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POLICY DIRECTION

The Global Energy Transition: Ecological Impact, Mitigation and Restoration

Integrated policymaking is needed to deliver climate and ecological benefits from solar farms

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Abstract

1. Multi-purpose land use is of great importance for sustainable development, particularly in the context of increasing pressures on land to provide ecosystem services (e.g. food, energy) and support biodiversity.
2. The recent global increase in land-take for utility-scale ground-mounted solar farms (hereafter referred to as solar farms) to meet Net Zero targets presents an opportunity for enhanced delivery of ecosystem services, especially in temperate ecosystems where solar farm development often results in land use change away from comparatively intensive agricultural land management. Solar farms have long operational lifespans, experience low levels of disturbance during operation and can be managed for ecosystem services beyond low-carbon electricity generation, including food production and biodiversity conservation.
3. Here, we briefly synthesise the mechanisms by which solar farm development and operation may impact natural capital and ecosystem services, and provide policy recommendations for policymakers and the solar farm sector.
4. Solar farms can deliver environmental benefits for hosting ecosystems while minimising negative impacts, with outcomes depending on location, construction techniques, and land management practices. However, the historical misalignment between climate, nature, and land use policies has hindered efforts to simultaneously address the climate and biodiversity crises through land use change for solar farms. For instance, existing public financial incentives in the UK that encourage landowners and developers to manage land for biodiversity largely exclude land with solar farms.
5. *Policy implications*: We call for public policymakers to identify appropriate opportunities to amend existing national laws that address climate and biodiversity separately to improve integration of multiple aspects of the climate-nature-land

use nexus into policymaking by: (1) formulating ecological and socio-economic indicators and metrics that are appropriate to underpin the development, implementation, and assessment of public policies; (2) adopting a cross-sectoral and cross-government approach to form public policies; (3) ensuring solar farms can access public financial incentives that encourage sustainable land use; (4) implementing land use policies that incentivise funding from non-government sources (e.g. private sector) into nascent nature markets; (5) embedding solar farms in biodiversity-inclusive spatial planning policies and decision-making; and (6) building equity and clarity into responsibilities and benefits for all actors involved.

KEYWORDS
biodiversity, ecosystem services, land use change, land use policy, natural capital, photovoltaic panels, planning, renewable energy

1 | INTRODUCTION

As the need to meet Net Zero greenhouse gas (GHG) emissions targets intensifies, the deployment of renewable energy technologies is accelerating around the world (IEA, 2023b). In particular, solar photovoltaics (PV) are projected to dominate global power supplies by 2050 (Nijsse et al., 2023). Globally, PV contributed twice as much new electricity generation capacity in 2023 as coal (Ember, 2024) and reduced annual CO_2 emissions by approximately 1.1 billion tonnes between 2019 and 2023 (IEA, 2024). PV's electricity generation grew, on average, by 26.4% annually between 2016 and 2022 worldwide (Ember, 2024), which was in line with the International Energy Agency's (IEA) Net Zero Emissions by 2050 pathway (IEA, 2023a). If the IEA's target is to be met, PV's share of global electricity generation needs to grow from 5.5% in 2023 to 43% in 2050 (Ember, 2024).

Solar farms accounted for approximately 52% of the projected PV deployment globally in 2023 (IEA, 2023c) and are expected to substantially increase the use of land devoted to electricity generation in the next three decades (Capellán-Pérez et al., 2017; van de Ven et al., 2021; Wachs & Engel, 2021). Since land use change is the dominant driver of biodiversity and ecosystem change (IPBES, 2019), this low-carbon energy transition risks exacerbating the biodiversity crisis to mitigate the climate crisis. However, there is considerable opportunity to design and manage solar farms to benefit nature (Figure 1; Hernandez et al., 2019; Randle-Boggis et al., 2020) given their long operational lifespans (25–40 years in most cases) and low levels of disturbance during operation. Indeed, concepts surrounding 'ecovoltaics' (Tölgyesi et al., 2023) and 'conservoltaics' (Nordberg & Schwarzkopf, 2023) have recently been advanced as land-sharing approaches to reconcile solar farm development with ecosystem restoration and wildlife conservation. Consequently, solar farms have the potential to help national governments achieve multiple objectives established by the Convention on Biological Diversity's (CBD) *Kunming-Montreal Global Biodiversity Framework* (GBF; CBD, 2022) and the UN's Sustainable Development Goals (United Nations, 2015) to halt and reverse biodiversity loss through land use change, biodiversity spatial planning, and the restoration of degraded ecosystems, especially if solar farms are built on brownfield and industrial soils and on low-to-medium grade agricultural land. For instance, around 72,900 ha of land in the UK (approximately 0.3% of total UK land area) may be occupied by solar farms in 2035 (Blaydes, unpublished digitised solar farm data) if current government targets are met (HM Government, 2023) and the proportion of total solar energy generated by solar farms remains at around 55% as of 2024 (DESNZ, 2024a, 2024b). This may offer considerable scope to create new habitats for biodiversity if land is converted within intensively managed landscapes.

Despite the potential for solar farms to deliver dual outcomes for climate and nature, the historical misalignment between global policy frameworks dedicated to addressing the climate (UN Framework Convention on Climate Change—UNFCCC) and biodiversity (CBD) crises have hindered efforts at the national level to develop integrated public policies and funding mechanisms that link Net Zero targets with nature recovery (Pettorelli et al., 2021). For instance, climate-driven policies in the UK (e.g. HM Government, 2023), mostly underpinned by the 2015 Paris Agreement (UNFCCC, 2015), have incentivised large-scale deployment of solar farms in recent years. However, even the latest biodiversity-focused policies enacted in the UK to meet the CBD's GBF targets (e.g. BEIS, DESNZ, Defra, & HM Treasury, 2023; Defra, 2023) have failed to make solar farms eligible for public financial incentives that would encourage biodiversity enhancements alongside low-carbon electricity generation. These shortcomings have recently been recognised in policy documents (Wentworth & Dance, 2020) and by the solar energy industry (SEUK, 2024) in the UK. In addition, despite recent advances in promoting 'Nature-based Solutions' as a synergistic approach to address climate and biodiversity challenges simultaneously (Seddon et al., 2021), barriers to their implementation, including those related to monitoring, finance, and policy, have hampered success in delivering positive biodiversity outcomes while addressing major global challenges like climate change (Seddon et al., 2020). Therefore, public policymakers worldwide must urgently develop national-level

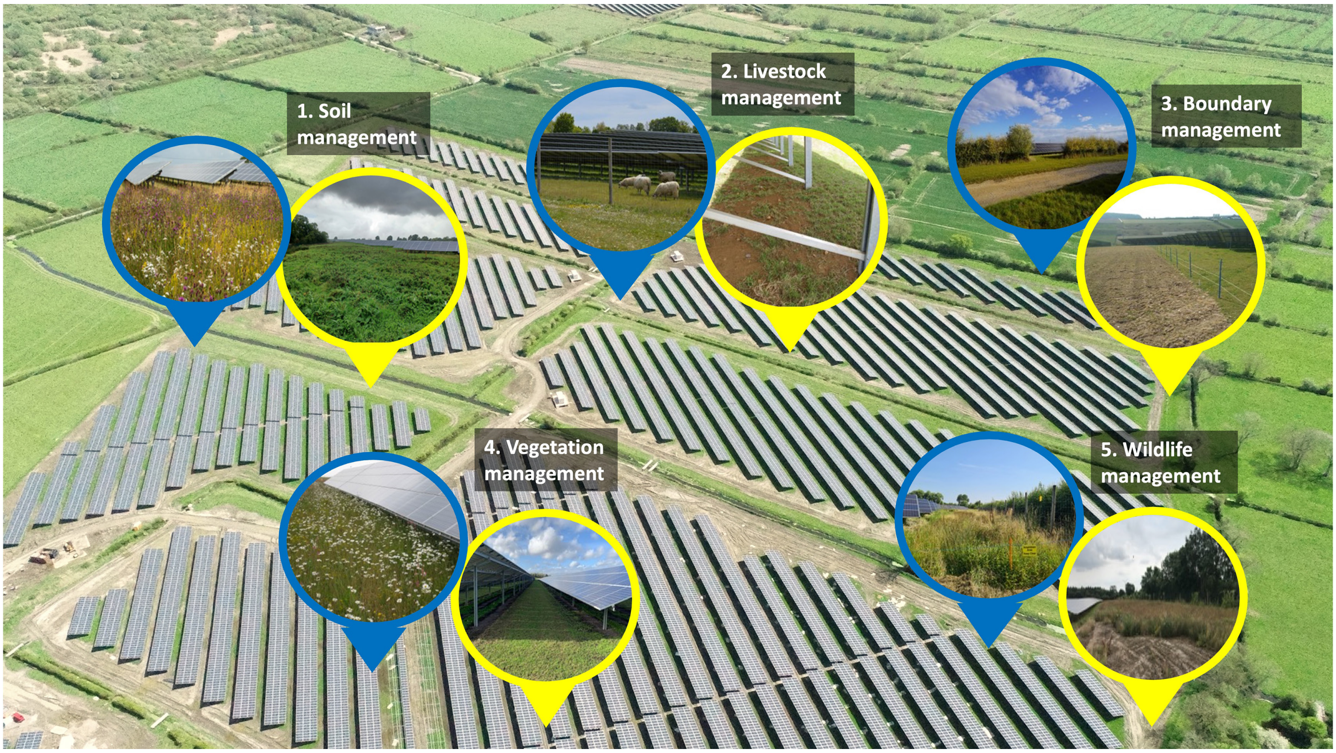

FIGURE 1 Examples of potential positive (blue circles) and negative (yellow circles) effects of solar farms on hosting ecosystems as a result of land management actions: 1—soil management and conservation (particularly during construction) to improve soil health can help provide diverse habitats for wildlife during operation and keep invasive species from outcompeting natives to form monocultures; 2—low intensity grazing can create structured habitats to benefit wildlife but intensive grazing can lead to areas of bare ground, especially under solar panels; 3—hedgerows around solar farms can provide habitats whilst fences offer no biodiversity value and can block wildlife movement; 4—moderate levels of mowing can help maintain wildflower meadows but intensive mowing and herbicide spraying can negatively impact grassland biodiversity; 5—solar farms with areas set aside for wildlife will be more likely to deliver positive outcomes for climate and nature than those without.

policies and financial incentives that not only integrate international policy documents and targets issued by the UNFCCC and CBD but can also support the solar farm sector to embed biodiversity-enhancing practices in their operations.

Here, we briefly outline the implications of solar farm development and management for natural capital stocks and ecosystem services provision (Section 2) and provide policy context and recommendations for public policymakers and the wider solar farm sector (Section 3 and Text S1).

2 | NATURAL CAPITAL AND ECOSYSTEM SERVICES ON SOLAR FARMS

Solar farms can have positive or negative effects on natural capital stocks (e.g. soil) and the delivery of ecosystem services (e.g. soil carbon storage) depending on location, site and climatic characteristics, and land management practices (Hernandez et al., 2014). These effects can be direct (e.g. solar panel shading of vegetation to affect species composition; Vaverková et al., 2022) or indirect (e.g. changes in plant species composition affecting other trophic levels; Lambert et al., 2023) and be measured both within the boundaries of the solar farm or the surrounding landscape (Blaydes et al., 2024; Guoqing et al., 2021).

Changes to microclimate caused by ground-mounted solar panels are likely to have significant and variable implications for ecosystem processes in different climates (Armstrong et al., 2016; Lambert et al., 2021; Vervloesem et al., 2022). For instance, increased seasonal and diurnal variation in air and soil microclimate caused by solar panels in temperate regions can lead to reduced photosynthetic rates and net ecosystem exchange, resulting in lower plant biomass and diversity under solar panels compared to control areas (Armstrong et al., 2016). In contrast, in regions where solar radiation is high (e.g. arid regions), shading by solar panels can lead to positive outcomes by reducing plant drought stress and enhancing food production (Barron-Gafford et al., 2019).

Land management practices within solar farms can also have positive or negative impacts on hosting ecosystems (Figure 1). Generally, management actions that have positive outcomes are those that promote plant species diversity (e.g. creation of wildflower meadows) and benefit fauna through habitat provision (Figure 1; Blaydes et al., 2021, 2024; Montag et al., 2016). For instance, increases in bumblebee density are expected to occur in solar farms that are managed as resource-rich meadows compared to turf grass (Blaydes et al., 2022), with potential positive implications for the surrounding landscape, crop pollination services, and species that feed on invertebrates. In contrast, sites with no active land management to promote the creation of habitats through, for instance, conservation cutting and grazing, may deliver fewer or no ecological benefits with adverse consequences for wider biodiversity (Lambert et al., 2022; Vaverková et al., 2022). In addition, potential ecological benefits delivered by solar farms may be limited if they are located in landscapes with high cover of semi-natural habitats that offer more favourable conditions for biodiversity than solar farms (Barré et al., 2024; Blaydes et al., 2024; Tinsley et al., 2023).

3 | POLICY RECOMMENDATIONS

Given the potential environmental benefits offered by solar farms, the development of appropriate public policies that integrate climate, nature, and strategic land use with the socio-economic and financial implications of solar farm development and operation (Figure 2) could result in land use change for solar farms that addresses the climate and ecological emergencies simultaneously. Public policymakers must urgently adopt a cross-sectoral approach to policymaking that would enable governments to deliver on national and international Net Zero targets and commitments while supporting and enhancing ecological outcomes and balancing multiple land use needs. Yet, despite the links between climate and nature (IPBES, 2019), public policies aimed at mitigating the climate and ecological crises have been historically siloed (Hogl et al., 2016; Nilsson & Persson, 2017; Urwin & Jordan, 2008; Wamsler et al., 2020), with solar farms largely omitted from nature-related policies. For instance, policies aimed at increasing biodiversity on agricultural land (Text S1) have had limited influence on solar farm development in the UK to date, and the links between Net Zero and nature recovery have only recently been acknowledged in policy documents (though land parcels containing solar panels remain ineligible for most public financial incentives; see Text S1 for a historical perspective on the UK policy context). However, the COP28 Joint Statement issued in December 2023 recognised the importance of addressing climate change, biodiversity loss, and land degradation together in a coherent, synergetic, and holistic manner, which may prompt development and implementation of integrated national policies. Such policies would not only address the historical misalignment between climate, nature, and land use policies and strategies (Di Gregorio et al., 2017; Finch et al., 2023; Owen et al., 2023) but also allow new and existing solar farms to fully realise the opportunities they present. Integrated policymaking will likely require a systems approach to fully consider the ecological, social, financial, and institutional implications of targeting several interconnected objectives (Figure 2; Martin & Lawson, 2022).

We call for public policymakers to identify opportunities to amend existing national laws that address climate and biodiversity separately and consider the six policy recommendations we offer below to (a) integrate climate, nature, and land use policies, and (b) embed the socio-economic and financial implications of the low-carbon energy transition into policymaking (see Figure 2 for an illustrative summary), particularly in the context of solar farm development and operation:

1. Formulate a suite of ecological and socio-economic indicators and metrics (Carvalho et al., 2023; Randle-Boggis et al., 2020; Tsoutsos et al., 2005) that underpin the development and assessment of public policies (European Union, 2022; TNFD, 2023). These indicators and metrics must be suitable for meeting a variety of policy needs (Cornforth, 1999), including site management policies (e.g. plant diversity indicators to inform site management practices) and policies linked to nature credit markers (e.g. Defra, 2023) that enable financial investment in nature through the sale of ecosystem services or natural capital stocks (e.g. soil carbon stocks).
2. Adopt a cross-sectoral (e.g. to include nature conservation and the solar farm and agricultural sectors) and cross-government departmental (e.g. to include those responsible for energy, land use, and the environment) approach to form public policies (Wagner et al., 2021; Wiedemann & Ingold, 2022) that are aimed at realising Net Zero and reversing biodiversity loss, particularly within the context of the low-carbon energy transition (Behnke & Hegele, 2024). This would deliver to the interconnected goals of the 2022 GBF and the 2015 Paris Agreement.
3. Widen access to public financial incentives that are currently directed at the agricultural sector (e.g. the Environmental Land Management scheme that provides public financial incentives to farmers, foresters, and land managers in the UK for improving the environment) to solar farm developers and operators to help them deliver multiple sustainability objectives (e.g. United Nations, 2015).
4. Implement land use policies that incentivise non-government funding (e.g. from the private sector) into nascent nature markets and integrate financial data with systematic conservation planning approaches (Bush et al., 2023; NatureFinance, 2023). In particular, land use policies that formally recognise the opportunities to deliver nature enhancements (e.g. Defra, 2023) through land management practices (e.g. Jackson et al., 2007) at solar farms could drive strategic financial investments into natural capital and ecosystem services provision. Such investments could further enable compliance markets within biodiversity-enhancing public schemes (e.g. Biodiversity Net Gain, which requires land development projects in England to deliver at least 10% increase in biodiversity compared to pre-development conditions). This should help remove barriers to entry and emphasise biodiversity considerations at the strategic land planning level to enable greater private sector participation in biodiversity financing (World Bank Group, 2020).
5. Embed solar farms in biodiversity-inclusive spatial planning policies and decision-making. This will help ensure solar farms are strategically located to deliver climate and ecological benefits while avoiding detrimental impacts (i.e. in light of other land use needs; Battersby, 2023; Nordberg et al., 2021). Given the complexities

FIGURE 2 Venn diagram illustrating the approach needed for public policymaking to integrate the climate-nature-land use nexus with socio-economic and financial considerations in the transition to low-carbon energy sources.

surrounding land use and management, this will require collaborative interdisciplinary scientific research incorporating expertise from different sectors and disciplines (e.g. ecology, landscape planning, social sciences).

6. Build equity and clarity into legal responsibilities and long-term financial (and other) benefits for landowners, land tenants, local communities, and solar asset owners and managers when transitioning from agricultural land to solar farms (Heras & Martín, 2020; NatureFinance, 2022; Scovell et al., 2024; van den Berg & Tempels, 2022). For instance, expectations around solar farms making financial payments in the form of 'community benefit' contributions to local communities are becoming increasingly common in the UK. However, inconsistencies at the national level surrounding formal institutional arrangements, as well as lack of clarity in application and valuation methods, have hindered delivery of desired outcomes (Kerr et al., 2017). Equity considerations in climate-related policies are complex and will require further research (Klinsky et al., 2017) to manage multiple trade-offs across time, generations, and social classes through the implementation of suitable policy packages (Brunckhorst et al., 2023).

4 | CONCLUSIONS

Solar farms, if appropriately deployed and well-managed, can demonstrably achieve benefits for biodiversity and ecosystem services while contributing to Net Zero. However, current energy-related policies tend to focus on GHG emissions and financial costs, while policies aimed at increasing biodiversity on agricultural land tend to exclude solar farms. To achieve dual outcomes for climate and nature and encourage multiple uses of the land, public policies must be supported by appropriate ecological and socio-economic indicators and metrics that will help develop, implement, and monitor suitable policies and financial incentives. Public policymakers must devise such policies across sectors and government departments, encourage non-government financial investment from the private sector, and provide access to all land-related public policies to solar farm developers and operators. In addition, policymakers must embed solar farms in biodiversity-inclusive spatial planning and deliver clear and equitable benefits for all actors involved, including local communities hosting solar farm projects. Under such conditions, solar farms could be well-positioned to help address the climate and biodiversity crises simultaneously.

AUTHOR CONTRIBUTIONS

Fabio Carvalho, Hing Kin Lee, Alona Armstrong, Hollie Blaydes, Lucy Treasure, and Laura J. Harrison led the writing of the manuscript. Fabio Carvalho, Hing Kin Lee, Hollie Blaydes, Lucy Treasure, Laura J. Harrison, Hannah Montag, Kristina Vucic, Jonathan Scurlock, Piran C. L. White, Stuart P. Sharp, Tom Clarkson, and Alona Armstrong conceived the ideas presented here, contributed critically to the drafts, and gave final approval for publication.

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CONFLICT OF INTEREST STATEMENT

Fabio Carvalho was co-funded by Clarkson & Woods Ltd, Hing Kin Lee and Kristina Vucic are employed by NextEnergy Capital, Hollie Blaydes was co-funded by Low Carbon Investment Management Ltd, Lucy Treasure was co-funded by Eden Renewables LLC, Hannah Montag is employed by Clarkson & Woods Ltd, Jonathan Scurlock is employed by the National Farmers' Union, and Tom Clarkson is Managing Director of Clarkson & Woods Ltd.

DATA AVAILABILITY STATEMENT

This manuscript does not use data; therefore, no data are archived.

STATEMENT ON INCLUSION

Our study brings together authors from different roles within ecology and the wider industry and policy contexts, including academics, practitioners, research students, and industry and policy insiders based in the country where the study was carried out. All authors were engaged early on with the research and study design to ensure that the diverse set of perspectives they represent was considered from the onset. Our research was discussed with stakeholders from within the UK solar energy sector to seek feedback on industry best practice and the policy implications of research results.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Text S1. UK policy context.

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