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SPECIAL FEATURE: OVERVIEW ARTICLE

The Dawn of Solar Photovoltaics: Emergent political economies at the solar-agri-land nexus

Farming the sun: the political economy of agrivoltaics in the European Union

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Abstract

What kind of agricultural practices do agrivoltaic systems incentivise? Under what circumstances can they deliver the promised benefits, and who is likely to bear the costs? Presented as a win–win solution for developing solar energy while enhancing farmland productivity, agrivoltaics offer several advantages—including decentralised electrification, improved crop yield, and thus increased farmers' income. Compared to traditional utility-scale solar, however, agrivoltaics generally entail higher installation costs and material requirements, lower energy generation, and thus increased cost of electricity production. Drawing on William Kapp's theory of social costs and ecological political economy, this article examines agrivoltaics developments within the latest EU-level policy initiatives on energy, agriculture, and climate change. Despite room for optimism regarding the comparative advantages of agrivoltaics, the findings reconcile these benefits with multiple trade-offs inherent in alleged 'win–win' solutions. Addressing the dual objectives of energy and agricultural transitions, the uncritical deployment of agrivoltaics risks perpetuating the prevailing 'cheaper food paradigm', characterised by capital and energy-intensive agricultural techniques, trade globalisation, wage compression, and the displacement and/or deferral of environmental harm. Additionally, rent-seeking behaviour among landowners leasing to energy developers could inflate agricultural land prices, thus exacerbating land ownership intensification and the financialisation of European farmland. This article concludes by advancing a few avenues to reinvest the rental income of agrivoltaics to facilitate the transition to agroecological farming practices.

Keywords Agrivoltaics · Energy transition · Green transition · Agroecology · Social costs · Solar energy

Introduction

This article investigates the political economy of agrivoltaic systems, wherein solar photovoltaic panels and agricultural activities are synergistically co-located on farmland. Focusing on the European Union (EU) and its member states, the article aims first to identify the social and environmental costs associated with the deployment of agrivoltaics, and then analyse their role at the intersection of agricultural and energy transition agendas.

The world installed capacity of solar photovoltaics increased tenfold in the decade between 2012 and 2022, with China alone adding more photovoltaics in 2023 (> 216 GW) than the entire installed capacity of solar energy in the USA (IRENA 2024). This surge is primarily driven by a steep drop in Chinese monocrystalline module costs, leading not only to a rush in new installations, but also to a global glut. This has prompted experimentation with less efficient systems, including using photovoltaic modules as fences (Mnyanda et al. 2024) or, indeed, integrating them into agricultural production. However, several factors threaten to hinder the roll-out of solar energy. Globally, there are growing concerns about labour and environmental standards along the life cycle of solar energy systems (Mulvaney 2019; Sovacool et al. 2020; Stock 2021; Stock and Birkenholtz

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2021; Roos 2023), as well as trade competition and geopolitical strategies limiting technological transfers and the availability of critical materials[1] (Bazilian 2018; Vezzoni 2023). Additionally, low-carbon energy sources such as solar, wind, and biomass are orders of magnitude less energy-dense than fossil fuels (van Zalk and Behrens 2018), resulting in a substantially larger land footprint and potential conflicts over land access. This is a key point of contention of low-carbon energy (McCarthy 2015; Bridge 2018; Brock et al. 2021; Knuth et al. 2022), raising issues over land access, ownership, stewardship, and land-system change.

Against this background, agrivoltaics are presented as an alleged win–win solution (Chatzipanagi et al. 2023; Goldberg 2023; Pascaris et al. 2023; Trommsdorff et al. 2024), promising to deliver both for farmers and energy developers, while offering a legitimation strategy to 'increase public acceptance of solar siting on agricultural land' (Moore et al. 2022, p. 9). On one hand, they aim to optimize crop yield while harnessing complementary electricity production via solar panels. On the other hand, already on a small scale (i.e. below 2 ha), the revenue streams from electricity generation can be substantially higher than those provided by any agricultural activity of an equivalent size (Dinesh and Pearce 2016; Trommsdorff et al. 2023). These cash flows could offer a financial buffer to transition away from industrial farming over the lifespan of the agrivoltaics system (roughly 25 years). However, given the political economy characterising industrial agriculture, which kind of farming practices stand to benefit from agrivoltaic systems? Under what circumstances can they deliver the promised socio-economic and environmental benefits and, conversely, who is likely to bear the costs?

In line with other scholars complementing technical studies with political economic analyses of agrivoltaics (Hu 2023), as well as their impact on local agricultural economies (Moore et al. 2022), we address these questions by reviewing the latest developments in energy, agricultural, and climate policy in the European Union (EU). Conceptually, this article draws on William Kapp's theory of social costs to reframe the ongoing attempts to transition away from fossil fuels as a cost-shifting exercise. Kapp, a founding figure of institutional economics and a growingly fierce critic of the market price mechanism, extensively explored the endogeneity of social and environmental harms that economists conventionally label as 'externalities'. In contrast, according to Kapp (2016, 1974, passim), externalities are an integral part of the economic system and should be redefined as the relative capacity of social actors to shift costs onto others. In this article, we shall refer to these unaccounted-for planetary health damages by market prices as the expression of 'cost-shifting' dynamics characterising any type of capitalist development, including low-carbon energy systems. Without accounting for the ways in which technology can be exploited to entrench uneven and harmful social–environmental relations, alleged 'win–win' solutions like agrivoltaics risk reproducing old patterns of systemic exploitation.

The green transition as a cost-shifting exercise

The currently unfolding green transition is a process of capital formation and accrual, whereby new artefacts like low-carbon energy are developed with the intent of displacing fossil fuel extraction and combustion.[2] Tellingly, capitalist development harbours both the seeds of its own demise and renewal. Schumpeter famously referred to this as the process of 'creative destruction', according to which 'the intrusion of new commodities or new methods of production or new commercial opportunities' revolutionises the industrial structure from *within* (Schumpeter 2003, p. 31). Innovation and discovery expand the technical frontier of production, enabling new entrepreneurs to enter the market with an unmatched advantage over the competition, thus compelling others to either catch up or succumb. This process defines the essential economics of capitalist 'creative destruction'. Yet, it does not represent the whole picture.

As markets do not operate in a vacuum, the expansion of the commodity form rests on a potentially conflictual incursion into other social and environmental domains. On these premises, Karl Polanyi (1944/2001) waged a famous critique against the commercialisation of 'fictitious commodities' such as land, labour, and money. The creation of market value requires the transformation of the existing social fabric and ecological networks, invariably leading to the disruption of the status quo. Hence, capitalist economies have never been and cannot be static (Schumpeter 2003). Now, as long as the price mechanism serves as the primary enabler of value creation, all goods and services that remain outside the market cannot be valued as such (O'Hara 2009, p. 226).

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[1] This is not to say that there are not enough minerals available to install over 70 TW of solar energy, as in most climate change scenarios (cf Haegel et al. 2023, p. 40). The issue remains debated, however, concerning the marginally decreasing economics of extraction, degrading quality of input materials, and the overall contribution of recycling and efficiency gains to sustain the long-term replacement of solar infrastructure every 25 years.

[2] It should be noted that the 'energy transition' is yet to materialise—and rather an 'energy addition' has been taking place (York and Bell 2019). So far, low-carbon sources like solar and wind are simply piling up on top of previously installed generation capacity to meet the demand of an expanding world economy.

These postulates are the starting point of Kapp's theory of social costs.

Social costs can be defined 'as systemic and large-scale damages caused by markets' (Kapp 2016, p. i). Traditionally, these have been considered exogenous, as implied by the (neo)classical notion of externalities. Kapp's contribution to economic theory lies in reframing externalities as an endogenous component of profit-led investments. Accordingly, externalities are not cases of market failure, but cost-shifting success stories. If social costs are an integral part of the economic system, they should be redefined as the relative capacity of social actors to shift costs onto others. Rather than being an unfortunate exception, cumulative forms of environmental degradation such as climate change, biodiversity loss, and soil depletion are the expression of a successful mechanism of capital accumulation (O'Hara 2009; Stoddard et al. 2021). Industrial modernity thus advances following the path of least resistance. It shifts the burden of development onto those with less bargaining power—such as lower classes lacking market control, national minorities, and Indigenous groups without institutional representation, non-human nature missing legal status, or future generations without authority over the present.

Whether wielded locally at the expense of marginalised populations and habitats or on a global scale, these unaccounted harms represent a pervasive socialisation of costs, with the flip side being the privatisation of economic benefits. To be clear, it is not out of some sadistic perversion that capitalist entrepreneurs engage in cost-shifting, but the concurrence of the price mechanism, a lack of accountability, the idealisation of disruptive innovation, and the socialised prioritisation of gross domestic product (GDP) growth incentivise shifting costs onto others as a hidden metric of economic success. Without a coordinating mechanism, the mere thrust to maximise entrepreneurial profits results in paradoxical outcomes, as 'optimal solutions by micro-economic units will not give rise to social optima; on the contrary, they may and will coincide with a disruption of the natural and social environment' (Kapp 1970, p. 844).

Cost-shifting manifests as an economic form of schismogenesis, namely, a self-reinforcing mechanism of social differentiation. Enterprises that manage to displace/defer more harm are comparatively more successful, whereas those bearing the costs—whether environmental systems, humans, or other sentient beings—are increasingly less capable of resisting further damage. For example, borrowing from Hokkanen's (2024) study of soil depletion in the EU, the systematic exploitation of farmland by industrial agricultural practices degrades soils' structure, thus leading to compaction and runoff of nutrients. The ensuing loss in fertility is ultimately compensated for by increased synthetic inputs and heavier tilling practices, which lead to further disturbance and soil deterioration. Such losses are hardly reversible within a human timescale, especially when subsumed to the logic of 'sunk costs' by following generations of developers. A brownfield, for instance, is an ideal site for solar parks because its degraded state compared to neighbouring land makes it suitable for further artificialisation. A photovoltaic power station could improve the environmental quality of the site, although it would not, in principle, restore the ecological integrity of the land before it was turned into a brownfield. Globally, already a quarter of farmland is in a degraded state (Webb et al. 2020), and the installation of new long-lasting infrastructure can trigger further environmental degradation, as in the case of utility-scale solar (Choi et al. 2020). An exception would be to design lower-density photovoltaic installations prioritising ecological processes, as suggested by the notions of 'ecovoltaics' (Sturchio and Knapp 2023) or 'conservation-agrivoltaics' (Time et al. 2024). Still, this does not disprove the essential fact that the logic of market-mediated capital accumulation favours the maximisation of profitable activities at the neglect of the 'free gifts' of nature and society.

To counteract the cumulative consequences of cost-shifting, societies elaborate complex checks and balances. These are generally regulatory measures to redistribute revenue, prevent harm, and secure the provisioning of essential services like healthcare, food, sanitation, energy, and education. When these systems fail to deliver, different forms of collective protectionism ensue or, at the very least, their political acceptability greatly increases. In essence, this Polanyian double movement historically has 'consisted in checking the action of the market in respect to the factors of production, labor, and land' (Polanyi 2001, p. 137). The counter-movement underscores a mechanism for social protection (i.e. decommodification of provisioning services) that rebalances social forces and prompts institutional change: a reading of Polanyi's scholarship shared also by Kapp (Kapp 1978 in Berger 2024). It remains debated, however, whether the effectiveness of the market-society historical dialectics also holds against the incommensurable, cumulative, and fundamentally uncertain damages to the natural environment. Accordingly, Kapp has argued for a preventive approach to social–environmental harm, a notion condensed in the precautionary principle. It is within the tension between market reform and collective action that this article reviews the interplay of the energy and agricultural transition as a complex set of trade-offs behind alleged win–win solutions.

The dual energy and agricultural transitions

The so-called 'green transition' is an attempt to fundamentally restructure the material and energetic foundations of industrial modernity (Haberl et al. 2011). It essentially entails a broad transformation of provisioning systems, including the organisation of agri-food systems. While solar energy is not the only low-carbon energy source in the green transition agenda, its deployment on farmland engenders interesting interactions at the intersection of agricultural and energy transitions.

Solar energy is most productive when installed as utility-scale ground-mounted photovoltaics on flat lands close to grid connection points. Farmland is thus often targeted for solar siting, offering a blank slate for energy developers to install photovoltaics free of artificial barriers and natural hurdles, such as wetlands or endangered endemic species (Goldberg 2023). This siting strategy pressures landowners and farmers to discontinue agricultural activities (Spangler et al. 2024), hence provoking different forms of bottom-up resistance. Contestations arise against the enclosure of common land, the destruction of sacred sites, land-use changes that transfer benefits elsewhere, and other disruptions to local livelihoods (Mulvaney 2013, 2019; Stock and Birkenholtz 2021). Beyond social conflicts, utility-scale solar also carries environmental trade-offs. It can negatively affect wildlife (Moore-O'Leary et al. 2017), hydrological connectivity (Grippo et al. 2015), and topsoil biota (Mulvaney 2019, chap. 6), while requiring additional deforestation and mining (Laing 2022). Although these impacts may be comparatively less severe than those caused by fossil fuel extraction and combustion, efforts to transition towards low-carbon energy systems are not exempt from social and environmental harm. The unresolved conflicts over the large-scale deployment of solar energy underscore a missed opportunity to reconfigure the exploitative social institutions ingrained in the current fossil fuel-based world economy (Dorninger et al. 2021; Dunlap 2024; Roos and Hornborg 2024). Moreover, as we have seen, scaling up photovoltaic systems intersects with another transition: that of the agricultural sector.

Agricultural production, and the broader agri-food system, are major drivers of the 'Global Syndemic': namely the confluence of obesity, undernutrition, and climate change (Swinburn et al. 2019). Despite already producing enough calories to feed a world population of 8 billion and counting (Holt-Giménez et al. 2012; Kc et al. 2018), over 3 billion people currently suffer from malnutrition (Webb et al. 2020), with a bewildering higher incidence of obesity than hunger (Benton and Bailey 2019). At the same time, agri-food systems contribute up to a third of greenhouse gas emissions (Vermeulen et al. 2012; Campbell et al. 2017; Zurek et al. 2022). Land-use conversion to farmland has been the main cause of biodiversity loss over the past half a century (Benton et al. 2021), and agriculture remains the main driver of at least three other planetary boundaries: biogeochemical flows, land-system change [which disrupts biosphere integrity and is responsible for up to 70% of deforestation worldwide (Tittonell et al. 2020)], and freshwater use (Campbell et al. 2017). However, these processes call for a distinction, for it is not agri-food systems in general that should bear the honours and burdens of the current planetary predicament, but rather a specific agricultural model driven by productivism (Benton and Bailey 2019; Lähde et al. 2023), bringing the industrial logic of commodity standardisation, corporate concentration, and economies of scale from the factory to the field (Tittonell et al. 2020; Patel and Goodman 2020; Clapp 2023; Hokkanen 2024). In this article, drawing from Benton et al. (2021) (see also, Patel and Moore 2018; De Schutter et al. 2020; Lähde et al. 2023), we define the expansion of agricultural output driven by intensive artificial inputs, trade globalisation, wage compression, and displacement/deferral of environmental harm as the 'cheaper food paradigm' characterising industrial agriculture.

In Europe, the (trans)formation of agriculture as a global industry has been driven by the Common Agricultural Policy (CAP). Since the post-WWII era, the CAP has been utterly successful in systematising mass production of cheap calories for the European continent. Yet, the modernisation of agri-food systems has also empowered large corporations to 'increasingly act as gate-keepers to the high-value markets of rich countries, weakening the position of small-scale suppliers of raw agricultural products' (De Schutter 2017, p. 713). Plagued by ever-tightening profit margins for most farmers, Europe has evolved into a competitive exporter of agricultural commodities amidst mounting local discontent. In recent years, successive waves of farmers' protests have rocked the political debate in most European countries and, in several instances, hindered the establishment of stricter environmental standards.[3] These protests are generally framed as reactionary responses to climate policy. However, beneath this simplistic narrative lies discontent with the ongoing transformation of agri-food systems into a global industry favouring transnational corporations (Clapp 2023) and large-scale infrastructural developments driving small producers out of business (Albizua et al. 2019).

The current CAP subsidy scheme remunerates farmers on a per-hectare basis, thereby favouring land ownership intensification (van der Ploeg et al. 2015), while persistently underachieving in terms of environmental (Pe'er et al. 2020; Candel et al. 2023) and health benchmarks (De Schutter et al. 2020). Ironically, European agriculture remains a source of malnutrition (mostly in terms of overweight and obesity rates) and unsafe exposure to carcinogenic substances (Benton and Bailey 2019), while exporting

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[3] On March 25th, a critical vote to approve the EU Nature Restoration law got postponed last minute after eight member states withdrew support or opposed the legislation. The law, whose aim to restore the health of European biomes had already been substantially watered down from its original targets, was deemed a politically sensitive topic ahead of the European elections of June 2024.

deforestation and biodiversity loss beyond European borders (Fuchs et al. 2020). Therefore, the key challenge of the 21st-century agriculture is to overcome the perverse consequences of the 'cheaper food paradigm', while maintaining high levels of productivity (Deguine et al. 2023).

Several high-tech options are currently being explored to address the unsustainability of industrial agriculture—such as satellite-controlled machinery, cellular agriculture, or vertical farms. These solutions are often framed within the increasingly popular banner of 'Climate–Smart Agriculture' (Clapp et al. 2018; Karlsson et al. 2018; Newell and Taylor 2018). Conversely, low-tech solutions have also been proposed to move beyond the 'cheaper food paradigm'. They primarily concern the transition to various forms of agroecological practices (Altieri et al. 2015; Tittonell et al. 2020; Anderson et al. 2021; Deguine et al. 2023), such as organic farming, permaculture, regenerative farming, as well as the more politically charged notions of food democracy and food sovereignty (Leitheiser and Vezzoni 2024; Tilzey 2024). Agrivoltaics systems sit astride high- and low-tech solutions. The following sections explore their interaction with the contingent political economic forces at play in the European Union.

Methodology

Researching the political economy of 'green transitions'

The remainder of this article integrates the theory of social costs presented in "The green transition as a cost-shifting exercise" with scholarly discussions on agricultural and solar energy policy, within the broader regulatory initiatives on climate change. The objective is to contextualise which kind of agriculture could and should benefit from developing agrivoltaic systems in the EU, as well as the environmental and social consequences this may entail. Key questions for the 'green transition' include 'who, where, and on whose terms' pays the costs or reaps the benefits of greening capitalism (Newell et al. 2021; Hudson 2024). Therefore, the analysis in this paper draws on notions and discussions from political economy, investigating the relational interplay of market organisation, state governance, technological change, rent and ownership structures, as well as forms of resistance to these processes.

The move away from destructive and yet highly profitable fossil fuels demands more than just regulating and nudging private actors; it also requires a fundamental economic restructuring that markets alone struggle to address (Christophers 2024). Simultaneously, new technical innovations like agrivoltaics often reinforce rather than challenge dominant policy paradigms, such as those promoting free markets, ecological modernisation, standardisation of farming practices, and corporate consolidation (Clapp et al. 2018; Leach et al. 2020; Clapp 2023). Agriculture is laden with trade-offs, whether between competing uses of resources (e.g. crops for food vs biofuel), different policy objectives (e.g. economic growth vs environmental stewardship, food security vs climate mitigation), or contrasting interests (e.g. large vs small producers, owners vs tenants) (Vermeulen et al. 2012; Albizua et al. 2019; Guyomard et al. 2023). The absence of critical thinking behind narrowly conceived solution-oriented narratives leaves little room for reflexive adaptation to the root causes of present global challenges (Newell and Taylor 2018). However beneficial they may seem, low-carbon technologies are not inherently emancipatory or guaranteed to ease social costs and environmental destruction (McCarthy 2015; Vezzoni 2023, 2024; Dunlap 2024; Roos and Hornborg 2024). These issues extend beyond mere policy-making, as the negotiation of collective action must come to terms with what is materially viable; and they are not just about economics either, for distribution and investment needs are not dictated by universal efficiency metrics and uncontested aims. Accordingly, the social processes behind the transformation of provisioning systems like energy and agriculture can be better framed as a question of ecological political economy.

Still, the power relations underpinning these ecological–political–economic processes demand historical contextualisation—e.g. when did they originate? Where and how do they manifest? How will these relations possibly evolve?—since they are always the expression 'of specific accumulation strategies at various economic and political scales in specific spatio-temporal contexts' (Jessop 2013, p. 9). Therefore, given the primacy of context, this article focusses on the European Union as a case study to understand the political economy of agrivoltaic systems.

Data

The mainly empirical focus of this article is instructed by a content analysis of the latest versions of key policy documents published during the first term of the von der Leyen Commission (2019–2024). In the EU, national agricultural and energy policies are concerted among member states through policy frameworks like the Common Agricultural Policy (CAP) and, since the approval of the final versions in December 2019, the National Energy and Climate Plans (NECPs). Designed to coordinate the EU's climate and energy targets, the NECPs provide insight into the transformation of European agricultural and energy systems. Within each NECP, member states are required to define their 2021–2030 decarbonisation goals and related energy policy measures for sectors such as agriculture, real estate, transport, and manufacturing. More recently, member states have been requested to adapt their national plans to take stock of the novelties brought by the COVID-19 pandemic, the

Table 1 List of policy documents analysed

Category	Documents	Month, year
National energy and climate plans (NECPs)	24 NECPs updates	Jun–Dec, 2023
	EU-wide assessment of the NECPs	Dec, 2023
Common agricultural policy	Summary of CAP Strategic Plans for 2023–2027	Nov, 2023
European Green Deal	Farm-to-Fork	May, 2020
	Solar Strategy (REPowerEU)	May, 2022
	Renewable Energy Directive (Fit for 55 package)	Nov, 2023
EC reports	Mapping and analysis of CAP strategic plans	Jun, 2023
	Overview of the Potential and Challenges for Agri-Photovoltaics in the European Union	2023

Russian–Ukraine war, and several EU initiatives in response to these crises. The updated drafts were due by June 2023.[4] These are included in Table 1, which summarises the policy documents analysed in this article.

In addition to the NECPs, Table 1 includes key European-level policy documents concerning solar energy, common agricultural policy, and land use published since 2019. Under the European Green Deal agenda, these encompass the Farm-to-Fork strategy to reform agri-food systems, the EU Solar Energy Strategy (part of the REPowerEU), and the 2023 update to the Renewable Energy Directive under the Fit for 55 package. While the 27 national plans for the 2023–2027 CAP are also important documents for the analysis carried out in this article, they have already been thoroughly assessed in a recent report by the Joint Research Centre (JRC) of the European Commission, identifying the potential and challenges for agrivoltaics in the EU (Chatzipanagi et al. 2023). Instead of duplicating their findings, we include this publication in Table 1 and complement it with two additional reports: the summary of CAP Strategic Plans for 2023–2027 published in November 2023 (European Commission 2023a), and an in-depth general commentary on the CAP Strategic Plans published in June 2023 (ECORYS et al. 2023). Before delving into the analysis of the policy documents in Table 1, the next section presents a literature review of the benefits and drawbacks associated with agrivoltaics.

Agrivoltaics: a solution for European farmers?

Overview of an emerging technology

The idea of integrating solar photovoltaics with food production has been around since the early 1980s, initially proposed by German scientists.[5] The first reported proof of concept was developed in France in the early 2010s (Dupraz et al. 2011; Dinesh and Pearce 2016), tallied by other pilot projects and increasingly larger installations also in other European countries, such as Germany and Italy (Agostini et al. 2021). Prior to these scientific advancements, a few small-scale entrepreneurial installations appeared in Germany (Trommsdorff et al. 2021) and in Japan (Sekiyama and Nagashima 2019)[6] already in the late 2000s. However, it was in China that the agrivoltaics began to develop on larger scales during the 2010s (Hu 2023). Lastly, the US Department of Energy started supporting agrivoltaics research only in 2015 (Macknick et al. 2022). After this brief historical background, the following sub-sections summarise the pros and cons of agrivoltaic systems.

Benefits of agrivoltaics

Agrivoltaics offer several potential advantages compared to the two land uses they aim to replace: open-field agriculture and utility-scale ground-mounted solar photovoltaics (GM-PV). Unlike conventional GM-PV, agrivoltaics accommodate or, at least in Europe, prioritise the continuation of agricultural activities. Compared to open-field farming, agrivoltaics provide various environmental benefits,

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[4] As of December 2023, only 24 updated NECPs had been submitted. The missing NECPs are from Austria, Bulgaria, and Poland. A final version is to be sent by June 2024.

[5] A key figure in the theoretical development of agrivoltaics was the physicist Adolf Goetzberger, who in 1981 founded the Fraunhofer Institute for Solar Energy Systems.

[6] The nearly identical concept of 'solar sharing' to define stilt-mounted PV modules above crops was already patented in 2004 by the Japanese engineer Akira Nagashima.

although their impact on agricultural yields varies based on the climate zone and crop types. Generally, they are most beneficial in hot and water-limited agroecosystems (Weselek et al. 2021; Warmann et al. 2024). The shade provided by the panels can reduce water consumption through lower evapotranspiration, thereby increasing moisture levels and reducing irrigation needs (Dinesh and Pearce 2016). Agrivoltaics can also shelter perennial crops like orchards and fruit trees from extreme weather events (Trommsdorff et al. 2023). Additionally, idle land beneath solar modules can favour endemic plant communities and habitats for pollinators (Macknick et al. 2022; Gomez-Casanovas et al. 2023). The uneven distribution of light and rain by solar arrays can increase environmental heterogeneity, thus promoting plant diversity (Weselek et al. 2021; Sturchio and Knapp 2023).

Compared to GM-PV, agrivoltaics subtract less land for alternative uses, such as food production. This aspect is particularly advantageous for energy developers seeking access to farmland. When integrated with regenerative practices like rotational grazing, organic permaculture or beehives, agrivoltaic systems can also enhance soil carbon sequestration (Macknick et al. 2022). For landowners, agrivoltaics represent a remunerative option, as the profit margins of solar electricity production (provided subsidised prices or long-term contracts, as currently seen in several high-income countries) are substantially higher than those from most farming activities (Dinesh and Pearce 2016; Agostini et al. 2021; Trommsdorff et al. 2023).

Drawbacks of agrivoltaics

Although less explored than its benefits, the literature also highlights several drawbacks, primarily concerning crop yield losses, reduced energy production, and social acceptability.[7]

Crop yield losses are a direct consequence of the shading effect, often estimated by the ground cover ratio (GCR). While crops like fruit trees and leafy vegetables may benefit from partial shading, agrivoltaics often result in a yield loss proportional to the GCR (Weselek et al. 2021; Wagner et al. 2023; Dupraz 2023). Conversely, a higher GCR increases electricity production per hectare, potentially leading to higher profits.

Although estimating exact figures across countries is challenging due to the absence of a standardised definition, agrivoltaic systems typically exhibit power densities in the range of 0.2–0.9 MW/ha, with most projects falling somewhere in between, at 0.55 MW/ha (Schindele et al. 2020; Agostini et al. 2021; Feuerbacher et al. 2022; Chatzipanagi et al. 2023, p. 7; Trommsdorff et al. 2024, p. 50). Compared to fixed-tilt GM-PV systems, which are on average 0.87 MW/ha (Bolinger and Bolinger 2022), agrivoltaics generally report 1.6 times less installed solar capacity. As a result, agrivoltaics are less profitable and more expensive to install (as further explored in Sect. "Market Dynamics"), although the exact values depend on factors such as location, installation size, agronomic optimisation (e.g. tilting or moving panels), and the mounting structure height. Overall, commercial profit margins from electricity generation are thinner for agrivoltaics than for GM-PV (Feuerbacher et al. 2022).

However, if land availability ceases to be a limiting factor, the whole discussion on thinner profit margins per hectare becomes less significant. Proponents argue that agrivoltaics' revolutionary potential lies precisely in their ability to be deployed in areas where GM-PV installations would not be permitted (Warmann et al. 2024). This brings us to the third major issue with agrivoltaics: social acceptability. Farmers have shown reluctance to embrace agrivoltaics due to concerns over increased site complexity (Pascaris et al. 2023), funding availability (Trommsdorff et al. 2024), higher operational costs (Macknick et al. 2022), and the risks associated with reducing crop yields while constraining future farming activities (Gomez-Casanovas et al. 2023). Landowners may exhibit a more favourable attitude towards agrivoltaics, primarily due to higher rents compared to those generated by agricultural production. Nevertheless, the price effects on agricultural land could potentially harm farming revenues (Chatzipanagi et al. 2023, p. 15), as discussed in Sect. "Land Use and Rent".

State policy

The EU has outlined ambitious targets for solar energy in its Solar Energy Strategy, part of the REPowerEU initiative launched in May 2022 (European Commission 2022). The strategy aims to install over 400 GW[8] of solar photovoltaics by 2025 (from 163 in 2021 GW, and 255 GW in 2023), and almost 750 GW by 2030. If achieved, solar energy could contribute up to 4–6% of the EU's gross available energy (Vezzoni 2023). Currently, however, the continent is not on track to meet these targets, not even by replicating the record new solar installations of 2023 (56 GW, a 40% increase from the second-highest yearly installed capacity in 2022).

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[7] Concerning the environmental impact assessment of agrivoltaics, it should also be noted that the resource requirements (minerals and metals) of the mounting infrastructure could be orders of magnitude higher than those of conventional sources of electricity (e.g. for a comparative case on the Italian electricity mix, see Agostini et al. 2021).

[8] Unless otherwise specified, installed capacity is expressed as DC. In the case of the REPowerEU target, a conversion factor of 1.25 from AC to DC values has been applied.

Since 2020, utility-scale solar has lost market shares over rooftop installations (further bolstered by the European Solar Rooftop Initiative in the REPowerEU), due to increasing financing and installation costs, market risk, and permitting issues (SolarPower Europe 2023a). In response, the Solar Energy Strategy introduced a policy initiative identifying 'renewable go-to areas in which permitting will be simpler and faster than elsewhere' (European Commission 2022, p. 6, emphasis in original). The Strategy reiterates the importance of member states considering 'incentives for the development of agri-PV while designing their National Strategic Plans for the Common Agricultural Policy', including 'through the integration of agri-PV in renewable energy tenders' (European Commission 2022, p. 7). Concurrently, the Farm-to-Fork initiative of 2020 suggests placing solar panels on farm buildings, and that 'such investments should be prioritised in the future CAP Strategic Plans' (European Commission 2020, p. 6).

Agrivoltaics, however, need a legal definition accompanied by European regulatory frameworks and industrial standards (Macknick et al. 2022; Chatzipanagi et al. 2023; Dupraz 2023; Trommsdorff et al. 2024). Germany took the lead in May 2021 by adopting legislation for agrivoltaics standards (SPEC 91434 developed by the German Institute for Standardization), defined as the combined use of land for both agricultural and photovoltaic electricity production, giving precedence to farming activities (Trommsdorff et al. 2024). This sets a maximum crop loss at 66% of the reference yield without photovoltaic installation (Chatzipanagi et al. 2023) and introduces a tier system differentiating between elevated solar panels and inter-row systems. In Italy, the Ministry of the Environment published guidelines for agrivoltaic installations in June 2022, setting parameters such as a maximum land area occupation ratio (LAOR)[9] of 40%, the continuation of agricultural activity, a minimum of 60% energy production compared to a conventional photovoltaic system, and a tiered categorisation of supporting structures. Compliance with these terms is essential to access funds from the Recovery and Resilience Plan, which allegedly earmarks over €1 billion for agrivoltaics (Chatzipanagi et al. 2023, p. 15). France has taken a different approach with Decree No. 2024-318 of April 2024, allowing up to 40% land cover by photovoltaic systems, but introducing a strict tolerance of no more than 10% crop yield loss. However, as noted by Dupraz (2023), this target is unlikely to be reached for most crops with GCR exceeding 20%. To the date of writing, other EU countries, including Spain (the second European country per solar installed capacity), have yet to advance agrivoltaic standards.

Concerning the Common Agricultural Policy (CAP), only four countries—Germany, Italy, the Netherlands, and Slovenia—have referred to agrivoltaics in their CAP Strategic Plans (SolarPower Europe 2023b, p. 14), and one-third of member states are planning to support solar energy investments in agriculture (ECORYS et al. 2023, p. 543). However, none have defined specific targets for solar energy integration in agri-food systems or provided dedicated financial support (Chatzipanagi et al. 2023, p. 3). This lack of commitment was also noted by the EC assessment of the updated NECPs (European Commission 2023b, p. 3), highlighting that despite broad consensus around the need to drastically reduce the environmental impact of agriculture, emission reductions have been too slow. Among the 24 NECPs reviewed in this study, only Romania makes explicit reference to the promotion of agrivoltaic projects (mostly to substitute for diesel generators in irrigation pumping systems), and the Italian NECP briefly mentions 'agrisolar' as the installation of photovoltaic panels on farm buildings. Other NECPs generally focus on improving energy efficiency and increasing the penetration of low-carbon energy in agriculture (e.g. Germany, France, and the Netherlands).

Notwithstanding the introduction in the CAP 2023–2027 of two indicators for monitoring the pace of renewable energy in relation to climate change, the focus remains on extracting and recovering biomass for energy production (Chatzipanagi et al. 2023). During the 8th State of the Energy Union, the European Commission reiterated these concerns, suggesting to increase the focus on areas 'where the progress has been recently far too slow (i.e. agriculture), or where reductions have even moved in the wrong direction in recent years (i.e. LULUCF)' (European Commission 2023c, p. 19).[10] Interestingly, despite these concerns, no policy direction is offered concerning the kind of farming practices that should accompany the development of agrivoltaics. Given the centrality assigned to the prevalence of agriculture in most published guidelines, however, it seems plausible that agrivoltaic systems will be eligible for the CAP direct payments regardless of the type of farming (ECORYS et al. 2023). This is at odds with the Farm-to-Fork objective to expand organic farming to at least 25% of the EU's agricultural land (European Commission 2020, p. 8). The agnostic approach to farming practices also represents a missed opportunity for reducing reliance on energy-intensive synthetic agricultural inputs.

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[9] The LAOR is the ratio between the area of the PV system (including the modules, wires, poles, access roads, etc.) and the total agricultural area covered by the agrivoltaic system.

[10] The State of the Energy Union provides a yearly report of the EU energy strategy. LULUCF stands for land use, land-use change, and forestry.

Table 2 Comparison of agrivoltaics and ground-mounted solar (GM-PV), assessing land equivalent ratio (LER), capital expenditure (CAPEX), operating expenditure (OPEX), levelised cost of electricity (LCOE), and installed solar capacity per hectare (power density)

Metric	Compared to GM-PV
LER	1.35–2.30 (Gomez-Casanovas et al. 2023); 1.7 (Dupraz et al. 2011); 1.23–2.05 (Amaducci et al. 2018)
CAPEX	+ 50% (Agostini et al. 2021); + 73% (Schindele et al. 2020); + 80% (Trommsdorff et al. 2023)
OPEX	Roughly equivalent (between 1/3 to 1/5 of CAPEX) (Mamun et al. 2022; Trommsdorff et al. 2024)
LCOE	+ 38% (Schindele et al. 2020); + 50% (Trommsdorff et al. 2024); + 58% (Trommsdorff et al. 2023)
Power density (MW/ha)	0.2–0.9 (Chatzipanagi et al. 2023); 0.52 (Feuerbacher et al. 2022)

Market dynamics

Estimating costs, revenues, and overall profitability of agrivoltaic systems is challenging, due to the high dependency on contextual factors such as scale, topography, agricultural production, and photovoltaic technology, as well as the specifics of the energy market (e.g. electricity prices) (Agostini et al. 2021; Feuerbacher et al. 2022) and government support (Schindele et al. 2020; Trommsdorff et al. 2023). Despite these complexities, some generalisations can be made when comparing agrivoltaic systems to conventional alternatives. Since revenues from electricity generation are substantially higher than those from agricultural production (Dinesh and Pearce 2016; Trommsdorff et al. 2023), comparative studies have primarily focussed on assessing agrivoltaics vis-à-vis GM-PV, as summarised in Table 2. Although results vary due to site-specific features, studies of pilot cases in Europe generally agree on four key points about the economics of agrivoltaics: they display higher productivity per land area, higher capital expenditure (CAPEX), similar or slightly lower operating expenditure (OPEX), and thus generally higher levelised costs of electricity (LCOE).

The most common metric used to assess productivity per land area is the land equivalent ratio (LER)[11] (Amaducci et al. 2018). LER values exceeding 1 indicate that the agrivoltaic system is more efficient than the conventional alternative land uses, and indeed values range between 1.23 and 2.30. Regarding initial investments, CAPEX is largely driven by the higher cost of the mounting substructure, the photovoltaic modules, as well as the planning and installation phases (Trommsdorff et al. 2024). These factors can almost double the demand for starting capital. Although some efficiencies could be discounted from the initial costs (e.g. fencing is not required, and the panels could replace protective structures for orchards and crops), CAPEX can still be expected to be at least 50% higher than an equivalent GM-PV. Conversely, the operating costs of agrivoltaics do not significantly differ from those of conventional photovoltaic systems. Typically, overall OPEX represents only a fraction ranging from a fifth to a third of CAPEX. These are useful considerations to understand how the LCOE of agrivoltaics compares with alternatives. While some authors have demonstrated that energy optimisation techniques (e.g. tracking systems) can produce sufficient additional electricity to offset the extra CAPEX, studies report LCOEs that are 38%−58% higher than conventional GM-PV systems. Nevertheless, most authors concur that economies of scale could enhance the overall cost-effectiveness of agrivoltaics (for an overview, Feuerbacher et al. 2022).

A final point to consider, often less explicitly addressed (except in a few studies, cf Trommsdorff et al. 2023), is the role of feed-in tariffs and renewable power purchase agreements (PPAs) in de-risking the investment environment. Without these supports, agrivoltaics would require substantially higher electricity market prices. Unfortunately, market trends seem to point to the opposite direction (Christophers 2024). Compared to fossil fuels, the marginal cost of generating electricity with wind and solar is close to zero. Since the costs associated with low-carbon electricity production are largely captured by CAPEX, there is a strong incentive to maximise production at all times. Intuitively, the higher the share of solar and wind power in the electricity mix, the higher is the risk of oversupplying the grid, and thus the lower is the average spot price on the market. This reduces producers' profitability, a phenomenon known as the cannibalisation effect of solar and wind energy, already observed both in Europe (Chan Yao Chong and Brunetti 2023) and the USA (López Prol et al. 2020). Prices tend to drop during the central hours of the day, when solar energy generation is at its peak. Already in 2023 and 2024, all European electricity markets have repeatedly experienced zero and negative electricity prices (AleaSoft Energy Forecasting 2024). In sum, market prices captured by solar energy are inversely related to their increasing market penetration, a trend that, without government intervention, is likely to become more prominent in the second half of the 2020s.

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[11] The land equivalent ratio combines energy and agricultural production in agrivoltaics, after dividing each one for the conventional yield of GM-PV and farming alone for the same land area.

Land use and rent

Agrivoltaic systems offer a significant advantage not only in terms of comparative profitability against agriculture, but also in providing a dual-purpose solution for energy developers (Barron-Gafford et al. 2019). Unlike utility-scale GM-PV, land-use change is not a barrier for agrivoltaic systems. While the installation of artificial infrastructure will inevitably alter microclimatic conditions, it could also generate a variety of ecosystem services (Sturchio and Knapp 2023), while improving crop resilience and reducing water consumption (Warmann et al. 2024), provided that adequate farming techniques are implemented (Time et al. 2024). In the EU, this should also be reconciled with member states' targets for land under organic agriculture (e.g. the 25% objective in the Farm to Fork) or for integrating conservation areas into farmland (such as Germany's NECP). The ideal conditions for maximising the environmental benefits of agrivoltaics are mostly found in regions exposed to advancing desertification, such as Mediterranean countries.

While agrivoltaic systems require larger areas for installing the same solar capacity (up to 1.6 times the land footprint of GM-PV), the main economic factor possibly deterring further expansion of agrivoltaics is the effect of power density on the LCOE. This also includes the extra support structures and wiring for agrivoltaics. Additional materials, for example, can take about 1 tonne of additional steel per hectare compared to GM-PV systems (Agostini et al. 2021; Wagner et al. 2023). Since these raw materials are usually extracted outside of Europe, the environmental and social costs of mining and manufacturing for European consumption should be considered when assessing the contribution of agrivoltaics to the dual energy and agricultural transitions.

Although land-use change does not appear to hinder the development of agrivoltaics, it nevertheless raises concerns about the cost of renting farmland. Landowners find low-carbon energy infrastructure particularly attractive, as the rent generated by solar leasing alone is often higher than the net income generated by crop yields (Gomez-Casanovas et al. 2023). In Europe, the difference is stark. The average yearly agricultural rent across European countries was 199 €/ha in 2022 (ranging from 32 to 354 €/ha for permanent grassland, and 77 to 510 €/ha for arable land) (Eurostat 2024). In comparison, yearly lease agreements for solar projects range from 1000 up to 10,000 €/ha, with average values in countries like Germany settling between 3000 and 3500 €/ha. For many landowners, this represents a tenfold increase in capital income from renting out their property. If scaled to occupy 5–10% of European farmland as some proponents would argue (Feuerbacher et al. 2022; Chatzipanagi et al. 2023), agrivoltaics could profoundly impact land ownership, effectively exerting upward pressure on farmland prices. For some European regions—such as Central and Northern France, Bulgaria, and Slovakia—over 90% of the utilised agricultural area is rented (FADN 2023). While providing a benefit for landlords, the increased cost of leasing farmland would be transferred onto the balance sheets of productive leaseholders—a textbook case of cost-shifting for the green transition.

Increasing the market value of agricultural land also entails distributive issues, as farmland consolidation has worsened over the past decades. In 2023, 1% of farms controlled 70% of farmland globally (IPES-Food 2024). For European agriculture, the percentage is slightly more even (3% of farms controlling 52% of farmland), although the trend is markedly towards concentrated ownership, with estates over 100 ha (representing only 3% of farms) increasing by 18% in size between 2005 and 2016 (Eurostat 2018; European Court of Auditors 2022). Agricultural land has increasingly become a financial asset (Fairbairn 2014, 2020; Clapp 2023). Particularly in the aftermath of the global financial crisis of 2009, investors' appetite for safe havens turned to farmland, treated as an asset class 'like gold with yield' (*passim*, Fairbairn 2014, 2020). Farmland generates rental income (or agricultural yields if managed directly) while securing a hedge against inflation largely detached from stock market volatility.

However, also the financialisation of farmland is exerting upward pressure on farming costs, particularly for leaseholders and small producers. Land price inflation over the past decade has increased farmland value worldwide (up to over four times in certain agricultural hotspots, like the Brazilian state of Maranhão or the US state of Iowa) (IPES-Food 2024). In Europe, these trends have been favoured by the CAP, providing subsidies as direct payments on a per-hectare basis, thus incentivising larger estates (van der Ploeg et al. 2015; De Schutter et al. 2020). This is illustrated by 75% of farmers, mostly small and subsistence farms, receiving 15% of total direct payments in 2020 (and almost half of all farmers received less than € 1250) (European Commission 2021). The deployment of agrivoltaics could feed into this speculative process of land price appreciation which, drawing from Madeleine Fairbairn's extensive work on the financialisation of farmland, 'may itself be the cause of social and ecological harm' (Fairbairn 2020, p. 54). The transformation of agricultural land into pure financial assets, entailing the dissociation of the productive activities from the marketed value of farmland, hides a mechanism of costs socialisation which Kapp's theory of social costs helps to tease out.

The political economy of agrivoltaics in the EU

The development of agrivoltaics responds to a hierarchy of pressures. First and foremost, solar developers need access to installation sites, which are often farmland. Secondly, agrivoltaics offer the potential to improve farmers' income. In Europe, despite improvements over the past decade, agricultural income remains roughly 40% lower than the average. Lastly, the pursuit of 'win–win' solutions represents an additional driver for agrivoltaics (Hu 2023; Trommsdorff et al. 2024). Whilst ecological modernisation remains the dominant approach to climate policy (Stoddard et al. 2021)—as evidenced in the European policy initiatives reviewed in this article—innovations promising to deliver 'more with less' are prioritised, for they leave dominant modes of social organisation untouched.

In this sense, agrivoltaics exemplifies the growing allure of climate-smart agriculture (Clapp et al. 2018; Karlsson et al. 2018; Newell and Taylor 2018). As the story goes, climate-smart solutions alone can produce clean energy, increase farmers' income, and even improve agri-food systems' resilience to changing climatic conditions. This implies that farming conglomerates can carry on with their business-as-usual practices, farmland ownership concentration can remain uncontested, mass-market consumers can continue mindlessly buying food commodities, whereas politicians may have a reassuring message to sell to their electorate. However, is framing agrivoltaics as a win–win solution a rightful description of the technology?

Despite evidence that multipurpose land use can deliver higher productivity per area and improve crop resilience while generating low-carbon electricity, the benefits of agrivoltaics remain highly context specific (Moore et al. 2022; Trommsdorff et al. 2024; Warmann et al. 2024). Moreover, the site's characteristics should be measured against alternative options and possibly conflicting policy objectives. The logic of cost-shifting suggests paying greater regard to the trade-offs behind win–win solutions. To date, for instance, few studies have assessed the benefits of agrivoltaics compared to different agricultural practices such as agroforestry, rotational grazing, permaculture, agroecology, or a combination of these (cf, Adolfo et al. 2023; Time et al. 2024). The evidence so far points to inconsistent results of cost–benefit analyses, which vary widely and remain highly uncertain (Gomez-Casanovas et al. 2023, p. 14). Thus, there is no conclusive answer to the question of which type of agriculture stands to benefit from agrivoltaic developments in Europe.

On one hand, experimental cases have shown the cost-effectiveness of agrivoltaics improves when farming relies on hand tools and small machinery (Trommsdorff et al. 2024, p. 38). The supportive structures complicate the operation of large machinery underneath and between them (Agostini et al. 2021), potentially affecting energy optimisation (Macknick et al. 2022) and increasing insurance premiums due to higher risk.[12] These considerations have led Schindele et al. (2020, p. 14) to conclude that, for agrivoltaics, 'organic farming thus appears to be more suitable than conventional farming methods'. However, on the other hand, these issues may be short-lived, as most studies are limited to experimental settings over relatively small areas (e.g. between 1 and 5 ha). With big corporations developing more sizeable agrivoltaic projects, the economies of scale associated with industrial farming on large estates (e.g. above 50 ha) can exceed the above-mentioned costs related to mechanisation and insurance risks.

In all these cases, it is hard to generalise a priory whether agrivoltaics will prove beneficial to both the energy and agricultural transitions. Instead, the crucial issue concerns the purpose for which agrivoltaics are developed. If intended to facilitate the large-scale deployment of low-carbon energy to mitigate climate change, agrivoltaics must not compromise on their overall environmental impact. This begets consideration for the type of farming that is practised beneath and in between the solar arrays, as agriculture significantly contributes to anthropogenic climate change and other environmental harms. Conversely, without consideration for the social and environmental milieus, the rent derived from installing agrivoltaics is likely to be used to uphold the same market relations, industrial practices, and social institutions that created the need for developing 'win–win' or 'climate-smart' technologies like agrivoltaics in the first place.

Moreover, the high CAPEX (i.e. orders of magnitude higher than that of agricultural activities) means that access to funding can seriously constrain the ownership structure of agrivoltaic systems. Without adequate public support for farmers and small landowners, agrivoltaics at scale are more likely to be financed by equity from energy developers and large landlords with deep pockets. Agricultural estates engaged in industrial farming may dedicate only a portion of their land to agrivoltaics, potentially increasing profits without altering their core business model. In the absence of a more decisive regulatory framework, this can exacerbate the social and environmental harms identified by CAP critics, such as land ownership intensification (van der Ploeg et al. 2015) and poor environmental and health outcomes (Benton and Bailey 2019; Pe'er et al. 2020; De Schutter et al. 2020; Candel et al. 2023). Moving forward, multinational integrated energy companies are likely to play a more prominent role, with the likes of TotalEnergies, Enel (with its subsidiary Enel Green Power), and Iberdrola already embracing agrivoltaics. While the business case for landowners is clear, it remains uncertain how benefits will be distributed among energy developers, farmers, and local communities as energy majors seize bigger shares of the agrivoltaics market. What is certain, however, is that currently no

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[12] For instance, combined harvesters for open-field agriculture can be 15 m wide and run on 600–800 Hp engines that could cause serious damage to the agrivoltaic system.

technical standard or governmental scheme guarantees that agrivoltaics will undermine the dominance of the 'cheaper food paradigm'. As illustrated in "The dual energy and agricultural transitions" and "Land Use and Rent", the social–environmental harms caused by both industrial agriculture and farmland concentration (increasingly treated as a financial asset) are effectively shifting costs onto third parties. In the case of farmland financialisation, these costs are borne by farmers leasing land as well as by those that will be prevented from accessing farmland in the first place. In the case of industrial agriculture, the health and environmental damages of an agricultural model predicated on the 'cheapest food paradigm' relapse on the whole of society. Moreover, in the European Union, this often involves exporting the environmental impact of material extraction elsewhere (including for the extraction and manufacturing of materials for the energy transition).

Alternatively, I argue that the cash flows generated by agrivoltaic systems (whether due to higher lease contracts or electricity generation) could be repurposed for converting farmland to agroecological farming practices. In the current European macroeconomic policy framework, this could take the form of a public fund managed by a specialised development bank (for instance, on the model of the German Landwirtschaftliche Rentenbank), or an investment vehicle run as a special funding mechanism of the European Investment Bank (like the InvestEU during the COVID-19 pandemic) to (1) finance the deployment of agrivoltaics, and (2) mutualise the revenues of solar energy generation to provide a financial buffer for agricultural holdings transitioning away from industrial farming. While higher penetration and hence decreasing capture prices may hinder the profitability of low-carbon electricity generation (Chan Yao Chong and Brunetti 2023; Christophers 2024), photovoltaic projects can nevertheless assure rather stable, even if meagre, net cash flows for about 25 years. This could be the collateral against which a public bank or funding instrument could raise funds to finance the deployment of agrivoltaics for those small landowners who would otherwise lack access to capital markets.

The mandate of such a public instrument must consider not only the environmental implications of agrivoltaics (transitioning towards agroecology, producing low-carbon energy, protecting against desertification) but also its incidental social harms, such as speculative pressure on land prices and the exacerbation of farmland concentration. In Europe, this calls for coherence across policy domains, aligning objectives of the CAP and the National Energy and Climate Plans so that environmental policies are not simply 'fixing problems created amongst other reasons by agricultural support policies' (OECD 2003, p. 12 in De Schutter et al. 2020).

Conclusions

The profit motive alone is insufficient to ensure that agrivoltaics will not perpetuate the environmental and social harms seen in industrial agriculture, which remains a significant contributor to climate change, biodiversity loss, deforestation, soil erosion, desertification, and disruption of nutrient cycles. If agrivoltaics are deployed to address climate change and mitigate global environmental damage, the type of agriculture funded by the rental income from agrivoltaics should not be a secondary concern. Instead, this rent could be directed towards subsidising agroecological practices or, ideally, providing a financial buffer for farmers transitioning away from industrial farming.

If, on the contrary, agrivoltaics are allowed to operate under market principles, they will likely follow the path of least resistance and highest profitability. This could result in reinforcing entrenched practices among industrial farmers and landowners who prioritise revenue maximisation, potentially leading to undesirable lock-ins and path dependency. Agrivoltaic systems are not simply a win–win technological fix; they rather require a contextual assessment of the existing ecological, political, and economic trade-offs associated with their deployment (Moore et al. 2022). Ignoring non-market costs concerning land transformation, material extraction, semi-permanent infrastructure, and farmland ownership could shift the costs of the green transition—such as inflated farmland prices and perpetuation of industrial farming—onto communities and regions ill-equipped to cope with them.

As a possible solution, this article suggested that a public funding vehicle could subordinate the development of solar energy on farmland to the adoption of agroecological practices. A guiding framework for this type of agrivoltaic system could be derived from notions like 'ecovoltaics' (Sturchio and Knapp 2023) or 'conservation-agrivoltaics' (Time et al. 2024), using solar modules to induce 'environmental heterogeneity [that] may be able to assist in the restoration of many degraded land-cover types in need of remediation' (Sturchio and Knapp 2023, p. 1748). The land types that should be prioritised for the development of ecovoltaics include water-limited agroecosystems in arid regions, intensive grazing pastures, severely degraded or abandoned agricultural land, and brownfield sites like decommissioned mining areas. Overall, fully exploiting the existing potential of rooftop photovoltaics (e.g. on commercial structures, residential buildings, and parking lots) should take priority over developing agrivoltaics on farmland. In turn, agrivoltaics represent a qualitative improvement compared to the social and environmental impacts of GM-PV. They should thus be considered the least bad alternative once the potential for solar development in built environments has been thoroughly exhausted. The development of an adequate expansion strategy vis-á-vis alternatives, the harmonisation of policy domains and national standards, and the assessment of the socio-environmental benefits of deploying agrivoltaics at scale are tasks for future research endeavours.

Overall, this article contributes to further refining Kapp's theoretical approach to social costs by applying it to a concrete case study. While the theory of social costs has led to a thriving scholarly debate on the shortcomings of the notion of 'externalities',[13] these have often remained at an abstract level—that is, theoretical and foundational. Here, my intervention declines the cost-shifting mechanism into an unavoidable moment of the green transition. No matter how urgent or well intentioned, economic development is not immune to it. At the intersection of agriculture and solar developments, cost-shifting plays out by polluting farmland, displacing farmers, exporting environmental extraction to faraway regions, and reducing the diversity of rural landscapes. Yet, as shown in the case of the nexus of energy and agricultural policy, the dominant paradigm in the EU remains committed to the possibility that 'win–win solutions' will somehow bypass contentious issues over land ownership and farming practices.

Admittedly, this article has focused largely on the European Union, and the findings should be calibrated against the idiosyncrasies of its regulatory framework. While some results can be generalised across jurisdictions, one should refrain from drawing nomothetic arguments about the political economy of agrivoltaics, instead giving primacy to the specificity of each context. Whether agrivoltaics will result in widespread social and environmental benefits or rather entrench existing forms of exploitation of humans and the rest of nature remains, at the end of the day, an empirical question—one which warrants further scrutiny.

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[13] See for example the works of Sebastian Berger (Berger 2017), the anthology he curated on Kapp's scholarship (Kapp 2016), but also the central role that Kapp's conceptualisation and methodological approach play in the social ecological economics of Clive Spash (Spash 2024).

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