoltaic sector must consider not only technical and environmental benefits, but also the ethical, geographical, and political implications (Dahlin, 2021). It is crucial to investigate who defines the optimization criteria for algorithms, who controls territorial analysis platforms, and how the advantages of digital transition are allocated. The transformation of agricultural landscapes into "algorithmic landscapes" raises important questions about protecting place identity, preserving traditional agricultural knowledge, and legitimation of automated decision-making processes (Scognamiglio, 2016). These insights can shed light on the potential impacts of these changes on local communities and their resources. By identifying the stakeholders involved, we can more effectively address issues of equity, representation, and the influence of external forces shaping agricultural practices and outcomes.

AI governance that is sensitive to local contexts should rest on three fundamental pillars: (1) transparency and flexibility in the algorithms used for the design and management of agrivoltaic systems; (2) active involvement of local communities in the modeling and application of territorial data; (3) spatial contextualization of technological solutions to ensure alignment with the landscape and socio-cultural characteristics of the area in question.

Ultimately, the integration of AI and agrivoltaics underscores the importance of a critical geographical perspective in approaching the digital transition. This perspective involves more than just determining optimal locations for system installation; it requires an examination of how technology reshapes the interactions among landscape, production processes and power dynamics. When governed responsibly, AI can serve as a powerful ally in enhancing rural resilience, promoting environmental justice, and ensuring that the energy transition does not compromise territorial equity.

In summary, agrivoltaics should be viewed solely as a technological solution for energy and food production but rather as a territorial infrastructure that transforms land use, value chains, and power relationships. The adoption of AI in this domain is anything but neutral; it significantly affects decision-making, localization, and the distribution of costs and benefits. Therefore, achieving a "just transition" requires clear criteria for spatial equity and tools to assess distributive effects both at local and regional scales.

From an algorithmic standpoint, the shift from "technical optimization" to algorithmic governance entails three key elements: (1) transparency regarding models and data, which include through documentation of sources, quality, coverage, and limitations; (2) explainability of decisions, ensuring that justifications are provided for both selected and excluded locations; and (3) multi-actor accountability, which entails independent audits, version tracking, public registries of models. In the absence of these proper safeguards, AI risk can reinforce existing biases and exacerbate land-use conflicts.

From an institutional perspective, the evidence points out several key needs: (1) the establishment of a polycentric and place-based governance model; (2) collaboration with farmers and local communities; (3) clear mechanisms for benefit-sharing which may include royalties, fee reductions, environmental and social funds; (4) provisions that ensure the continuity of agricultural production and (5) public monitoring tools to assess yields, biodiversity, and landscape impacts both before and after implementation.

In this framework, the Quadruple Helix model plays a vital role in harmonizing the interests of public, private, scientific, and civic sectors. This approach shifts the focus from "downstream" acceptability of projects to "upstream" legitimization, ensuring that all stakeholders are actively engaged in the decision-making process (Carayannis & Campbell, 2009; 2012).

Operationally, this necessitates algorithmic transparency and accountability through the use of model and data sheets, error metrics, versioning, and periodic audits. It also requires clear criteria for spatial equity, including minimum thresholds for local returns and mapping of land-use trade-offs. This should be complemented by integrated ex ante assessments that consider environmental, agronomic, and social factors incorporating meaningful public consultation. Additionally, standardized benefit-sharing mechanisms should be implemented, such as template contracts, community funds, and equity stakes in energy cooperatives. Public dashboards can provide near-real-time monitoring of production, yields, biodiversity, and social impacts (Jobin, Ienca & Vayena, 2024).

Additional, experimental designs remain essential for estimating causal impacts on yields and incomes. This requires multi-scale longitudinal datasets that combine remote sensing with administrative data, implementation of local calibration protocols for AI models, and conducting international comparisons of benefit-sharing mechanisms to evaluate their effectiveness in conflict reduction. All of these efforts should be underpinned by open standards and independent validations to address potential bias and ensure generalizability (Carayannis & Campbell, 2009; 2012; Jobin et al., 2024).

AI-enhanced agrivoltaics can serve as a catalyst for numerous opportunities, but their success hinges on the transparency and accountability of data and models used. Ultimately, decisions must be grounded in metrics of territorial equity, and the transition to sustainable practices can only be considered genuinely "just" if it delivers value back to the local communities.

In conclusion, the integration of AI within agrivoltaic systems signals not just a technological upgrade, but a structural reconfiguration of territorial governance and regulatory power. Approaches formalised under frameworks such as the EU AI Act demonstrate how regulation itself becomes a geopolitical instrument, enabling Europe to project normative influence whilst curbing asymmetric dependencies along global AI–energy value chains. At the same time, evidence from peripheral and off-grid regions in Global South illustrates that AI-driven agrivoltaics may either entrench extractive hierarchies of data and land, or – if shaped through participatory, place-aware governance – convert digital oversight into a territorial public-value asset. What is ultimately at stake is not optimisation alone, but who sets the criteria, who controls spatial analytics, and how benefits and externalities are territorially allocated. A genuinely just transition therefore rests on polycentric accountability, ex-ante impact assessment tied to local evidence, and equitable benefit-sharing mechanisms that retain decision authority with territorial communities, rather than remote platform monopolies. In this sense, geography must continue to serve as a critical regulatory compass, ensuring that AI and agrivoltaic co-deployment strengthens – rather than compromises – territorial justice, community resilience, and the democratic legitimacy of rural energy futures.

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