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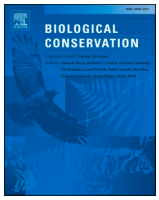

Perspective

Ecovoltaics: Framework and future research directions to reconcile land-based solar power development with ecosystem conservation

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ABSTRACT

Renewable energy production is gaining momentum globally as a way to combat climate change without drastically reducing human energy consumption. Solar energy offers the fastest developing solution. However, ground-mounted solar panels have a high land requirement, which leads to conflicts with other land use types, particularly agriculture and biodiversity conservation. The dual land use of agrivoltaics, i.e., continuing agricultural production under and between solar panels, may alleviate farmers' concerns, but less effort has been made to reconcile solar development with biodiversity conservation. Here we provide a framework for creating a win-win situation for this growing challenge using recent literature on solar park habitats complemented with ecological theories. We also highlight important knowledge gaps that future research should address. Our framework uses a unique land-sharing approach and is based on five pillars that cover key aspects of solar park planning and maintenance: (1) eco-smart siting in the landscape, which considers ecological interactions with the landscape matrix and trade-offs between multiple small vs. fewer large solar parks; (2) eco-smart park layout to address the ecological aspects of the spatial configuration of solar park infrastructure; (3) creation of diverse, novel grassland ecosystems with high ecosystem service provisioning capacity using a trait-based ecosystem design approach; (4) management of the novel ecosystem throughout the lifespan of the solar parks; and (5) ensuring stakeholder engagement to integrate this in a viable business model with high community acceptance. With this framework, we open the way for a new multifunctional land use type: the ecovoltaic park.

1. Introduction

Anthropogenic climate change, caused by greenhouse gas emissions since the Industrial Revolution, is one of the greatest challenges for modern civilization (Pörtner et al., 2022). Curbing further emissions by phasing out fossil fuels and promoting renewables in the energy sector is a major strategy for climate change mitigation (Sims, 2004; Watson and Hudson, 2015; Nathaniel et al., 2021). For example, the Green Deal of the European Union (EU) aims for a 55 % reduction of emissions by 2030 compared to the 1990 level and to reach carbon neutrality by 2050

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(European Commission, 2019). This ambitious plan received an unplanned boost in 2022 due to the global energy market disruption and the need to end Europe's dependence on Russian fossil fuels. The resulting REPowerEU plan now includes a massive scaling-up and speeding-up of renewable energy development, such as doubling photovoltaic (PV) capacity by 2030 (European Commission, 2022). PV technologies appear to be the kingpin of most climate and energy strategies worldwide (Gazdag and Parker, 2019; Kougias et al., 2021; Blaydes et al., 2022). For example, PV accounted for 1.5 % of the energy generation in the United States in 2018, but is projected to increase up to 15-fold by 2040 (Cole et al., 2018). Mega-PV parks are also being built in all other major economies such as India (Vyas et al., 2022) and China (Tsafack et al., 2022). Investing in solar energy is indeed a viable option as it is inexhaustible and its globally available amount, estimated at about 2500 terawatts, far exceeds human demand (Georgiou and Skarlatos, 2016).

Renewables, however, have their downsides. Utilizing hydropower by constructing dams alters the hydrodynamics of watercourses and blocks the longitudinal migration of aquatic organisms (Nyqvist et al., 2017), while wind turbines can kill birds and bats (Aschwanden et al., 2018) and cause acoustic pollution (Jianu et al., 2012). The problem with solar power is its large land footprint (Watson and Hudson, 2015, Späth, 2018, Van de Ven et al., 2021). PV panels can be mounted on rooftops and other urban infrastructure, but utility-scale PV parks are often deployed on the ground. Considering that an area of between 1.5 and 3.5 ha is required to generate 1 MW of electric power (Blaydes et al., 2021; Walston et al., 2021), the aforementioned increase in the share of PV in the energy production of the United States alone can lead to land conversion of up to 1.75 million ha to PV parks. Accordingly, the US Bureau of Land Management has designated 350,000 ha of land as Solar Energy Zones with an additional 7.7 million ha open for potential solar development (BLM (Bureau of Land Management), 2018). According to Van de Ven et al. (2021), certain regions of the world with high energy demand such as Europe, Japan, and India may have to dedicate 0.5–5 % of their land to PV parks by 2050. This large land requirement has already led to conflicts with other land use stakeholders (e.g., Späth, 2018, Roddis et al., 2020, Hermoso et al., 2023). Given the exponential spread of PV parks, this trend will continue to intensify and potentially undermine the path to achieving climate targets, if the conflicts are not resolved.

The lowest rate of conflict associated with ground-mounted PV can be expected on brownfields and other types of abandoned industrial areas, but such easy sites are running short, and croplands are also increasingly converted (Semeraro et al., 2018; Oudes et al., 2022). This may lead to a loss of food and feed production or the translocation of agricultural production into natural ecosystems, thereby leading to their destruction. Partial continuation of agricultural production in PV parks is possible, albeit often requires expensive modifications of the PV installations (Willockx et al., 2022). These mixed-production areas, where agricultural activities take place under and among PV panel rows, are often referred to as agrivoltaics and represent a promising compromise between energy production and agriculture (Dinesh and Pearce, 2016; Santra et al., 2017).

Nature conservation is another, but often neglected, contender in the competition for land (Fischer et al., 2014; Späth, 2018). Due to the global decline of biodiversity and the deterioration of natural habitats, the present decade has been declared the Decade of Ecosystem Restoration by the United Nations (Aronson et al., 2020). The EU's Biodiversity Strategy for 2030 and its Nature Restoration Law also call for restoration actions on 20 % of its territory and for the establishment of protected areas in further 4 % of its territory (European Commission, 2020; Paulus and Sprackett, 2021). Avoiding anticipated conflicts with PV development thus calls for strategic forward-thinking. The construction of PV parks usually leads to land degradation, as it requires vegetation clearing and ground soil leveling (Lambert et al., 2022), and instead of the potential natural vegetation, turf grass is maintained by regular mowing, often complemented with chemical weed control to prevent panel shading and reduce fire hazard (Uldrijan et al., 2021; Vaverková et al., 2022). However, an increasing number of studies applying ecosystem and landscape models suggest that solar parks could also be created and maintained in an "eco-friendly" manner, resulting in co-benefits for energy production, nature conservation, and ecosystem service provisioning (Randle-Boggis et al., 2020; Walston et al., 2021; Blaydes et al., 2022). Despite these promising scenarios, empirical evidence is still scarce (but see for example Dolezal et al. (2021) and Lambert et al. (2022)).

The environment that PV parks provide to species has no equivalent in the wild. PV panels alter microclimate, light regime, hydrology, and soil respiration rates (Armstrong et al., 2014, 2016; Pisinaras et al., 2014; Dolezal et al., 2021; Lambert et al., 2021), require special management to avoid panel shading (Uldrijan et al., 2021), have a disturbance frequency of 20–30 years due to their operational lifetime (Semeraro et al., 2022), and generate special electromagnetic fields with potential effects on organisms (Molina-Montenegro et al., 2023). As a result, PV parks can be considered novel ecosystems (Hobbs et al., 2009) that may be inhabited by a subset of the surrounding species pool following novel assembly mechanisms.

In general, our understanding of PV park impacts on the flora and fauna is far from complete (Uldrijan et al., 2021; Vaverková et al., 2022), which hinders strategic planning while also calling for more focused research. Here, we provide a framework for creating a win-win situation for solar power development and nature conservation by complementing the emerging literature on PV park habitats with ecological theories developed for non-PV habitats. We also identify important knowledge gaps that future research should address. Our framework uses a unique land-sharing approach and is based on five pillars that cover all major aspects of PV park planning and maintenance: (1) eco-smart siting in the landscape, (2) eco-smart park layout, (3) creating the optimal novel ecosystem, (4) managing the novel ecosystem, and (5) ensuring the engagement of PV developers to bring all this together in a viable business model. With this framework, we pave the way for a new multifunctional land use type, the *ecovoltaic* park (Fig. 1).

2. Eco-smart siting in the landscape

The main priorities for site selection in PV park planning have so far been (i) the intensity of solar radiation, (ii) the availability of grid connection, and (iii) minimizing ecological risks, such as conversion of protected (semi-)natural areas (Gove et al., 2016; Oudes et al., 2022). According to some regional assessments, these criteria are not particularly restrictive. Watson and Hudson (2015) found that approx. 15 % of South Central England is at least moderately suitable for PV development. Closer to the equator this proportion can be even higher due to increasing solar radiation. Given these large potential areas suitable for PV park development, ecological aspects of siting can be among the most important decision criteria. We propose to consider three main aspects: the original natural value of the site, the natural value of the landscape, and the size of the PV park.

As a rule of thumb, the establishment of PV parks on (semi-)natural habitats is incompatible with the concept of ecovoltaics, as it would lead to a significant degradation of the ecosystem during the construction phase, and the final, "ecologically enhanced" state would probably not reach the original conservation value, resulting in a net loss of biodiversity. Ecovoltaic parks should only be attempted to be established where the other pillars of the ecovoltaic concept result in a net positive effect on biodiversity and associated ecosystem services, e.g., on brownfields and abandoned croplands. This criterion is indispensable to exclude that the ecovoltaic concept is used to "greenwash" a PV investment (de Freitas Netto et al., 2020).

In terms of the natural value of the surrounding landscape, PV parks can be established in landscapes with low nature value (typically croplands), with little native flora and fauna, or in landscapes with a

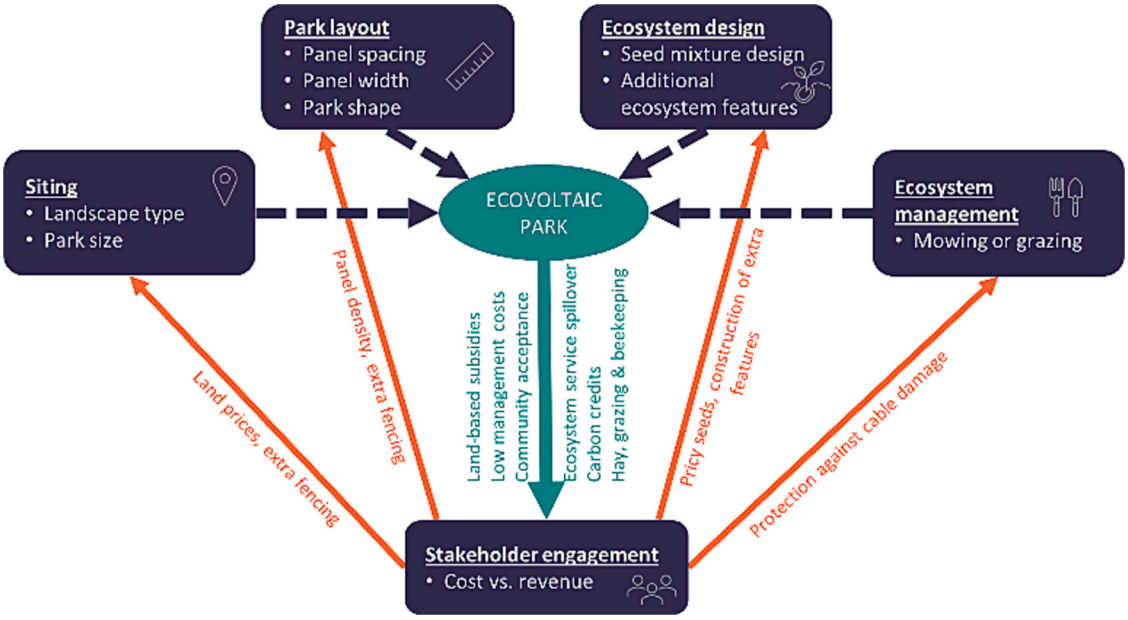

Fig. 1. Proposed framework for creating and maintaining ecovoltaic parks with the ultimate aim to reconcile solar power development with biodiversity conservation and the delivery of ecosystem services. Four key ecological aspects (siting, park layout, ecosystem design and management) should be considered for the shift from conventional photovoltaic to ecovoltaic parks. These may incur additional costs for developers (red arrows), but an established ecovoltaic park can return the investment through various direct or indirect benefits (green arrow). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

higher proportion of (semi-)natural habitats. Using evidence from small natural landscape features, such as mid-field grassland fragments (Cousins, 2006; Lindborg et al., 2014; Lindgren et al., 2018; Deák et al., 2020), we assume that the assembly of biotic communities in PV parks of low nature value landscapes is constrained by dispersal limitation. Yet, the added value of such ecovoltaic parks for supporting landscape-level biodiversity and ecosystem services can be high despite their limited local conservation value. This added value may include populations of species and the provisioning of ecosystem services that are rare or absent in the surrounding low nature value landscape. According to Blaydes et al. (2021) ecovoltaic parks in homogeneous and intensive agricultural landscapes may have the potential to be reservoirs of pollinators, while Gazdag and Parker (2019) and Oudes et al. (2022) highlight the opportunities for pest control arthropods in PV parks, if designed for and managed in an eco-friendly way.

Ecovoltaic parks can also be established on degraded localities (incl. croplands) of otherwise high nature value landscapes. These parks may develop considerably higher local conservation value due to the vicinity of propagule sources but would have weaker add-on landscape-level impacts on biodiversity and ecosystem service provision. However, because the habitat properties of ecovoltaic parks differ significantly from those of (semi-)natural ecosystems, ecovoltaic parks can provide complementary habitats and thus add further value (cf. Justus and Sarkar, 2002). Complementarity with (semi-)natural habitats may include, for instance, reducing microclimatic extremes and wind speed beneath PV panels (Armstrong et al., 2016), making PV parks suitable shelters for non-xerothermic arthropods of adjacent open habitats on hot summer days and for flying insects in windy periods.

Planning the size of PV parks also affects siting, as the target PV capacity is a preset value to achieve the renewable energy target of an administrative territory (Hermoso et al., 2023). For example, Virginia's goal of 40 % renewable by 2030 would require 31.7 km^2 of land for solar parks (Evans et al., 2023). Such numbers can only be reduced if the efficiency of converting solar power into electricity increases with technological development, which should be encouraged from the perspective of biodiversity conservation. Nevertheless, the target PV capacity can be reached by allocating either a few sites for large parks or many sites for smaller parks. This decision is analogous to the well-known "single large or several small" (SLOSS) debate of conservation science (Diamond, 1975; Fahrig et al., 2022). Here, research must examine how large an ecovoltaic park needs to be to achieve a predefined level of biodiversity and ecosystem service provision. If small parks satisfy the requirements, a larger number of them may be a better option than fewer but larger PV parks. Several small sites have a higher overall edge-to-area ratio than fewer larger sites, increasing the importance of both inward (e.g. pesticide exposure) and outward effects (pollination or pest control), which also need to be considered.

Major knowledge gaps:

- Empirical evidence on the impact of the natural value of the landscape on PV park biodiversity
- Quantifying multiple aspects of landscape-wide benefits and trade-offs of ecovoltaic parks
- Guidance for PV park size by adopting questions and principles from the SLOSS debate

3. Eco-smart park layout

Once the site is selected and the park size is determined, the park layout can be adjusted to create ecovoltaic instead of conventional PV parks. Park shape affects edge-to-area ratio, which has the same consequences as described above for size. There is modeling evidence that elongated shapes allow for a higher rate of pollinator spillover from wildflower-rich PV parks to adjacent cropland than square shapes, while shape did not affect pollinator density inside the parks (Blaydes et al., 2022). However, as with the previous questions, this has not been tested in real PV parks.

Spacing of panel rows is another park parameter with potential ecological consequences. Conditions for native flora and fauna are generally unfavorable below the panels due to reduced light availability and the interception of precipitation (Armstrong et el. 2016, Vaverková et al., 2022), although these studies are mostly from temperate regions. In drier and hotter climatic zones, shading (despite the interception of precipitation) may have a facilitative effect on plant life (Tanner et al.,

2020), consistent with the stress gradient hypothesis, which describes the balance between competition and facilitation (Bertness and Callaway, 1994). Thus, the panel-gap ratio in parks might be adjusted according to the expected effects of panels (suppressive vs. facilitative) based on local climatic conditions. Where a facilitative effect prevails, a denser arrangement of panels may be chosen for ecovoltaic parks, while in a suppressive situation, wider spacing is preferable. Heterogeneity within the park and its consequences for biodiversity may also be affected by the width of panel rows, as wide panels may introduce a coarser-grained environmental heterogeneity, while heterogeneity elicited by narrower panel rows would likely be finer-grained. Panel width also affects overall park size, so the potential negative impacts of solar development can be reduced by densely packed rows, as long as this does not compromise the potential positive effects of the park, which otherwise follows the ecovoltaic concept.

The layout of solar park infrastructure items may also affect the electromagnetic fields (EMF) they generate. It has been shown that EMF affects the behavior of pollinators, with consequences on the generative propagation of plant populations (Molina-Montenegro et al., 2023). This effect has never been studied in solar parks, so we do not know whether this is a matter to be considered when designing an ecovoltaic park.

Solar park infrastructure is almost always surrounded by fences to prevent theft and vandalism, as well as injuries caused by sharp and electrically charged metal parts. However, fences can hinder the movement of animals that are harmless to the park, such as hedgehogs (Hof and Bright, 2009); thus, PV park fences reduce habitat connectivity in the landscape more than necessary. This could be alleviated in an ecovoltaic park by providing appropriately sized gaps in the fence or by replacing some parts of the fence with hedgerows that are permeable to small animals.

Major knowledge gaps:

- Empirical evidence on the effects of park shape on biodiversity and fluxes to and from the surrounding landscape
- Guidance for panel size, row spacing, and row width to best meet the needs of the optimal novel ecosystem
- Effects of EMF on pollinators (and other species groups) and how to prevent them, if needed
- The effect of PV park fencing on habitat connectivity and guidance how to improve it

4. Designing the optimal novel ecosystem

Conventional vegetation in solar parks consists of short, species-poor turf grass (Uldrijan et al., 2021; Vaverková et al., 2022). However, the lack of regular soil disturbance in PV parks could theoretically allow for the establishment of more species-rich target communities (Uldrijan et al., 2021). Considering the need for avoiding panel shading, short grassland is the most appropriate target. Grassland restoration is a well-researched field (Prach et al., 2014; Engst et al., 2016; Tölgyesi et al., 2019), and a wide range of techniques have been developed to support community assembly (Török et al., 2011). Recovering grasslands may need a lot of time, often centuries, until they are indistinguishable from ancient reference grasslands (Nerlekar and Veldman, 2020). Practitioners face two major challenges in creating optimal species-rich novel grasslands in ecovoltaic parks: First, PV parks have a limited lifespan of 20–30 years, and long-term approaches for restoration are not realistic (Walston et al., 2021), as their continued grassland cover is not ensured afterwards, as long as ecovoltaic grasslands are not recognized as high nature value ecosystems and are treated accordingly. Therefore, practitioners need to reach a satisfactory level of plant community assembly as quickly as possible. Secondly, there are no ancient references with which to compare restoration success. Instead, the optimal species composition needs to be designed for each location by combining technical requirements and ecological knowledge.

To tackle these challenges of plant community assembly, practitioners cannot rely on passive processes (i.e., secondary succession) but need active interventions, particularly the introduction of the propagules of selected plant species. There are several selection criteria to design a site-specific, tailor-made mixture from the regional grassland species pool. Species should be short enough that they do not reach the lower edge of the panels (see also Semeraro et al., 2022). The height of the lower edge of the panels can vary from park to park. Once this value is known, the upper limit of plant height can be determined. Short species typically include tussock grasses and crawling and rosette-forming forbs. These species are not necessarily good above-ground competitors of tall weedy species (Craine and Dybzinski, 2013), so further selection for good below-ground competitive ability provided by a deep and dense root system is recommended (Casper and Jackson, 1997).

PV parks have various micro-environmental patterns that could also be considered during species selection and the sowing methodology. Heliophytic species do not perform well below the panels, while shade-tolerant species avoid the gaps (Lambert et al., 2022). Differences in the species composition of plant communities under and between panels develop during spontaneous community assembly (Vaverková et al., 2022), so planners may speed up this differentiation (and reduce wasted resources) by using two different seed mixtures, one for the gaps and one below the panels. Species that prefer forest edges or woodlands in the regional species pool may be better suited for areas below the panels, while open grassland species should perform better in the gaps. However, panels are not identical in their effects to woody species of forest edges and woodlands. Although panels intercept precipitation like tree canopies, they do not absorb moisture from the soil, do not affect the spectral composition of the light as photosynthetically active tree canopies, do not affect the nutrient regime in the same way, and do not produce a litter layer or allelopathic compounds (Scholes and Archer, 1997; Mariscal et al., 2004; Tölgyesi et al., 2020). The effects of these differences on the optimal species composition below the panels should be explored in future research.

Designed plant communities in ecovoltaic parks should be substantial sources of ecosystem services. Therefore, considering effect traits, i.e., traits that influence ecological functions (Lavorel and Garnier, 2002), is also recommended during species selection. Grasslands provide a wide range of ecosystem services, including pollination, carbon capture and storage, fodder production, erosion control, and recreation (Zhao et al., 2020). Pollination has received the greatest attention in relation to PV parks, even though most studies are model-based (Walston et al., 2021; Blaydes et al., 2022) or are extrapolations from non-PV landscapes (e.g., Blaydes et al., 2021), without validation with empirical data. To strengthen pollinator populations, insect-pollinated forbs should have a high share in the seed mixture and should include species whose flowering period covers the entire growing season from early spring until fall, which is also a requirement for wildflower strips and fields in agri-environmental schemes (Szitár et al., 2022). Late-season flowering species may be especially important to fill the “hunger gap” for pollinators (Blaydes et al., 2021). Since vegetation removal is difficult to avoid during PV park maintenance completely (see also later), species capable of aftermath flowering should be preferred.

Similar to pollination, pest suppression by the spillover of predatory arthropods to surrounding agricultural areas can be more efficiently achieved by the novel ecosystem of ecovoltaic parks than by the turf grass of conventional PV parks. This is expected because high structural complexity of the vegetation (ensured by high species and trait diversity) can reduce negative interactions among predatory arthropods and support their spatial complementarity, leading to increased predation pressure in and around their focal habitat (Holland et al., 2016, Michalko et al., 2017). The suitability of an ecosystem to support pest control also depends on the type of the surrounding agricultural areas (Michalko and Birkhofer, 2021). The highest spillover occurs between ecosystems that are similar to each other (Hogg and Daane, 2010), so the proposed novel grassland may be efficient for herbaceous crops but may

have limited bio-control effect on tall perennial agroecosystems such as orchards due to the lack of arboreal predators (Paredes et al., 2013) Therefore, ecovoltaic parks surrounded by landscapes rich in such agroecosystems could include patches of woody vegetation such as hedgerows in places where they cannot cast shade on the panels. However, the role of solar parks in biological control services in agroecosystems has not yet been examined.

Carbon sequestration in the soil is another important grassland ecosystem service. There is a synergy here with the requirement for species with a dense root system, as roots are the most important sources of soil organic carbon content (Huang et al., 2021). A dense root system is also beneficial for erosion control (Gyssels et al., 2005). Optimizing for high fodder production in ecovoltaic parks is difficult because tall species with high above-ground biomass should be avoided. The proposed species-rich, short but continuously flower-rich plant communities will also have outstanding aesthetic value for people recreating in the neighborhood of ecovoltaic parks, as shown in other pollinator habitat enhancement studies (cf. Wratten et al., 2012). Eventually, to find the set of species that best meets the above criteria, practitioners can draw on expert knowledge, but can also browse public trait databases for plant species such as TRY (Kattge et al., 2020), BiolFlor (Kühn et al., 2004) and PADAPT (Sonkoly et al., 2022) to identify species with appropriate height, flowering, rooting and other features. The composition of our experimental seed mixture compiled on the basis of favorable trait values and sown in Hungarian ecovoltaic parks is shown in the online Appendix to the paper (Table A1, Fig. A1).

Some papers also call attention to the advantages of creating additional ecosystem features for the ecological enhancement of PV parks. These include hedgerows, wetland patches, ponds, artificial nesting places for bumblebees, etc. (Gazdag and Parker, 2019; Oudes et al., 2022). Hedgerows could even replace some of the fences around the park and would enable easier movement of animals and thus increase habitat connectivity. These additional ecosystem features are expected to further increase biodiversity and the capacity to provide ecosystem services but also increase construction and maintenance costs. Presently, there is very little empirical data on the beneficial effects of these elements in PV parks.

Major knowledge gaps:

- Comparative studies about the restoration success of different restoration methods
- Experience in the trait-based design of seed mixtures and their application to create optimal species composition and ecosystem services in ecovoltaic parks
- Tests on the need for considering micro-heterogeneity in ecovoltaic parks for the design of seed mixtures and implementation
- Assessments of the fauna and trophic relationships of the species-rich novel grassland
- Empirical evidence on the effectiveness of additional ecosystem features in ecovoltaic parks

5. Managing the novel ecosystem

PV park vegetation is commonly managed intensively to maintain short turf grass without tall weeds (Uldrijan et al., 2021; Vaverková et al., 2022). The proposed vegetation of ecovoltaic parks requires lower management intensity, but cannot go without management. Many regions undergoing rapid PV development, such as Western Europe and the eastern states of the US, are located in forested biomes; therefore, the lack of vegetation management would eventually lead to spontaneous woody plant encroachment (Eldridge et al., 2011), resulting in panel shading. A certain intensity of management is also often required to maintain high plant species diversity (Habel et al., 2013), which has beneficial effects on higher trophic levels, such as pollinators, too (Blaydes et al., 2021). In high nature value grasslands, this disturbance is usually realized with low-frequency, late-season mowing or low-intensity livestock grazing (Tälle et al., 2016). Mowing can be difficult around the panel scaffolds, while grazing animals can also access these parts. Cattle and goats would certainly damage the panels; therefore, sheep seem to be the only viable solution, although they can also chew on electric cables (Vaverková et al., 2022). Beyond these technical considerations, different grassland types respond differently to mowing and grazing, although grazing has overall higher support (Tälle et al., 2016), especially in restored grasslands, where it accelerates plant community assembly due to the combined effects of epi- and endozoochorous propagule dispersal, micro-gap creation and subsequent plant species colonization (Kapás et al., 2020; Tölgyesi et al., 2022). However, the selective grazing strategy of sheep can lead to low abundance of forbs and high abundance of grasses, which may conflict with pollinator requirements. The importance of such trade-offs needs to be tested in the designed grasslands of ecovoltaic parks.

Major knowledge gaps:

- Experience with the effectiveness and feasibility of different management regimes (timing and frequency of mowing, livestock species and intensity of grazing, etc.) to support the assembly of the novel ecosystems of ecovoltaic parks

6. Stakeholder engagement

The proposed shift from establishing conventional PV parks to ecovoltaic parks seems costly, which may limit investors' interest. Extra costs can arise from the following five sources: (i) higher land acquisition costs if eco-smart siting does not favor the lowest-cost option, (ii) more fencing material if small and/or elongated ecovoltaic parks with high edge-to-area ratios are chosen, (iii) costs of sowing species-rich seed mixtures, (iv) management-related costs, for instance for securing electric cables to allow sheep grazing instead of herbicide application), and (v) construction and maintenance of additional ecosystem features. If ecovoltaic parks are to become a viable business model, these costs must be counterbalanced by direct or indirect benefits or reductions in other costs.

If implemented, the recommended short grassland vegetation is expected to require a lower level of management than conventional turf grass. The species-rich grassland vegetation (i) can yield high-quality forage (Bullock et al., 2001) that can be utilized by grazing locally or selling as hay, (ii) can be used for seed production for sowing in other ecovoltaic developments, and (iii) can even be used for beekeeping, although potential competitive effects on wild pollinators and effects on predators feeding on wild pollinators should also be taken into account. The economic use of the biomass, floral resources, and propagule production of the species-rich novel grassland also means that the ecovoltaic park could fall, at least in part, within the scope of land-based agricultural subsidies, such as the Common Agricultural Policy of the EU (Watson and Hudson, 2015). Furthermore, as the proposed grasslands in ecovoltaic parks can be regarded as high-nature-value novel ecosystems, they could be integrated into subsidy systems that promote nature conservation, such as the Agri-Environmental Schemes of the EU (Batáry et al., 2015). These subsidies would provide direct revenue; however, this mixed production type of land use should be thoroughly documented and recognized by the relevant legislation. Top-down support of solar park developers is also emerging in the United States, as a voluntary association of states allows PV developers to market their electricity as "pollinator friendly" if they meet certain environmental criteria (Wetli, 2020). Implementation of our ecovoltaic framework could introduce additional, potentially even more influential certificates.

An indirect benefit related to ecovoltaic parks is the potential for stronger community acceptance. An indirect benefit of ecovoltaic parks is evident in countries where the impact of PV development on biodiversity has to be offset by law. The overall negative impacts of an ecovoltaic development are smaller, if any; so less compensatory investment is required. Another indirect benefit is the potential for

stronger community acceptance. Some authors have reported that local communities could have strong opposition against ground-mounted PV developments, resulting in losses to investors due to failed projects (e.g., Roddis et al., 2020). The main concerns of local people are the degradation of the environment and the aesthetic value of the landscape, as well as the loss of agricultural land (Späth et al., 2018). The careful planning of an ecovoltaic park can alleviate these concerns. The initial environmental damage on the croplands and brownfields caused by construction activities can be quickly offset by the creation of the novel grassland ecosystem. The high biodiversity and flower-rich appearance can improve the aesthetic value, which compensates for the industrial-looking PV panels, and can potentially reverse the "not-in-my-back-yard" syndrome to a positive visual perception of the development (cf., Warren et al., 2005). Ecovoltaic parks could also provide a solution to the loss of agricultural land because, as in the case of agrivoltaic parks, the land continues to be used for certain agricultural purposes, including hay production, free-ranging animal husbandry, and/or beekeeping, but with additional benefits for biodiversity from targeted plant species introductions and specific habitat management. Further benefits include the provision of ecosystem services that can compensate for the higher costs of ecovoltaic parks. For example, carbon sequestration in the soil may be utilized in the form of carbon credits (see, e.g., Dumanski, 2004). Pollination and pest control services provided by predatory arthropods that spill over from ecovoltaic parks to surrounding croplands can increase agricultural production or reduce the need for pesticide applications (e.g., Lindgren et al., 2018, Blaydes et al., 2021).

Major knowledge gaps:

- Cost-benefit analyses of ecovoltaic parks
- Quantitative assessment of the community acceptance of ecovoltaic parks
- Quantification of ecosystem service levels in ecovoltaic parks and spillover to adjacent croplands

7. Significance of the *ecovoltaic* framework

We provided a comprehensive framework to reconcile the high spatial area requirement of solar development with biodiversity conservation through a unique land-sharing approach (Fig. 1). Our framework aims to establish a win-win situation for all stakeholders by promoting synergies while limiting trade-offs and conflicts between nature conservation, community acceptance as well as energy and agricultural production. At present, this framework is primarily based on modeling results and ecological theories developed for different ecosystems. This obviously entails uncertainties, so we propose the most pressing knowledge gaps for future research. Solar energy is rapidly taking over the global energy sector, both because of our goal to mitigate climate change and because of the global fossil fuel crisis. If ecological considerations are ignored now because there is no substantial empirical evidence, the utopia of a clean, sun-based future may turn into a dystopia, with (i) missed opportunities to utilize direct and indirect benefits for stakeholders, (ii) significant damages to biodiversity and the livelihood of local people, and (iii) growing conflicts with other sectors. We, therefore, recommend that the aspects in our framework be incorporated into legislation as soon as possible to promote an optimal green infrastructure for the future.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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