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A METEOROLOGICALLY BASED MODEL FOR THE RESTORATION OF AREAS AFFECTED BY SOLAR PARK

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Abstract

Solar parks are an important part of the transition to a low-carbon economy, but their development may alter soils, vegetation, and biodiversity. This study proposes a meteorologically informed model for ecological zoning and restoration, based on data of a solar park near Lukovit, Bulgaria, adjacent to the SPA BG0001014 Karlukovo. Microclimatic monitoring identified significant differences in temperature, soil moisture, and conductivity, while floristic surveys revealed both similarities with habitats 6210, 6240, and 62A0 and the absence of key diagnostic species. The restoration framework—based on local seed mixtures, rotational grazing, adaptive mowing, and biocorridor creation—aims to integrate renewable energy production with biodiversity conservation, thus enhancing the Natura 2000 ecological network.*

Keywords: *Solar Park; Restoration; Natura 2000*

Introduction

Solar parks present a critical component in the broader transition towards a low-carbon future. These facilities contribute to reducing greenhouse gas emissions and play a key role in the European Union's efforts to achieve climate neutrality by 2050 [1]. In response to the challenges associated with the deployment of renewable energy sources and the European Green Deal, there has been a rapid expansion in solar parks across Europe [2].

Despite the benefits of solar energy as a low-carbon source, its ecological impacts are substantial. Solar parks require extensive land areas, which can lead to the destruction or alteration of habitats at multiple spatial scales. The construction of such infrastructure has been found to have a detrimental effect on the physical properties of soils [3]-[15], to intensify erosion processes [16], and to hinder the establishment of vegetation [17]. During the operational phase, panels modify microclimatic conditions, including temperature, humidity, and solar radiation, which results in the formation of plant communities distinct from those in the surrounding areas [4], [6], [9]. It has been established that a reduction in light beneath panels exerts a detrimental effect on the germination, growth, and survival of heliophilous species [18], [19], [20], with the potential to shift community composition towards shade-tolerant species. This ecological process requires further investigation. Furthermore, alterations in precipitation patterns, soil moisture, and thermal fluctuations beneath the panels impose constraints on vegetation development and species diversity [15].

In view of the enduring consequences of these impacts, there is a clear need to implement ecological restoration strategies directly at the sites of electricity production. To restore

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ecosystems to their natural state, it is essential to consider both biotic and abiotic factors that influence the recovery of plant communities. Biotic factors include processes such as seed dispersal, competition, and facilitation, while abiotic factors refer to environmental conditions such as climate and soil quality. By considering these factors, we can ensure the successful restoration of ecosystems that resemble their natural reference states. It is evident that seed dispersal constitutes a pivotal phase within the broader context of the restoration process. The transfer of seed material has been established as a mechanism that accelerates succession and enhances species richness [22], [23]. Conversely, targeted seeding of a limited number of species constitutes a cost-effective alternative. Soil quality is also a key determinant. Construction-related disturbances and prior land use often reduce organic matter, in some cases necessitating the application of soil amendments [15], [24].

It has been established that the reduced light availability beneath solar panels has a detrimental effect on seed germination, plant growth, and survival. The ecological zoning of solar parks distinguishes two principal types of areas: beneath the panels and outside the panels. Each of these areas is characterized by specific microclimatic conditions and corresponding restoration requirements [1]-[7].

The under-panel zone is characterized by reduced solar radiation, lower daytime temperatures in summer, slightly elevated night-time temperatures in winter, and an uneven distribution of precipitation. These conditions restrict ecological productivity and reduce species richness. Consequently, restoration in this zone must consider shade tolerance, altered water regimes, and soil stability. This can be achieved through the application of adapted seed mixtures, soil improvement, and systematic monitoring [7], [9], [25].

Conversely, the inter-row areas are exposed to full solar radiation and more extreme drought, a phenomenon that is particularly relevant in regions such as Bulgaria. Soil in these areas is frequently degraded, yet they demonstrate greater potential for the recovery of communities that approach reference conditions. The most effective measures in this context include the transfer of seeds from reference habitats, the application of organic amendments, and management practices such as conservation mowing or grazing [26].

Despite these challenges, extant evidence suggests that, under appropriate management, solar parks may also function as resources for biodiversity. The maintenance of rich plant and animal communities is facilitated by several factors, including long-term operation, reduced anthropogenic pressure, and the opportunity to diversify habitats [25], [26]. Examples from the United Kingdom show that well-managed solar parks support the conservation of rare birds, pollinators, and mammals, while practices such as wildflower seeding and habitat enrichment enhance ecological productivity and resilience [27], [28].

This difference in impact emphasizes the necessity of frameworks for the ecological zoning of solar parks and the implementation of adaptive restoration measures. Using meteorologically based models that integrate climatic and ecological data is a good foundation for the eco-friendly construction and operation of solar parks. The aim of the model is to optimize spatial planning and to provide a framework for the development of restoration strategies [1], [15].

The objective of the present article is to develop a scientifically grounded, meteorologically informed model for the ecological zoning of a solar park near Lukovit and to propose restoration measures that reconcile energy and climate objectives with biodiversity conservation and sustainable land management.

Experimental part

Study area

The solar park is situated on a land plot (LP) with identifier 44327.26.18 in the locality "Byalo Pole," within the territory of Lukovit, Bulgaria (Fig. 1). The plot covers an area of 29,998 m², of which approximately 80% is developed according to the investment proposal, corresponding

to around 24,000 m² occupied by panels and service infrastructure. The facility is constituted by a ground-mounted solar park with an installed capacity of 3 MW. It consists of photovoltaic panels mounted on metal supporting structures anchored by precast reinforced concrete blocks. The structures rise to approximately 2 m above ground level, thus providing optimal exposure whilst allowing the development of limited grass vegetation beneath them. The nearest protected area within the Natura 2000 ecological network is SPA BG0001014 Karlukovo BG0001014. The management strategy employed at the site is currently rotational grazing by sheep.

Fig. 1. Solar Park location

The Lukovit region is distinguished by a temperate-continental climate, marked by warm, dry summers and relatively cold winters. The mean annual temperature is approximately 11–12°C, while annual precipitation ranges between 550 and 600 mm, with summer droughts being frequent. The relief is typically characterized by a karstic topography, featuring well-developed limestone plateaus, canyons, caves, and chasms. These geological features influence a specific hydrological regime, dominated by subterranean drainage. The soils are predominantly shallow rendzinas over limestone, moisture-deficient but calcium-rich, thus favoring the development of xerophytic and calciphilous plant communities. The presence of a rich flora and habitats of European conservation importance, including dry grasslands and steppe formations, is underpinned by these features.

1Methods

Environmental monitoring

For the purposes of this study, measurements of three ecological parameters – air temperature, soil moisture, and electrical conductivity (EC) – were conducted in a solar park located near the town of Lukovit, Bulgaria. The monitoring period occurred between 20 July and 19 August 2025. Within the designated area, three distinct groups of sensors were installed, corresponding to the presence of microclimatic zones – Zone 1 and Zone 2, shaded areas, and Zone 3, inter-row sunny areas:

- Zone 1 is located at the lowest edge of the photovoltaic panels. It is directly influenced by shading and surface runoff. The height of the panels in this zone ranged between 1 and 2 meters above ground level.
- Zone 2, the under-panel (upper edge) is located beneath the elevated section of the modules. This area exhibited more consistent shading but less restricted airflow. The panel's height ranged between 2 and 3 meters above ground level.
- Zone 3 is characterized by an inter-row illuminated zone, which is defined as the open space between panel rows that is exposed to direct solar radiation and typical field conditions. The distance between these panel rows was approximately 4 meters.

RS485 soil sensors were utilized to assess moisture, temperature, and electrical conductivity (EC). The measurements were taken at a frequency of 1 Hz (one per second), with the data being transmitted via a standard RS485/Modbus digital interface.

Statistical analysis

A range of conventional statistical methodologies were employed in the analysis of the data collected. The results were summarized using descriptive statistics. This involved the calculation of the mean, minimum and maximum values, and the standard deviation, to reflect parameter variability. A one-way analysis of variance (ANOVA) was performed to ascertain the statistical significance of any differences between zones. Linear regression analysis was employed to evaluate temporal trends and to ascertain the rate and direction of changes. In addition, correlation analysis was utilized to identify relationships between parameters, such as temperature, soil moisture, and electrical conductivity.

Comparative analysis of floristic composition

To assess the potential ecological value of the solar park, we compared the vegetation established within the three microclimatic zones (lower panel edge, under-panel, and inter-row areas) with the floristic composition of the target habitats in the special protected area (SPA) BG0001014 Karlukovo. The method included phytosociological descriptions and species identification within the park, comparison with diagnostic species lists for habitats 6210, 6240*, 62A0, 40A0*, and 6110*, and analysis of coinciding and missing elements. This approach enabled the determination of the degree of similarity with reference communities and the identification of priority directions for restoration actions.

Results and discussion

Field measurements and dynamics of environmental parameters

The study monitored temperature across three designated zones within the solar park (Fig. 2) to assess the influence of photovoltaic panels on the near-surface microclimate environment. Analysis of the temperature data showed clear differences between the zones in terms of both absolute values and the amplitude of thermal fluctuations. In Zone 1, temperatures ranged from 20 to 30°C, with the highest values recorded at the end of July. A gradual decrease was observed throughout August, with values stabilizing at around 22-25°C. Zone 1 exhibited moderately high temperatures compared to Zone 2, though not as high as those observed in Zone 3. Zone 2 exhibited the lowest temperatures of the three zones, typically fluctuating between 20 and 28°C and generally remaining 1-2°C lower than Zone 1. It was also characterized by the smallest amplitude of fluctuation, indicating greater thermal stability and the regulatory effect of panel shading. This characteristic may suggest the creation of a more favorable microclimate for vegetation, particularly during periods of summer heat stress. Zone 3 recorded the highest temperatures, reaching 36-37°C in August. This zone was characterized by greater variability and pronounced peaks resulting from direct solar radiation and the absence of shading. The thermal amplitudes in this zone were considerably larger, producing more extreme conditions for the biotic elements of the environment.

In Zone 1, the initial soil moisture content (Fig. 3) was around 22%, gradually declining to approximately 16% over the observation period. This moderate reduction rate suggests a partial limitation of evaporative processes, which may be due to the shading effect of the panel. In Zone 2, the initial value was around 24%, and the dynamics of soil moisture were even more moderate. By the end of the observation period, soil moisture levels had stabilized at around 18%, indicating optimal water retention in this area. This can be interpreted as resulting from the specific microclimate beneath the panel at a higher tilt angle, where shading is combined with better air circulation. In Zone 3, the most precipitous decline was observed, with a decrease from approximately 18% at the beginning of the period to around 7-8% by its end. This signifies marked soil desiccation under conditions of direct solar radiation and an absence of protective factors, resulting in substantially increased evaporative losses. The analysis reveals a clear difference between shaded and inter-row areas. Soil desiccation was found to be significantly slower beneath the panels, thus confirming the regulatory influence of photovoltaic panels on microclimatic conditions. Zone 2 was identified as the most favorable in terms of soil moisture retention, whereas Zone 3 experienced the greatest soil stress. The results revealed that

photovoltaic panels create conditions that promote soil moisture conservation, thereby mitigating thermal extremes and reducing evaporation. These characteristics should be considered a key factor in the development of plant communities and maintenance of ecological balance in areas under solar parks.

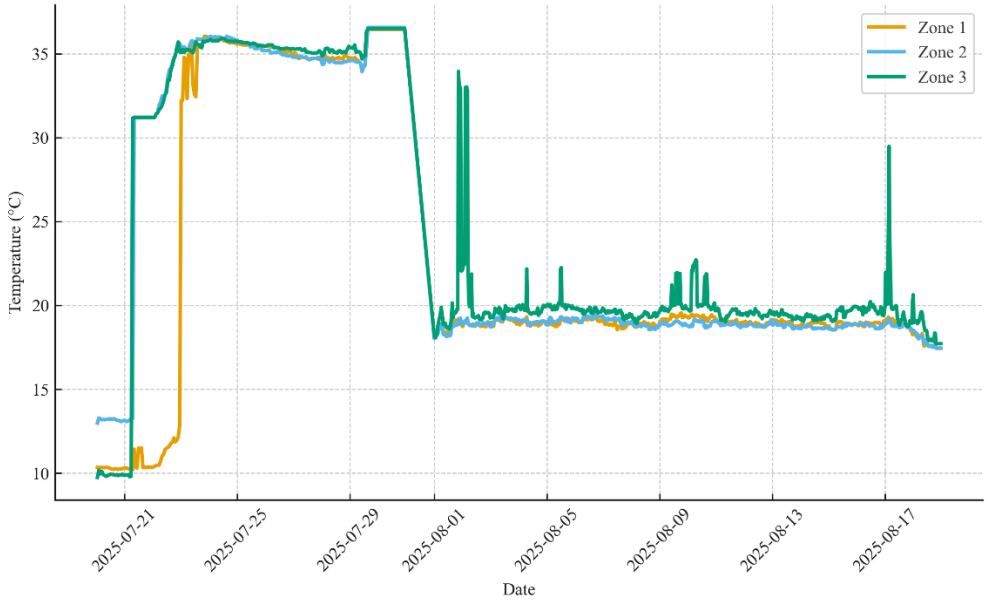

Fig. 2. Temperature dynamics

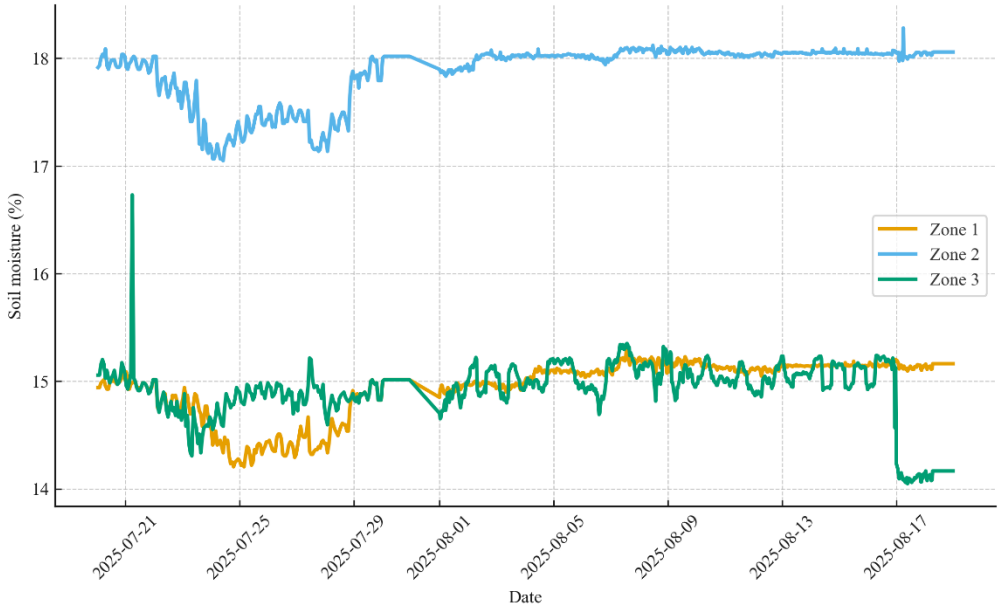

Fig. 3. Soil moisture dynamics

Measurements of electrical conductivity (Fig. 4) revealed distinct spatial differences between the zones, reflecting the influence of microclimatic conditions and soil moisture

dynamics. Initial values in Zone 1 were the highest (around 0.35–0.36 dS/m), gradually declining to around 0.12 dS/m by the end of the period. This indicates pronounced dynamics driven by a reduction in soil moisture and the subsequent dilution of dissolved salts in the soil solution. Zone 2 exhibited even higher initial electrical conductivity values (around 0.43–0.44 dS/m), exceeding those in Zone 1. Both Zones 1 and 2 showed a similar declining trend, although the reduction in Zone 2 was slightly more gradual. By the end of the monitoring period, values in both zones had converged to ~0.12–0.13 dS/m. This reflects more consistent moisture conditions and the stabilization of soil salinity. In Zone 3, electrical conductivity started at a much lower level (around 0.06 dS/m) and decreased gradually to around 0.04–0.05 dS/m. The absence of abrupt fluctuations indicates continuous moisture loss and a low concentration of dissolved ions. This is typical of soils with poorer salt content and reduced biological activity that are directly exposed to atmospheric influences. Analysis indicates a general downward trend in electrical conductivity across all zones, though the intensity of this process varied. Higher initial values and more pronounced dynamics were recorded beneath the panels (Zones 1 and 2), reflecting active changes in the soil solution resulting from the microclimatic effects of shading. In contrast, Zone 3 exhibited lower and more stable values, highlighting its limited salt content and less favorable conditions for soil processes.

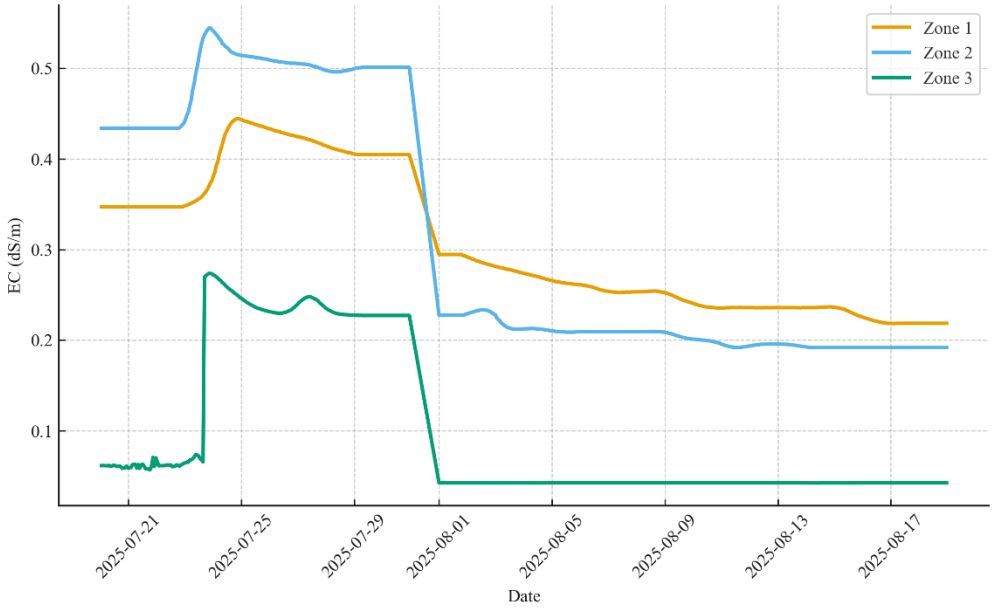

Fig. 4. Electrical conductivity dynamics

Statistical analysis

A statistical analysis of microclimatic and soil parameters revealed significant differences between zones, influenced by the arrangement of the photovoltaic panels. The application of descriptive statistics yielded a clear manifestation of structured trends. The mean temperatures recorded ranged from approximately 25.5°C in Zone 2 to approximately 31°C in Zone 3, which also exhibited the highest recorded extremes (up to approximately 37°C). The analysis revealed that soil moisture was best preserved beneath the panels, with mean values of approximately 19% in Zone 1 and approximately 18% in Zone 2. However, in Zone 3, it declined sharply to approximately 11%, with minimum values as low as approximately 7%. Electrical conductivity exhibited a similar trend, with higher initial values and more pronounced dynamics observed beneath the panels. The mean values recorded were approximately 0.22 dS/m in Zone 1 and 0.25 dS/m in Zone 2, while inter-row areas showed significantly lower values of around 0.05 dS/m in Zone 3. ANOVA tests confirmed

the statistical significance of these differences. For temperature, an F-value of 11.71 was recorded ($p < 0.001$); for soil moisture, an F-value of 5963.49 ($p < 0.001$); and for electrical conductivity, an F-value of 1638.84 ($p < 0.001$). These results clearly showed that panel placement significantly influences all studied parameters. Beneath the panels, conditions were more balanced, with lower temperatures, higher and more stable soil moisture levels, and moderately higher electrical conductivity. In contrast, inter-row areas were characterized by thermal extremes, critically low moisture levels, and an imbalanced salt content.

These findings are directly relevant to ecological studies. The spatial heterogeneity created by the microclimatic effects of the panels generates conditions for distinct vegetation groups. Beneath the panels, favorable moisture regimes and moderated temperatures support richer floristic communities, including shade- and moisture-tolerant species. Conversely, in inter-row areas, extreme climatic conditions result in the restriction of vegetation to xerophytic grasses, which have adapted to drought and heat stress. Solar parks thus function as a mosaic of microhabitats, whose structure is determined by the spatial distribution of panels and associated soil-climate gradients.

As could be seen by the statistical results, the solar park is not a homogeneous system but rather a dynamic space in which the microclimate beneath the panels provides conditions for greater biodiversity and more stable ecological functioning compared with inter-row areas. This result confirms the hypothesis that targeted restoration measures, aligned with the spatial heterogeneity identified, are indeed a strategy that can be successfully implemented. In consideration of the findings, the formulation of specific restoration measures for the individual zones is recommended. In Zone 1, conditions are semi-shaded, with moderate temperatures and gradually declining soil moisture. In order to prevent erosion and preserve soil structure, the introduction of resilient mesophytic grassland communities is required. Practices such as mulching and the maintenance of an organic layer are effective in reducing evaporation and promoting vegetation development. In Zone 2, the most balanced microclimate was recorded, with minimal temperature amplitudes and optimal soil moisture retention. These conditions are conducive to the proliferation of shade- and moisture-demanding plant groups, which can sustain high biodiversity. To capitalize on these conditions, it is recommended that rich grass cover be maintained through the introduction of species that enhance ecosystem services such as pollination, nitrogen fixation, and organic matter accumulation. This zone exhibits the greatest potential to become the most stable component of the ecosystem within the park. In Zone 3, exposure to extreme climatic conditions, characterized by high temperatures and severe soil desiccation, necessitates the introduction of xerophytic plant groups adapted to limited moisture availability and wide thermal amplitudes. Erosion control measures play a critical role in this zone, aiming to retain soil moisture and create conditions for stabilizing vegetation cover.

Ecological Restoration in SPA BG0001014 Karlukovo Context

The approach to ecological restoration within the solar park should differ depending on the area. For example, biodiversity maintenance and soil stability should be prioritized beneath the panels, while combating drought and erosion should be prioritized in inter-row areas. This targeted strategy will ensure the sustainable management of ecosystem resources within the solar park. This is corroborated by the phytosociological description of the study site. Field observations at the solar park revealed clear differentiation of plant communities according to exposure and microclimatic conditions.

The results provided evidence that the microclimatic contrasts created by panel placement drive a spatial differentiation of vegetation. Zone 1 and Zone 2 supported richer floristic diversity, including aromatic and melliferous plants as well as young shrub individuals. In the partially shaded under-panel areas, the following species were recorded: *Salvia nemorosa/S. verticillata, Thymus pannonicus, Origanum vulgare, Micromeria/Calamintha sp.,* and *Verbascum sp.,* along with young shrubs of *Crataegus monogyna* and *Rosa canina*. This pattern results from the semi-shaded environment created by the panels, with more balanced temperatures and higher soil

moisture. These zones thus function as "refugia," allowing the establishment of species more sensitive to extreme climatic factors. By contrast, open areas were dominated by xerophytic grass species typical of dry calcareous habitats. In Zone 3, the following taxa were recorded: *Festuca valesiaca/F. rupicola, F. arundinacea, Ajuga chia, Stachys recta, Bromus inermis, Elymus hispidus, Euphorbia sp., Lotus corniculatus, Achillea millefolium, Daucus carota, Scabiosa sp., Convolvulus arvensis, Teucrium chamaedrys, Carduus acanthoides,* and *Centaurea solstitialis*. This corresponds with the observed high temperatures and low soil moisture and conductivity, which restrict the species composition to stress-tolerant grasses with shallow root systems.

SPA BG0001014 Karlukovo forms part of the Natura 2000 network and is one of Bulgaria's most important areas for conserving natural habitats of European significance. It is characterised by a variety of ecosystems, including dry karst slopes, steppe grasslands, wetlands, river ecosystems and cave systems. Habitats of European significance are conserved, including: 3140 – Hard oligo-mesotrophic waters with benthic vegetation of Chara; 3260 – Water courses of plain to montane levels with vegetation of Ranunculion fluitantis and Callitricho-Batrachion; 40A0* – Sub-continental peri-Pannonic scrub communities; 6110* – Rupicolous calcareous or basophilic grasslands of the *Alysso-Sedion albi*; 6210 – Semi-natural dry grasslands and scrubland facies on calcareous substrates (*Festuco-Brometalia*), important for orchid diversity; 6240* – Sub-Pannonic steppic grasslands; 62A0 – Eastern sub-Mediterranean dry grasslands; 7220* – Petrifying springs with tufa formation (Cratoneurion); 8210 – Calcareous rocky slopes with chasmophytic vegetation; 8310 – Non-show caves; 91E0* – Alluvial forests with *Alnus glutinosa* and *Fraxinus excelsior* (*Alno-Padion, Alnion incanae, Salicion albae*); 91G0* – Pannonian forests with Quercus petraea and *Carpinus betulus*; 91H0* – Pannonian woods with *Quercus pubescens*; 91M0 – Balkan-Pannonian *Quercus cerris* and *Q. frainetto* forests; and 91Z0 – Moesian silver lime forests.

The sub-Pannonian steppe grasslands and semi-natural dry grasslands and scrub formations on limestone are of particular value, as they harbor rich orchid diversity and other rare plant species. Open limestone terrains are home to specific calciphilous grasslands and sub-continental peri-Pannonian scrub communities, forming a characteristic mosaic of open and semi-closed habitats.

Comparisons with the floristic composition of SPA BG0001014 Karlukovo reveal significant similarities in the vegetation found in the park, particularly with regard to the grassland communities belonging to the *Festuco-Brometalia* order. The presence *of Festuca, Bromus, Elymus, Lotus, Achillea, Thymus*, and *Salvia* indicates the formation of a vegetation mosaic closely resembling natural xerothermic pastures and steppe communities. At the same time, the absence of key conservation-relevant taxa such as *Stipa capillata*, *Adonis vernalis*, and *Dictamnus albus* underscores the potential for targeted floristic enrichment through restoration measures.

Table 1. Comparative analysis of the floristic composition

Category	***Species***	***Reference habitats (Natura 2000)***
Coinciding species	*Festuca rupicola*, *Festuca valesiaca*, *Bromus inermis*, *Elymus hispidus*, *Lotus corniculatus*, *Achillea millefolium*, *Thymus pannonicus*, *Salvia nemorosa*, *Origanum vulgare*	6210 – Semi-natural dry grasslands and scrubland facies on calcareous substrates; 6240* – Sub-Pannonic steppic grasslands; 62A0 – Eastern sub-Mediterranean dry grasslands
Missing species	*Stipa capillata*, *Adonis vernalis*, *Dictamnus albus*, rare orchids (*Ophrys* spp., *Orchis* spp.)	6210; 6240*; 62A0; 40A0* – Sub-continental peri-Pannonic scrub communities

Spatial heterogeneity in species composition is an indicator of a site's ability to support higher levels of biodiversity than uniform grasslands. This is particularly important in the context of ecological restoration, as it creates conditions that allow buffer habitats to be established around protected areas. The presence of melliferous and aromatic plants supports pollinator communities, and the presence of individual shrubs provides the basis for long-term vegetation structuring.

In this sense, the territory of the solar park has the potential to be transformed into a sustainable semi-natural habitat. Management strategies involving limited mowing, overseeding

with missing steppe species, and conserving established aromatic and melliferous plants could serve as a model for integrating renewable energy production with biodiversity conservation.

Examples from international practice showed that, under appropriate management, solar parks can be transformed into valuable resources for biodiversity. In the United Kingdom, measures such as the sowing of native wildflowers in inter-row spaces, the creation of buffer strips with natural vegetation, and the establishment of biocorridors linking the park to adjacent natural habitats are widely applied. These practices have been shown to increase floristic diversity and to support pollinator communities, amphibians, and small mammals [27], [28].

In Germany, the agrovoltaic (Agri-PV) approach has been developed, combining solar panels with extensive grazing or the cultivation of shade-tolerant crops. This reduces the risk of soil erosion, maintains grassland communities, and enhances the social acceptance of projects. A similar model has been applied in France, where rotational sheep grazing is used as an alternative to mechanical mowing. This practice reduces carbon emissions, stimulates the development of semi-natural grassland communities, and promotes the diversity of herbs and legumes. In the United States, particularly in Minnesota, legislation requires that new solar parks be sown with "pollinator-friendly" mixtures, thereby transforming parks into key habitats for bees, butterflies, and other pollinators. In the Netherlands, successful solutions include the establishment of ecological buffer zones along park peripheries. Here, unmown strips with tall grasses are maintained, serving as refuges for birds and small mammals while simultaneously improving ecological connectivity across the landscape [30], [31]. These examples clearly highlighted that renewable energy production and biodiversity conservation are not mutually exclusive objectives. Conversely, the integration of ecological practices into solar park management enables a synergy between sustainable energy generation and the protection of natural resources. This will allow solar parks to function concurrently as energy infrastructure and as semi-natural habitats.

The restoration of the solar park should be in line with the objectives of SPA BG0001014 Karlukovo

The restoration of the solar park as a natural habitat should aim to achieve consistency with the objectives of SPA BG0001014 Karlukovo, where the primary conservation focus is maintaining natural European habitats. Particularly significant among these are the semi-natural dry grasslands and scrub communities on calcareous substrates (6210), sub-Pannonian steppe grasslands (6240*), eastern sub-Mediterranean dry grasslands (62A0), subcontinental peri-Pannonian scrub (40A0*), and rupicolous calcareous grasslands (6110*). Restoration should be based on the principles of using local seed material and adaptive management through grazing and mowing, as well as systematic monitoring of results [20], [23].

In Zone 1, the conditions are semi-shaded with relatively high soil moisture retention. These conditions provide favorable prerequisites for restoring grass-legume communities with deep root systems that stabilize the soil and accumulate organic matter. Suitable species include *Festuca rupicola* and *Elymus hispidus*, combined with *Lotus corniculatus* and *Trifolium* spp. The introduction of individual shrubs such as *Rosa canina* and *Crataegus monogyna* would support the development of a mosaic resembling scrub formations characteristic of habitat 40A0*. Management through minimal grazing and late mowing would allow successful seed set and the maintenance of long-term stability [22]. Minimal grazing and late mowing would allow successful seed set and maintain long-term stability [22]. In Zone 2, where the microclimate is most balanced and conditions are favorable for richer floristic communities to develop, establishing grasslands with a high proportion of forbs and legumes is recommended. Including *Thymus pannonicus, Salvia nemorosa*, *Origanum vulgare,* and *Achillea millefolium* would provide a food base for pollinators. The targeted introduction *of Stipa capillata, Adonis vernalis*, and *Dictamnus albus* would bring the composition closer to the target habitats 6210 and 6240*. Management through low-intensity rotational grazing and restricted mowing (no more than twice a year) would maintain a mosaic structure and create conditions for conserving orchid diversity [25]. In Zone 3, which is exposed to direct solar radiation and extreme drought, restoration measures should focus on establishing xerophytic steppe communities. *Stipa* spp. and *Festuca valesiaca*, combined with calciphilous taxa characteristic of habitats 6110* and 6240*, would facilitate the development of resilient grassland assemblages. Sowing wildflower strips would

create biocorridors linking the park to the surrounding SPA BG0001014 Karlukovo, thereby supporting pollinator populations [15]. Limited and late mowing, combined with controlled grazing at the end of the growing season, would stabilize the soil and prevent erosion. Creating a vegetation mosaic should be accompanied by measures to support animal species of conservation concern. Melliferous and aromatic plants will sustain pollinator communities, while open and semi-open areas will provide habitats for rare birds and reptiles. Shrub belts would offer refuge for small mammals and enhance structural diversity.

Management practices for restoration

Management practices for restoring and maintaining the solar park as a natural habitat should align with the microclimatic conditions of each zone and the conservation requirements within SPA BG0001014 Karlukovo. A key principle is to implement a differentiated approach combining grazing, mowing, controlling invasive species, and creating a mosaic vegetation structure. This will help to strike a balance between biodiversity restoration and the long-term stability of the ecosystem. Erosion control measures that retain moisture and create conditions for stabilizing vegetation cover play a pivotal role [32]. The restoration program should be gradual: first, establishing a basic grass–legume and xerophytic cover (years 1–2); then, enriching with priority species and introducing targeted management practices (years 3–5); finally, maintaining and stabilizing a habitat mosaic (years 6–10). This would enable the park to evolve into a semi-natural habitat that is compatible with SPA BG0001014 Karlukovo habitats.

The effectiveness of restoration activities should be systematically monitored through soil moisture measurements, floristic surveys, and the detection of diagnostic species of the target habitats. Success will be measured by increases in species richness and the occurrence of taxa characteristic of habitats 6210, 6240*, and 62A0, as well as improvements in soil organic matter and enhanced pollinator activity. In this way, the park can be transformed into a semi-natural habitat that complements the regional ecological network and integrates renewable energy generation with biodiversity conservation [27], [28], [29].

Risks to restoration processes

Alongside the restoration potential, a number of risks need to be addressed. Invasive species may occupy niches in the event of an altered microclimate or nutrient-poor soils, necessitating systematic control. Maintaining a viable seed bank is essential for long-term success, as the limited calcareous soils do not guarantee natural recovery without additional seeds. There are also social and economic barriers, including the cost of local seed material, the need for continuous monitoring, and the acceptance of ecologically oriented practices by solar park owners and operators.

These risks and measures must be considered in the context of SPA BG0001014 Karlukovo, where priority habitats such as 6210, 6240*, 62A0, 40A0*, and 6110* are conserved. Successful restoration of the park will be significant not only locally but will also contribute to maintaining the connectivity and resilience of the Natura 2000 ecological network. This will transform photovoltaic panels into a buffer zone that supports biodiversity conservation objectives.

Conclusion

The study confirmed that the microclimatic conditions created by the arrangement of photovoltaic panels generate spatial heterogeneity that can be utilized for habitat restoration. A comparative analysis of the target habitat types of SPA Karlukovo (6210, 6240*, 62A0, 40A0*, 6110*) revealed substantial similarities, although the absence of several diagnostic species indicates the need for targeted enrichment measures. These findings suggest that solar parks could serve a dual purpose by combining renewable energy production with biodiversity support, thereby strengthening their role in achieving climate neutrality and nature conservation. Using adaptive restoration practices that take into account the microclimate could transform such facilities from potential ecological risks into territories that align renewable energy development with European conservation objectives.

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