

A. Final Report: ESS project BioPV

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1. Project Summary

Project Title: Photovoltaics, Humans and the Biosphere: A transdisciplinary approach fostering Alpine resilience (BioPV)

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Executive Summary:

BioPV set out to integrate techno-economic, ecological, and social dimensions to develop a comprehensive planning framework for ground-mounted photovoltaics (GMPV) in Alpine biosphere reserves, addressing the dual crises of climate change and biodiversity loss. The project aimed to generate usable, policy-relevant knowledge through inter- and transdisciplinary collaboration, with transferability to other mountainous regions and strong dissemination to scientific and non-scientific audiences. Core goals included: modelling robust, spatially explicit GMPV potentials for Austria; producing ecological siting criteria and monitoring recommendations; and incorporating social acceptance and energy justice into siting and design through participatory and collaborative planning methods.

High-resolution simulations across five biosphere reserves showed substantial GMPV potential under all scenarios. Even the conservative variant yielded multi-TWh annual generation, indicating reserves can meaningfully contribute to energy targets with economically robust sites. In addition, the team compiled ecological exclusion layers and value classes and developed an ecological sensitivity layer tailored to case regions. Monitoring recommendations link management measures to indicator species to evaluate biodiversity outcomes over time. Evidence and field insights support targeted design and maintenance measures, including structural diversity, seasonal restrictions on works, reduced panel coverage, wildlife-friendly fencing, and corridor integration, to promote species of conservation concern and enhance habitat functions at GMPV sites.

A large-scale survey including a conjoint experiment, complemented by walking interviews, show that meaningful participation, transparent procedures, and fair, locally shared benefits increase perceived legitimacy and support for GMPV. Preferences favoured regional ownership, early communication, and siting that enables regional self-

consumption and energy communities; concerns centred on distribution of financial benefits and wariness of large external investors.

A methodological centrepiece was the LandscapeLab, a serious game and immersive 3D/VR visualization toolkit that integrates techno-economic outputs, ecological conflict potentials, and social dimensions to enable participants to site, configure, and evaluate GMPV systems in real time, including LCOE feedback and biodiversity impact classifications based on plot-level ecological conflict potential. Built with high-resolution spatial data and the Godot engine, the Labs were implemented in five moderated workshops across three reserves, engaging 39 participants from citizenry and key regional sectors. The participatory laboratories improved the understanding of GMPV trade-offs, lowered entry barriers, and facilitated peer-level dialogue between laypeople and experts. Over 90% of participants rated the 3D visualization as appealing and realistic; nearly half reported that the workshops influenced their attitudes toward GMPV; and 86% advocated for more initiatives of this kind. The tool's perceived usefulness extends beyond PV to wind, spatial planning, habitat connectivity, and other infrastructure debates, supporting more informed and equitable local planning.

In addition, BioPV operationalized transdisciplinarity via an advisory stakeholder group including 24 organizations across administrations, NGOs, the energy sector, and biosphere reserve managements and three stakeholder workshops. The workshops were spaced across the project to co-define questions, test tools, and co-interpret results, complemented by ongoing updates and targeted consultations. Stakeholders co-shaped survey design, conjoint attributes, and recruitment. They also guided WebGIS usability and question framing to capture diverse siting preferences and reduce technical barriers to participation. Feedback during the second workshop directly informed the serious planning game's evolution, including visual screens, representation of energy production and goals, and integrating biodiversity indicators into the tool.

The project's dissemination strategy and policy orientation targeted actionable guidance for contested siting, offering a roadmap for decision-makers and aligning with EU and national climate-biodiversity objectives. By emphasizing aesthetic standards, conservation alignment, and participatory siting, BioPV advances UNESCO biosphere reserve guidance and contributes to EU biodiversity and restoration agendas through evidence-based biodiversity assessments at PV sites.

Together, these outcomes show that integrating spatially explicit techno-economic analysis with ecological safeguards and participatory social-scientific methods can identify viable, publicly acceptable GMPV pathways in sensitive Alpine contexts - supporting climate targets while upholding conservation and fostering regional ownership and learning.

2. Key Scientific Outcomes

2.1. Initial objectives

BioPV initially represents an integrated, transdisciplinary effort to study the potential contribution of alpine PV systems in achieving climate neutrality, highlight potential conflicts and synergies, understand viable and acceptable implementation scenarios, and finally, test a meaningful integration of a participatory framework to facilitate the deployment of renewable energy technologies. Framed by the European climate and energy policy goals and national requirements in the energy sector, the project specifically targets the local development of sustainable societies while addressing the current significant loss of biodiversity in alpine regions, positioning ground-mounted photovoltaic (GMPV) systems within two extraordinary current crises: climate change and biodiversity loss.

At its core, BioPV seeks to provide a comprehensive framework for the planning of GMPV in biosphere reserves by integrating techno-economic, ecological, and social aspects in highly sensitive areas of the Alps, with transferability to other mountainous or high-altitude regions (cf. Figure 1). The project concentrates on transition zones of biosphere reserves as a model for sustainable and innovative forms of human development, while recognising that photovoltaic systems integrated into buildings should always be given preference over placing installations in open spaces, and that any open-space siting in transition zones must be in harmony with the biosphere reserve's conservation goals and meet the highest possible aesthetic standards to avoid impairment of the landscape image.

To operationalise these goals, BioPV distinguishes between theoretical, site-independent and practical, case study-related work. The project aims at developing a thorough understanding of implications of GMPV systems on biodiversity, explicitly including opportunities for the promotion of biodiversity through measures tailored to selected organism groups, and delivering a GIS based layer for ecological sensitivity with monitoring recommendations to observe biodiversity promotion in the PV installations. Beginning with a criteria catalogue that defines no-go areas, preferential areas and management measures for promoting biodiversity at PV installations, it aligns siting and management with the avoidance or mitigation of negative ecological impacts based on scientific literature complemented with field data on selected insect groups gathered in study sites of GMPV in the case study regions.

On the techno-economic side, the initial objectives include an upstream potential analysis to determine rooftop and GMPV potentials in biosphere reserves by modelling high spatial and temporal resolution solar yields using slope, roof surface, altitude, land-use and distance to feed-in points, and calculating levelized costs of electricity (LCOE) to derive robust, technically and economically feasible potentials. Crucially, this potential is then refined by integrating GIS data with ecological rating values and data about social acceptance, thereby reducing the theoretical potential to one that is techno-economically, ecologically and socially feasible.

BioPV foregrounds determinants of social acceptance of PV systems in alpine regions among stakeholders and the local community, using qualitative and quantitative social-scientific methods, including walking interviews, a large-scale quantitative survey, and a conjoint study to capture preferences and trade-offs around size, location, ecological impact, and participation. The project explicitly recognises that deployment does not only rely on geographic, economic or ecological factors, but also on the acceptance of local population, stakeholders and decision-makers including aesthetic and landscape aspects, and intends to feed key acceptance parameters back into the recalculation of potentials.

A defining objective is to test a meaningful integration of a broader public in a participatory framework with public participatory GIS (PPGIS) and immersive VR technologies as essential tools to integrate laypersons' voices into expert debates and foster the acceptance of planned PV infrastructure. Through participatory planning, laboratories, gamification, public participatory GIS and immersive VR technologies, BioPV aims to develop and assess GMPV scenarios with participants from the region that would be immediately affected. This participatory orientation is embedded in the early establishment of an advisory stakeholder group, tasked with finalising research questions and selection of case study regions, providing input on preliminary results and analyses, and acting as a multiplier to broaden engagement and stimulate a fruitful transaction between the researchers and stakeholders.

The project's inter- and transdisciplinary objective is formalised through the intense collaboration of researchers from different disciplines (interdisciplinarity), and the interaction with stakeholders as well as the production of usable knowledge (transdisciplinarity). Adhering to strong sustainability, BioPV intends to propose actions that ensure the functioning of ecological systems while promoting sustainable development, thereby contributing to the "EU's biodiversity strategy for 2030" and "Austria's target of climate neutrality in 2040".

From the outset, BioPV positions dissemination as part of its objectives: a detailed knowledge transfer and dissemination plan, a project webpage, informational events for citizens, a webinar, and a major event presenting the final results to the public, press and interested stakeholders. The project also targets four scientific papers and aims to treat the knowledge production as a function of interaction between knowledge producers and users.

Finally, the initial objectives explicitly include policy relevance and transferability. BioPV seeks to deliver policy implications for the challenge of socially contested siting processes, and a multi-layered roadmap to the siting of PV systems in Austrian alpine regions and biosphere reserves, offering potentials, processes, and methods that support decision-makers. By ensuring transferability beyond the case studies, the project aims to promote social learning and improve the integration of diverse demands into the deployment and diffusion of renewable energy technologies.

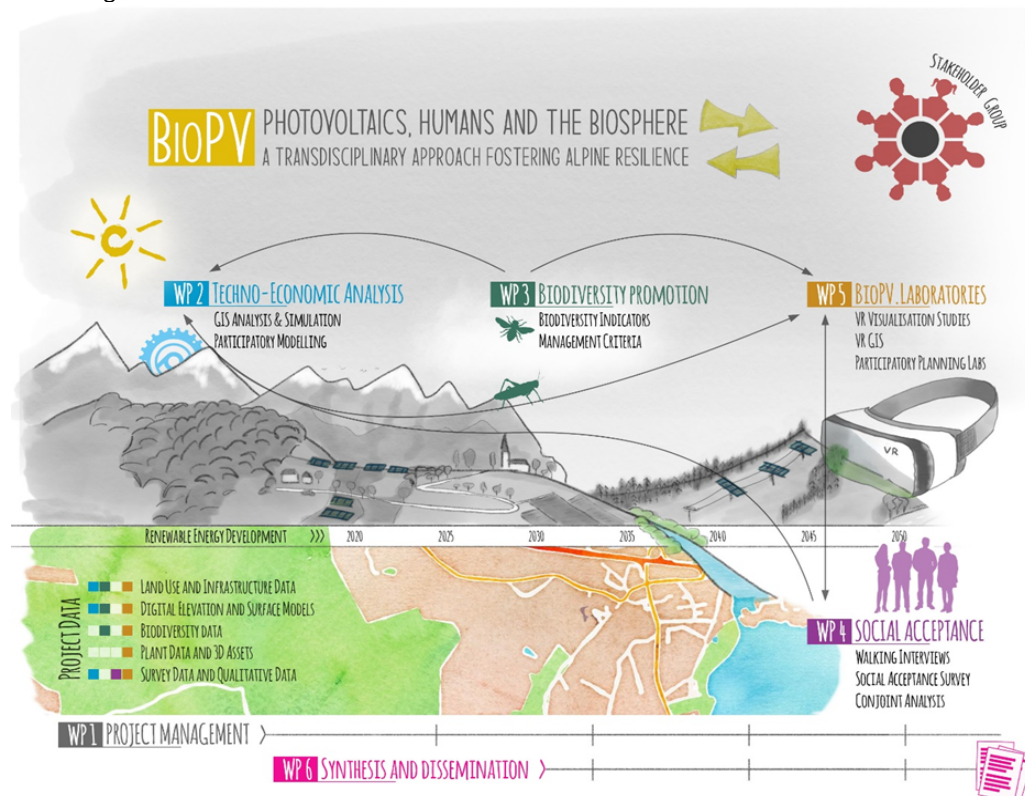


Figure 1: Structure of BioPVs workflow and work packages

2.2. Methods used/developed

Techno-economic modelling of the potential for ground-mounted PV systems in Austrian biosphere reserves

The analysis was conducted across five Austrian biosphere reserves representing diverse Alpine, pre-Alpine and floodplain alluvial lowland conditions: Großes Walsertal (192 km²), Lungau (1,009 km²), Nockberge (485 km²), Unteres Murtal (132 km²), and Wienerwald (1,056 km²). These protected areas combine conservation goals with sustainable regional development, making them ideal case studies for integrating renewable energy deployment with ecological and social considerations.

As a first step we performed a literature review which investigates the current state of knowledge on siting criteria for GMPV systems. The review analyses existing methodologies, tools, and models employed in site assessment and prioritization, with a particular focus on the integration of geographic information systems (GIS) data.

Based on the literature research (6,000 scientific publications were identified, thereof 448 selected for detailed analysis) we created a comprehensive overview of parameters when determining the location for GMPV systems, categorized into five main areas: solar radiation; land & topography; economics; infrastructure; and natural hazards. For the transdisciplinary assessment of further criteria see section 3.2.

The framework integrates geospatial tools and algorithms to process and analyse several different datasets, e.g. topography, land use, solar irradiation and electrical infrastructure such as transformer stations.

We operationalized the suitability and techno-economic feasibility through a differentiated assessment system that links technical and economic factors and reports results under three variants (Maximum, Medium, Minimum) (see Table 1 in Mikovits & Wiesenhofer 2025 / BioPV Factsheet #1 where all the criteria for the assessment are listed).

Biodiversity promotion

A systematic literature search was carried out via Scopus for the period 2012 to 2023 and double checked with Research Rabbit resulting after screening of keywords and abstracts in 93 articles (for more details see Hainz-Renetzeder et al. 2025).

Based on the IACS dataset used in the techno-economic assessment, we identified the IACS agricultural uses most likely being available for High Nature Value farmland (HNV) categories used by Bartel et al. (2011) and classified them into three categories. IACS categories classified as potentially highly valuable include mainly extensively used grassland, landscape structure elements such as hedges, ponds, or stone walls and fallow land. Valuable categories include mainly different types of grassland uses of medium intensity. All other categories include intensive agricultural activities (different types of arable land like crop, vegetable and energy biomass production). By spatially overlaying both layers (i.e. PV potential and HNV farming) in QGIS 3.34, we could identify conflict potential in the biosphere reserves.

For the field work and sampling of indicator groups we selected three existing GMPV systems for each biosphere reserve and nine reference areas that most closely corresponded to the landscape context and the previous land use before the GMPV was installed. Using the transect method, different microhabitats within the GMPV system (front edge, rear and below the panels, as well as the outer area and any special structures such as dead wood or hedges) and the reference areas were sampled for three indicator groups (wild bees, grasshoppers, butterflies) in five survey rounds (summers 2023, 2024) and the organisms were recorded in terms of species and number.

Statistical analysis was done in R 4.1.3.

A list of GIS-Layers on ecological value was prepared as input for the techno-economic modelling and the LandscapeLabs. Some layers were defined as exclusion zones for GMPV systems, others were classified into their ecological value. For the Biosphere reserves Wiener Wald, Natura-2000-habitats were available, for the Lungau, a biotope mapping and the Red List of biotopes in Austria could be used for ecological classification.

Analysis of social acceptance

Data were collected in January 2025 through a structured online survey incorporating a choice-based conjoint (CBC) experiment among a quota-based sample of Austrian residents living in or near three biosphere reserves. Recruitment and participant incentives were managed by a professional panel provider, and informed consent was obtained from all respondents. Quality controls comprised RLH-based exclusion of near-random conjoint responses (threshold 0.34) and removal of excessively fast completions (below 50% of median completion time), resulting in a final sample of 512 respondents and a median duration of about 13 minutes.

The questionnaire included socio-demographic variables (age, gender, education, political ideology, postal code) and psychometric scales measuring environmental concern, familiarity and place attachment, support for renewable technologies, perceived impacts of GMPV, activism intentions, energy justice orientations, and beliefs and norms. Exploratory factor analyses resulted in reliable subscales (Cronbach's alpha $\geq .69$). The CBC experiment varied five GMPV attributes - biodiversity measures, visibility, land use type, distributive justice mechanisms, and procedural participation - each operationalised at three levels across 12 choice tasks, supported by brief explanations and VR visualisations.

Conjoint data were analysed with hierarchical and mixed logit models to estimate part-worth utilities and attribute importance. Support for GMPV in biosphere reserves was modelled via multiple linear regression with psychological, social, and justice-related predictors, including checks for multicollinearity and residual autocorrelation.

In addition, a systematic literature review to examine the body of research on social acceptance in the context of GMPV was conducted. The review includes 65 research articles and focuses on the following research questions: Which theoretical conceptualizations are used in social acceptance research on GMPV? Which critical approaches and conceptualizations can be found? Which aspects and issues of public opposition and support are discussed in the context of GMPV?

To investigate local experiences and knowledge, 8–9 qualitative, semi-structured walking interviews per study region were conducted in July 2024, guided by literature on social acceptance and energy justice. Walking interviews along interviewee-chosen routes facilitated engagement with spatial dimensions. We selected 3–4 municipalities per biosphere reserve based on the tentative PV potential assessment and consultation with reserve management. Participants were identified via reserve managers, municipalities, and local organisations, aiming for a balance of stakeholders/decision makers and citizens (cf. Table 1).

Table 1: Overview of the walking interviews conducted in the three case study regions

	Lungau	Unteres Murtal	Wienerwald
Number of interviews	8 (4+4)	9 (5+4)	8 (4+4)
Time frame	22.-25.7.2024	23.-26.7.2024	11.-30.7.2024
Local residents' backgrounds	agriculture social profession local business (electrical installations recreation) nature conservation	agriculture military beekeeping forestry healthcare profession nature conservation biology banking energy community	retirement beekeeping hunting agriculture journalism village renewal small trade energy community
Local stakeholders' backgrounds	community politics tourism regional management biosphere reserve management	community politics agriculture hunting	community politics regional management energy sector agriculture hunting

The interviews were recorded and subsequently transcribed using the open-source AI-tool “noScribe”. The transcripts were checked for accuracy and corrected by the researchers where necessary and were then imported into MaxQDA for coding. We conducted a qualitative content analysis along key dimensions of energy justice, combining deductive coding based on the energy justice literature with inductive coding where appropriate.

BioPV-Laboratories

With the BioPV-Laboratories (‘LandscapeLab’) a novel approach was developed and tested for collaborative PV scenario development in three different biosphere reserves.

In the laboratories participants interact with a virtual map projected onto a table using simple game bricks to determine Go-/No-Go areas for PV expansion or to collaboratively plan and visualise PV installations. Different PV system parameters can be altered, to examine potential impacts or synergies on landscape and biodiversity. PV systems are immediately shown in immersive 3D on a projector or via VR glasses (cf. Figure 2).

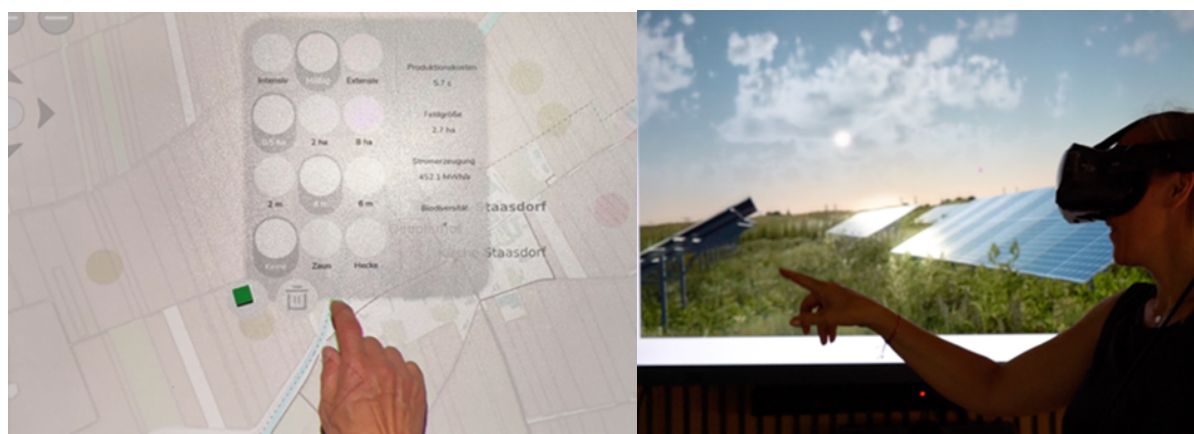


Figure 2: virtual map, game brick, and parameter configuration (left); 3D visualization and VR (right).

Developed with the Godot game engine, the toolkit supports high-quality interactive 3D and VR. Key data sources:

- Digital Terrain Model/Digital Elevation Model (grid, 1 m, BEV)
- Land Cover (raster, 1 m, INVEKOS, Copernicus, OpenStreetMap)
- Building polygons (vector, OpenStreetMap)
- Road network (vector, OpenStreetMap)

Five moderated workshops in Lungau, Unteres Murtal, and Wienerwald examined techno-economic, ecological, and societal aspects of regional PV siting. Thirty-nine participants included citizens and stakeholders from regional management, nature conservation, renewable energy, agriculture, spatial planning, and local politics. Invitations were guided by stakeholder mapping and key actors could nominate additional participants. Citizen labs were advertised via local websites and stakeholders; each lab involved 6–10 participants.

The game first identified suitable and exclusion zones considering economic, ecological, and societal aspects, then interactively visualized expansion scenarios, system designs, sizes, and management strategies. Participants evaluated options and discussed impacts relative to energy transition goals, biodiversity effects, and societal considerations. Questionnaires captured attitudes, knowledge, engagement, and workshop feedback (for more information on the toolkit see also section 2.7).

2.3. Achievements and new insights

Techno-economic modelling of the potential for ground-mounted PV systems in Austrian biosphere reserves

The simulations indicate substantial GMPV potential across the five biosphere study regions across all three scenario variants (see Mikovits & Wiesenhofer 2025 / BioPV Factsheet #1). In the Maximum scenario, permissive thresholds identify suitable agricultural land (alpine pastures, grassland, and arable land) up to more than one hundred square kilometres per reserve, translating into multi-TWh annual generation (cf. Table 2). As constraints and cost caps tighten in the Medium and Minimum variants, the technically viable area contracts; however, the remaining sites offer improved economic profiles with lower LCOE. Ultimately, the conservative scenario still yields a multi-TWh annual potential, suggesting that biosphere reserves can contribute significantly to energy targets without the need for marginally economic sites.

Spatially, the results highlight marked differences between biosphere reserves. Regions such as Nockberge and Unteres Murtal combine favourable solar resource, relatively low forest cover and short average distances to substations, which leads to both comparatively high area potentials and low LCOE across all scenarios. By contrast, more mountainous or densely forested reserves show a stronger sensitivity to the scenario assumptions: increasing slope-related cost uplifts and compactness penalties removes a larger proportion of parcels from the feasible set. These patterns underline the importance of explicitly representing terrain, land-use structure and grid topology in PV siting, as purely radiation-based screening would overestimate the economically usable potential.

Table 2: Results on the techno-economic potential in the biosphere reserves

Scenario	Biosphere reserve	Großes Walsertal	Lungau	Nockberge	Unteres Murtal	Wienerwald
	Total area (km ²)	192.0	1009.0	485.0	132.0	1056.0
max	GMPV potential (km ²)	13.6	106.4	251.0	36.9	93.7
	Electricity generation (TWh / year)	1.2	8.6	8.3	4.2	9.7
	LCOE (€ / kWh)	5.4	5.3	4.8	4.3	4.9
med	GMPV potential (km ²)	8.0	72.4	66.7	26.5	74.1
	Electricity generation (TWh / year)	0.8	5.8	6.5	3.1	7.7
	LCOE (€ / kWh)	5.0	5.1	4.7	4.2	4.7
min	GMPV potential (km ²)	4.2	36.6	46.2	20.7	54.6
	Electricity generation (TWh / year)	0.4	3.2	4.3	2.4	5.6
	LCOE (€ / kWh)	4.8	4.7	4.6	4.1	4.6

In addition, the analysis of rooftop and parking-lot PV indicates that already sealed surfaces can provide a non-negligible supplementary contribution to regional PV generation, particularly in more urbanized biosphere reserves (cf. Table 3). While the absolute potentials on buildings and car parkings are small compared to ground-mounted scenarios, they are associated with minimal additional land-use conflicts and can therefore play a strategic role in integrated deployment strategies. In aggregate, the combination of high-quality ground-mounted sites and targeted use of sealed areas offers a robust pathway to upscale PV in biosphere reserves while respecting both economic constraints and competing land-use objectives.

Table 3: Results of the building and parking area analysis

Biosphere reserve	Großes Walsertal	Lungau	Nockberge	Unteres Murtal	Wienerwald
Building area (ha)	51.0	280.0	148.0	244.0	1722.0
Building area suitable for PV (ha)	7.6	42.0	23.8	36.6	258.3
Electricity generation (GWh / year)	0.009	0.054	0.031	0.053	0.339
Parking space suitable for PV > 500m ² (ha)	2.7	27.0	20.0	13.2	86.3

Electricity generation (GWh / year)	0.002	0.023	0.017	0.012	0.074
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Biodiversity promotion

The results of overlaying GMPV potential with HNV categories show that there are large differences among the biosphere reserves, with “Unteres Murtal” having large areas with high PV potential and low HNV values available (Figure 3). Also, the Lower Austrian part of the Wienerwald biosphere reserve shows a high amount of priority areas. The share of highly valuable farmland with high PV potential is rather small and should therefore be excluded from any construction activities.

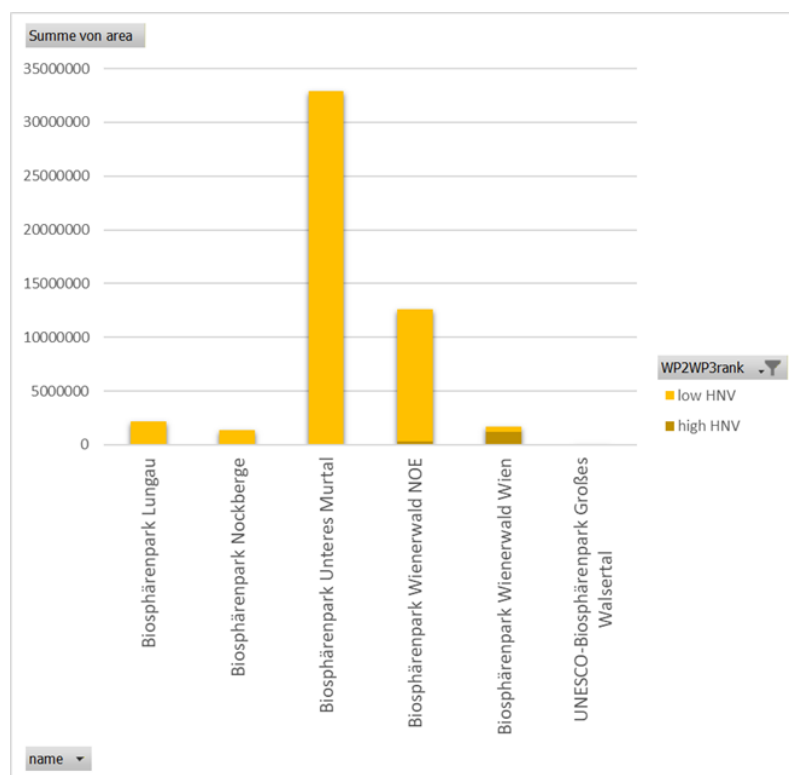


Figure 3: Total area in m², where high PV potential is overlaid with HNV values, shown for each biosphere reserve. Low HNV values indicate areas where the installation of GMPV systems should be prioritised in a manner compatible with biodiversity (priority areas). On the other hand, construction of PV systems should be avoided in areas with high HNV (conflict areas).

For the field work and sampling of indicator groups, the nine selected GMPV systems varied in size (400 m² to 30,000 m²) and land use history (e.g., arable land, grassland). Nine control areas with similar surroundings and land use served as comparisons. A total of 122 wild bee species (17% of the 700 species found in Austria), 46 butterfly species (36% of Austria's 208 butterflies) and 39 grasshopper species (19% of Austria's 127 species) were observed during the field surveys (Hainz-Renetzeder et al. 2025 / BioPV Factsheet #2).

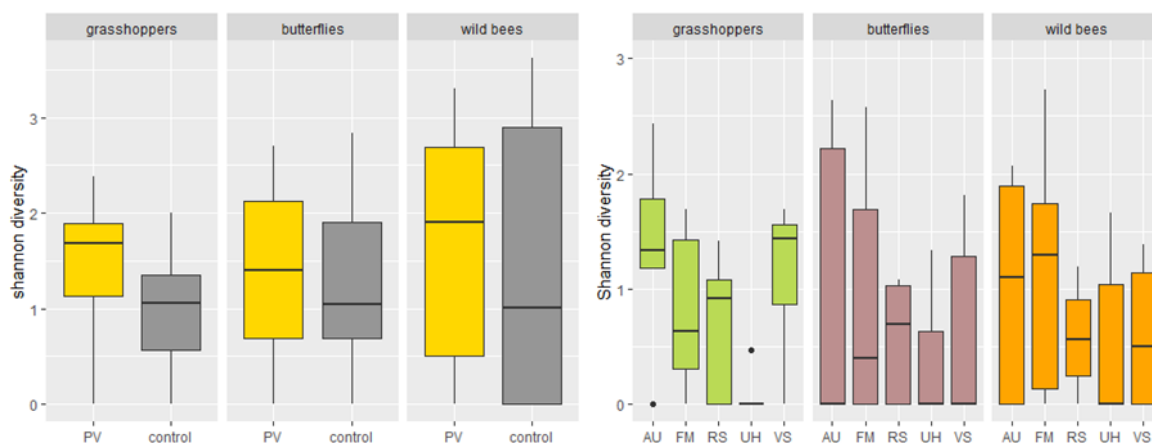


Figure 4: left) Shannon diversity index (representing biodiversity) of the three indicator groups in the GMPV systems (PV) and reference areas (RE); right) Shannon diversity index of the three indicator groups in the different transects of the GMPV systems; AU: outside of the panel areas, FM: special structures for promoting biodiversity, RS: backside of the panels, UH: below the panels, VS: front side of the panels

The Shannon diversity index (a commonly used index to measure biodiversity) of all three organism groups showed a large variation, both inside the GMPV systems and the reference areas (cf. Figure 4 left). This can be explained by the varying design and management of the sites. Within the GMPV systems, it was found that the transects outside

the rows of panels and the special structures for promoting biodiversity are particularly species-rich, while the areas below the panels tend to be species-poor. The front edge of the panels is rich in flower abundance and flower visitors in dry locations. In contrast, in moist locations, grasses dominate due to high nutrient input resulting in lower flower abundance and fewer wild bees and butterflies, but more grasshoppers than on the back of the panels. Based on these results and supported by literature, GMPV systems can serve as potential habitats for various species if they are designed and maintained appropriately (Hainz-Renetzeder et al. 2025 / BioPV Factsheet #2). The results underscore the need to integrate ecological measures into the planning and maintenance of such facilities to promote biodiversity while ensuring energy production. In addition to careful site selection, the following policy recommendations in the field of biodiversity promotion are formulated:

- Preservation and promotion of existing biotope structures
- Leaving areas unmaintained
- Creation of scrubby areas
- Creation of open ground areas
- Preserve and promote structural diversity: e.g., with deadwood, hedges, and stone piles
- Creation of perches and nesting habitats
- Creation of diverse flowering areas through site-adapted, alternating mowing
- Creation of diverse flowering areas through sowing with species-rich, autochthonous seeds
- No construction work during breeding and spawning seasons
- Maximum 40-50% area coverage by the panels
- Ideally no fencing, if unavoidable - minimum distance to the ground 15-20 cm - avoidance of barbed wire
- If greening of the fence elements is planned: Privacy hedge with a width of approx. 5 m, planted with plants native to the area that are adapted to the location. Rows of trees, hedges or ditches are preferable alternatives to fences.
- Migration corridors: Crossing aids for animals or embedding of corridor areas in large-scale facilities
- Minimization of soil compaction and displacement

Analysis of social acceptance

The survey shows that the way land is used for GMPV is the single most important design factor for public support, followed by biodiversity measures and visual exposure. Land use type had the highest relative importance (35.86%), outweighing biodiversity (21.65%), visibility (19.42%), procedural (12.57%) and distributional justice (10.51%). Residents strongly preferred GMPV on sealed or pre-impacted areas and near existing infrastructures (utility 73.33), while projects on ecologically valuable land were strongly disfavoured (-58.42), and installations on arable and grassland were moderately negative (-14.91). Siting on brownfields or already impacted land is central to acceptance; intrusions into high-value nature are least acceptable.

Biodiversity measures mattered: extensive measures were clearly positive (28.56), some measures positive (9.01), none strongly rejected (-37.57). Visual impacts showed a similar gradient: visible from living areas disliked (-32.30), only from paths/roads slightly positive (9.47), non-visible preferred (22.83).

Energy justice features were less influential. A citizen participation model with a share of returns was preferred (13.10), a one-off payment negative (-12.37), energy community membership neutral (-0.72). Information-only processes were negative (-13.95), while feedback (5.03) and a tangible say (8.92) increased support, indicating meaningful participation and ongoing, collective benefit-sharing over one-time compensation.

Regression results ($R^2 = .571$, adjusted $R^2 = .551$) showed intentions to engage in renewable energy activism as the strongest positive predictor ($\beta = .418$, $p < .001$), followed by perceived social norms ($\beta = .221$, $p < .001$). Positive impact perceptions ($\beta = .114$, $p = .003$) increased support; negative impact perceptions decreased it ($\beta = -.121$, $p = .004$). Other variables were not significant. For more details see Sposato et al. 2025 / BioPV Factsheet #3.

Qualitative interviews explored local citizens' and stakeholders' experiences, preferences and problem perceptions regarding GMPV in biosphere reserves, and examined distributive, spatial, procedural and recognition justice. Interviewees strongly preferred siting GMPV on already built-up or contaminated areas (rooftops, parking lots, brownfields) rather than open land, arguing that agriculturally valuable land should be reserved for production; some saw opportunities on marginal land with steep slopes or poor soils. Participants discussed potential land use conflicts and synergies with nature and biodiversity conservation, supported expert assessment of biodiversity impacts, and trusted existing spatial planning. In areas perceived as ecologically low-value (e.g., large corn fields around Unteres Murtal), many emphasized biodiversity co-benefits, expressing broad interest in dual land use formats such as Agri-PV or biodiversity-oriented designs to raise acceptance.

Visual impacts were widely debated and context-dependent: installations are less conspicuous in flat landscapes (Unteres Murtal) than in hilly regions like Lungau, and regional identity shapes perceptions. Preferences emerged for smaller projects and careful visual integration (following hill lines, using hedges or barriers). Views diverged on distance to infrastructure or settlements: remoteness can hide projects, while proximity can limit new roads and grid needs.

Distribution of financial benefits was important; envy over profits could fuel opposition, while citizen co-investment and profit-sharing were seen as fair. Many trusted existing governance and worried that extensive direct participation could complicate decisions, yet residents wanted more transparent, early communication and opportunities to engage. Interviewees favoured locally or regionally owned projects, viewed large (inter)national investors as profit-focused, and supported goals like energy independence and self-sufficiency mainly at the regional level, while contributions to national targets were more contested, with a preference to produce electricity near where it is used.

BioPV-Laboratories

The LandscapeLab combines the outputs from all the other BioPV workpackages and allows players to interact with them by siting and configuring photovoltaic plants, based on a game logic developed in an iterative inter- and transdisciplinary process together with project partners and stakeholders. A brief overview is given in Figure 5.

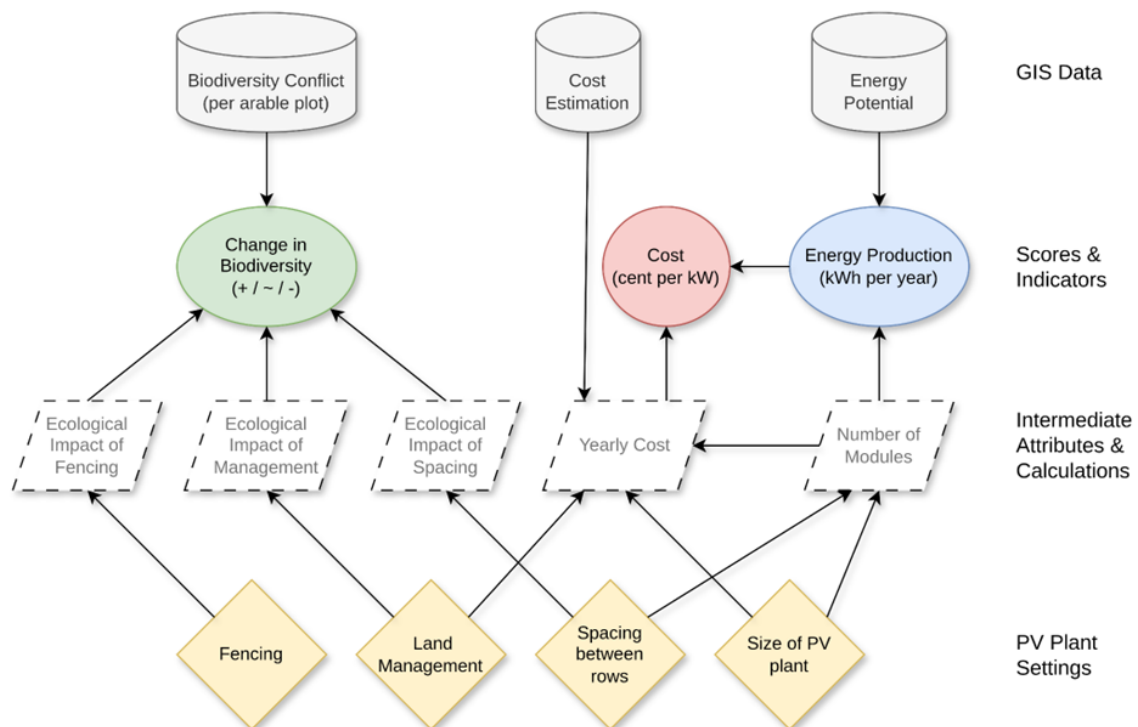


Figure 5: Flow chart diagram of the serious game logic, showing how GIS datasets are connected to attributes and user inputs.

Ecological data were integrated by assigning an Ecological Potential for Conflict (EPFC) to each agricultural plot (from IACS) as part of the spatial analysis for biodiversity promotion. Each adjustable PV option was then classified for biodiversity impact (positive, negative, or neutral) based on the EPFC of the plot's previous land-use. For example, extensive ecological management has a positive biodiversity impact on plots with low or medium EPFC, but a negative impact on plots with high EPFC.

Using outputs from the techno-economic model, the total energy production is calculated for each virtual PV system created in the labs. Combined with the system's total cost we derive the LCOE (ct/kWh) and display it to the participants on the interactive gameboard.

To show a PV system's visual impact, every configurable parameter is represented accurately in the landscape visualization (cf. Figure 6).



Figure 6: Visualization of different management methods of PV fields: intensive (left, graveled and regularly mowed, distance of 2m between modules), medium (center, mowed and mulched, 4m between modules), and extensive (right, measures taken to promote flowering plants, 6m between modules).

The results of the case-study laboratories emphasize the strong interconnection among ecological, economic, technical, political, and social aspects, and show how different, sometimes conflicting, interests intersect (cf. Figure 7). The key criteria and decision-making factors can be grouped into three main areas: landscape and ecology, society, and technology and economics.

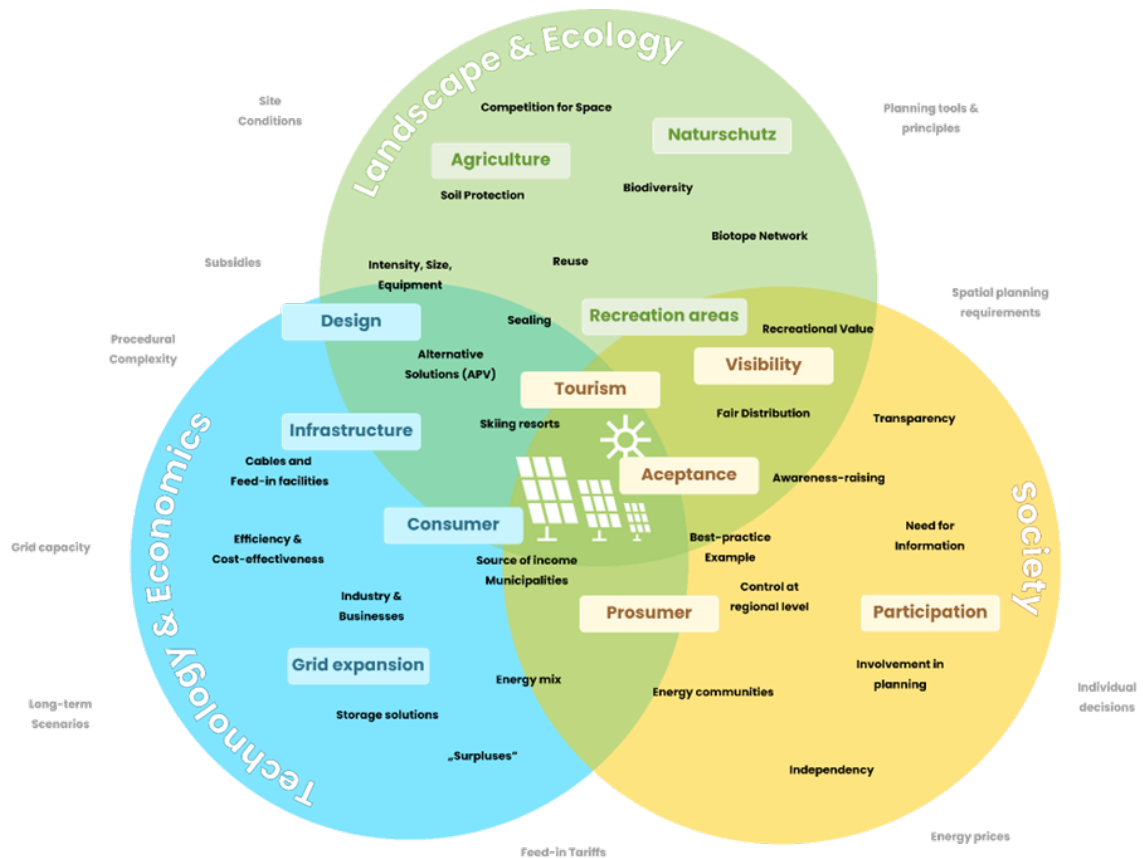


Figure 7: Key areas of decision making and site selection criteria for the expansion of GMPV resulting from the case-study laboratories.

Lab discussions focused on how to expand GMPV while protecting farmland, especially high-quality soils. Key concerns were visibility near homes, recreation areas, and tourist sites, along with biodiversity impacts. Many also saw chances to use PV sites to improve habitat connectivity. Proximity to existing energy infrastructure and the costs for grid expansion was critical across all project areas. There was broad support for siting near existing infrastructures (e.g., ski lifts) and along motorways and railways. Perceptions of aesthetic and ecological value differed by region. In tourism- and recreation-oriented regions (Lungau, Wienerwald), appearance, visibility and impact on landscape aesthetics were central. In intensively farmed areas with existing PV sites (Unteres Murtal), these considerations were secondary. Integrating renewables into spatial planning was seen as essential for planning certainty and better decisions. Where official PV development zones were defined (Styria/Unteres Murtal), it guided expansion and allowed larger, more numerous sites. Where guidelines were less prescriptive, discussions were broader and planning developed more cautiously. The findings underscore that public acceptance improves when people can participate in the planning process and when there are opportunities for regional energy consumption. Participants stressed the importance of co-creation, transparency and fair allocation between municipalities and regions. They expressed strong support for self-consumption and energy communities, and discussed regional self-sufficiency, and justice questions (where projects are located, who develops them, and who benefits).

2.4. Discussion of Findings in Relation to Recent Scientific Discourse

Scientific literature on the impact of GMPV on biodiversity is scattered and scarce (Gómez-Catasús et al. 2024, Lafitte et al. 2022). In BioPV, we added to these reviews and focused on the Central European conditions to specify the knowledge gaps. Additionally, we evaluated on how the possible biodiversity impacts of GMPV systems are addressed in spatial planning and spatial siting criteria in Austria. Direct impacts on biodiversity still show large variation and ambiguous results (Table 4), thus planning and the formulation of mitigation criteria also varies a lot.

Table 4: Number of articles dealing with indirect and direct impacts on biodiversity; articles include statistical as well as conceptual and review papers, number of statistical papers in brackets. Biodiversity level studied include different biodiversity indicators as well as spatial models. (Hainz-Renetzeder et al. 2025)

Impacts	Number of articles	Biodiversity level studied	Clarity of results
alteration of environmental conditions	24 (16)	site condition properties	clear results of altered conditions
population composition & diversity	31 (25)	plants, arthropods, bats, birds	large variation in results
habitat loss, degradation and fragmentation	24 (15)	protected areas, wilderness areas, land cover, modelled habitats	ambiguous results
impact on movement and behaviour (resident & migratory species)	7 (4)	pollinators, butterflies, bats	ambiguous results
mortality & collisions	17 (7)	birds, bats, aquatic insects	large variation in results
exotic plant invasions	5 (1)	non-native plants	higher cover of neophytes

Spatial siting criteria for GMPV in Central Europe are guided by the mitigation hierarchy (Kiesecker et al. 2010): first, avoid high-conservation-value areas, then reduce impacts where development proceeds. Guidelines consistently exclude legally protected areas, especially those with high IUCN status; but treatment of valuable habitats outside protected areas is inconsistent across the spatial planning guidelines (Hainz-Renetzeder et al. 2025). Some do not address this issue, while others vary between exclusion and conflict (on-site assessment) zones. Some Austrian planning frameworks label "suitability zones", but inclusion of nature conservation criteria differs greatly among provinces and guidelines. The different regulations within Austria lead to uncoordinated and non-transparent integration of nature conservation into siting of GMPV systems, underscoring the need for a harmonized, evidence-based approach and comprehensive ecological data.

Overall, strategic, standardized conservation planning is required to balance energy expansion with habitat protection in siting decisions.

To overcome this drawback, we used the frame of "High-Nature-Value farmland", a concept emerging in the 1990's (Baldock et al. 1993), which acknowledges that many species are dependent on traditionally extensively used cultural landscapes and related semi-natural elements (Parrachini et al. 2008). Based on the IACS dataset used for the techno-economic assessment, we identified the IACS agricultural uses most likely being available for HNV based on categories used by Bartel et al. (2011). Thus, we identified areas where high PV potential conflicts with high HNV values (conflict areas) or not (priority areas).

The sustainable development of climate change mitigation measures is a good example where biosphere reserves act on the forefront for establishing best-practice examples. The biodiversity-compatible planning, design and management of GMPV systems is also a topic of international interest, e.g. biosphere reserve Rhön (Germany). In scientific literature, Nordberg & Schwarzkopf (2023) as well as Tölgyesi et al. (2023) describe a possible design and associated research gaps for the concept of an "ecovoltaic" (Tölgyesi et al. 2023) or "conservoltaic" (Nordberg & Schwarzkopf 2023) park as a basis for establishing win-win-situation for biodiversity and energy generation. Still a point of criticism is the largely hypothetical approach, as there are major gaps regarding an effective implementation (Tölgyesi et al. 2023): What is the optimal shape and size of a solar park? What is the perfect panel spacing, panel width, panel height? For which organism groups do solar parks act as a barrier? Which seed mixtures and which management fit the local conditions and can effectively generate multiple ecosystem services for the surrounding landscapes? Which factors can be specified generally, and which differ from site to site?

The German Federal Agency for Nature Conservation (2024) stresses the fact that the site conditions, the immediate surroundings and the species found there also play a major role in the development of biodiversity in the GMPV systems. Not every species can be settled everywhere. From a nature conservation perspective, the design and maintenance of GMPV systems should therefore be based not only on ecological criteria but also on target biotopes and species. Target species are species of high conservation importance that need to be given priority protection and promotion in a particular region, for example, the skylark, whinchat, brown hare, or wild bees. Basing the implementation of GMPV systems on these concepts, biosphere reserve could establish best-practice examples for targeted win-win-situations for sustainable climate change mitigation together with solid nature conservation activities.

In terms of social acceptance and energy justice, the results echo international research showing that meaningful participation, transparent procedures, and fair benefit-sharing arrangements increase perceived legitimacy and support for renewable energy projects. The preference for citizen participation models with a share of returns over one-off payments is in line with evidence that long-term, collective benefit schemes are perceived as more just and less "buying off" opposition. The high importance of social norms and activism intentions as predictors of support also dovetails with behavioural and social-psychological studies that emphasise the role of normative climates and collective engagement in energy transitions, suggesting that communication strategies and participatory formats that foster pro-renewable norms and empower local actors can be particularly effective.

In the context of participatory planning, international policy-oriented assessments highlight the potential of co-location approaches (such as agrivoltaics and multi-functional land use) to reconcile climate and biodiversity goals, and the present results suggest that citizens are responsive to such attempts when they are made visible and credible in project design. This is mirrored by the learning experience in the case-study laboratories of BioPV, which was rated very positively by participants. The workshops enhanced understanding of the impacts of ground-mounted PV and fostered collaborative, peer-to-peer learning. Nearly half of participants reported that the workshops influenced their attitudes toward ground-mounted PV. In addition, 86% advocated for more initiatives of this kind in their region (cf. Figure 8). Further potential application areas for the tool included wind energy, habitat connectivity, spatial planning, tourism infrastructure, transport infrastructure, healthcare services, and housing projects and their impacts.

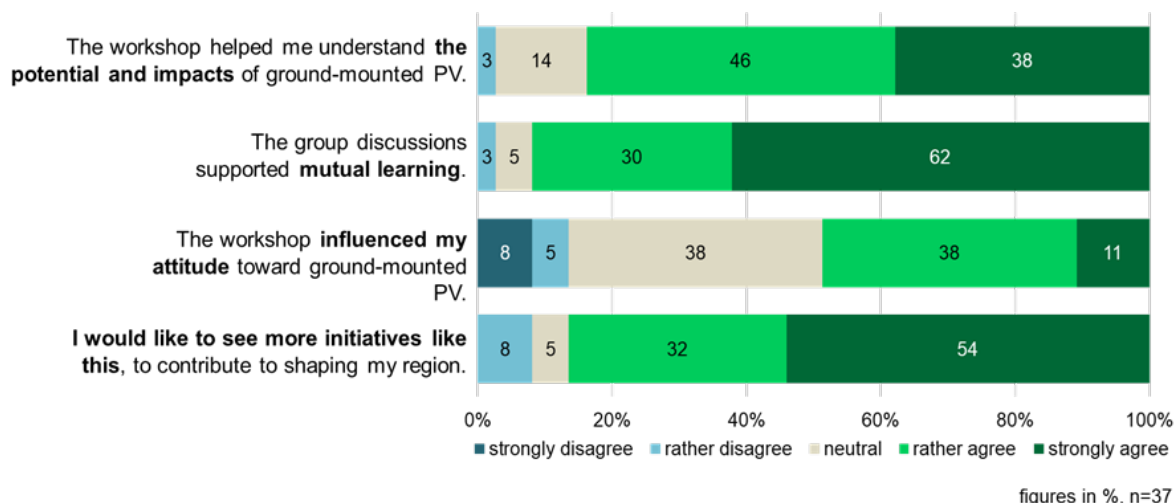


Figure 8: Participant's feedback on the learning experience from the case-study laboratories.

The use of virtual reality renderings in this study further connects to a growing literature on visualisation tools (e.g., PPGIS, scenario maps) that enhance laypeople's understanding of land-use implications and can support more informed and equitable local planning. The technological framework and graphical implementation of the LandscapeLab, used as a planning tool during the case-study workshops, were rated very positively by participants. Over 90% found the graphical quality of the 3D visualization appealing and realistic. Participants considered the interactive map easy to use and were able to navigate and orient themselves well within the 3D environment. Overall, the planning game was perceived as engaging and inspiring, contributing to participants' understanding of the potential and impacts of ground-mounted PV (cf. Figure 9).

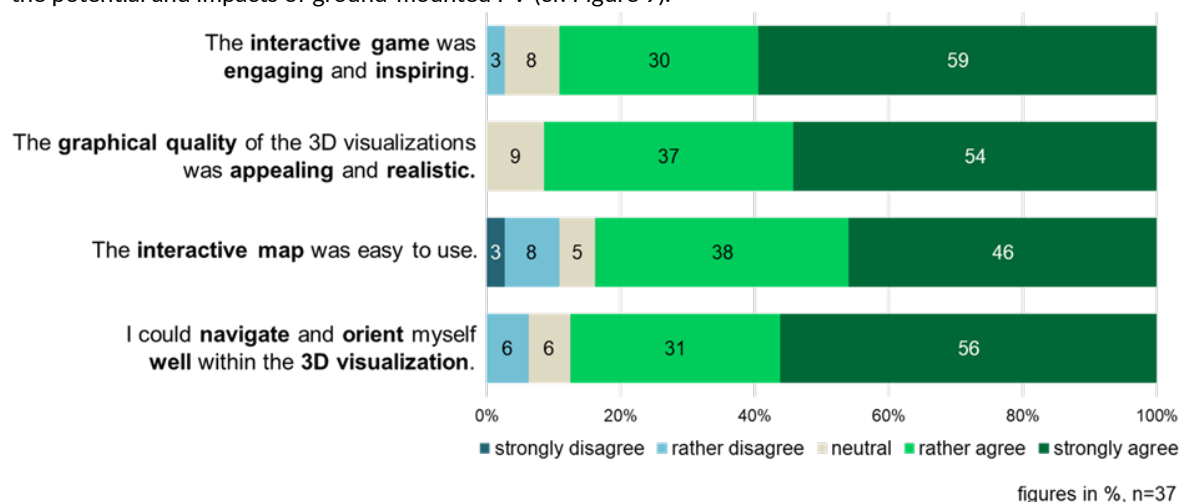


Figure 9: Workshop participants' feedback on the planning game, visualization, and user experience of the LandscapeLab.

The results of the case-study workshops demonstrated that data-driven methods and extensive visualization capabilities enable active exploration of the impacts of ground-mounted PV installations. Moreover, the gamified approach lowers entry barriers and promotes peer-level dialogue between laypersons and experts.

Overall, the study contributes to international debates by linking ecological siting criteria, biodiversity measures, and energy justice dimensions in a single empirical design focused on biosphere reserves, a context where the tensions between renewable expansion and conservation are especially pronounced.

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Gómez-Catasús, J., Morales, M. B., Giral, D., del Portillo, D. G., Manzano-Rubio, R., Solé-Bujalance, L., Sardà-Palomera, F., Traba, J., & Bota, G. (2024). Solar photovoltaic energy development and biodiversity conservation: Current knowledge and research gaps. *Conservation Letters*. <https://doi.org/10.1111/conl.13025>

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Nordberg, E. J., & Schwarzkopf, L. (2023). Developing conservoltaic systems to support biodiversity on solar farms. *Austral Ecology*, 48(3), 643–649. <https://doi.org/10.1111/aec.13289>

Paracchini, M. L., Petersen, J. E., Hoogeveen, Y., Bamps, C., Burfield, I., & van Sway, C. (2008). High Nature Value Farmland in Europe-An estimate of the distribution patterns on the basis of land cover and biodiversity data. <https://data.europa.eu/doi/10.2788/8891>

Tölgyesi, C., Bátor, Z., Pascarella, J., Erdős, L., Török, P., Batáry, P., Birkhofer, K., Scherer, L., Michalko, R., Košulič, O., Zaller, J. G., & Gallé, R. (2023). Ecovoltaics: Framework and future research directions to reconcile land-based solar power development with ecosystem conservation. *Biological Conservation*, 285, 110242. <https://doi.org/10.1016/j.biocon.2023.110242>

2.5. Connection to International Programs (UNESCO, UN, Future Earth, LTER, EU, ect.)

BioPV complies with all four suggestions of the position paper of the Austrian National Committee for the UNESCO Programme ‘Man and the Biosphere’ for using renewable energies and PV systems in particular

- *“Under the development objectives for biosphere reserves in Austria as laid down in the catalogue of criteria for Austrian biosphere reserves, it is prohibited to install any large-scale plant in open spaces in core or buffer zones. [...]*
- *Photovoltaic systems integrated into buildings are permitted in all zones and should always be given preference over placing installations in open spaces.*
- *When planning the siting of photovoltaic plant in open spaces in the transition zone, it is imperative to examine whether the plant would be in harmony with the biosphere reserve’s conservation goals. The installation of such plant in areas of nature conservation value would not be considered compatible with biosphere reserve goals.*
- *When planning the installation of photovoltaic plant in open spaces, the highest possible aesthetic standards will have to be observed in order to avoid any impairment of the landscape image.”*

BioPV makes a major contribution to the mission and targets of this position paper insofar as new forms of human environment interactions could be tested in transition zones and then be implemented beyond. The project focuses on investigating the relationship and potential contradictions of nature conservation, climate protection and renewable energy development. Social and ecological aspects are emphasised, because these issues often prevent projects from being implemented. As the energy transition depends on many local decisions, there is a strong need for better conflict management and participation in planning and decision-making processes. By considering adequate processes to apprehend potential impediments, BioPV offers valuable insights in the field of sustainable energy production while fostering resilience.

Biodiversity assessments in GMPV are becoming increasingly important in the context of current EU strategies and funding programs. Initiatives such as the EU Biodiversity Strategy for 2030, the Common Agricultural Policy (CAP), and the Nature Restoration Law aim to combine the expansion of renewable energy with the protection and restoration of ecosystems. Species surveys of wild bees, butterflies, and grasshoppers in PV systems, like in BioPV, provide essential scientific evidence to evaluate whether, and under which conditions, such installations can contribute to biodiversity conservation. In particular, identifying biodiversity-promoting structures and site-adapted management practices supports the development of nature-friendly PV concepts and can therefore make an important contribution to achieving European conservation and sustainability goals.

2.6. Publications (as of May 2026)

2.6.1 Peer-Reviewed

1. Mikovits, C., Grabner, I., Bauer, A., Kern, T., Kral, I., Schauppenlehner, T., Schmid, E., Schönhart, M., Schmidt, J. (2026). The techno-economic potentials of agrivoltaic installations in Austria, *Renewable Energy* 263, 125494, <https://doi.org/10.1016/j.renene.2026.125494>.
2. Bittner, K., Baumgartinger, M., Schauppenlehner, T. (2026). Playful Complexity: Using a Serious Game with Immersive 3D Visualization to Balance Economy, Ecology, and Landscape Impact of Photovoltaic Plants. *JoDLA – Journal of Digital Landscape Architecture*, 11-2026. <https://doi.org/10.14627/537770026>
3. Hainz-Renetzeder, C., Schauppenlehner, T., Scherhauser, P., & Pachinger, B. (2025). Navigating the Nexus between Renewable Energy and Biodiversity: Impacts and Mitigation Strategies for Ground-Mounted Photovoltaic Systems. *Landscape Online*, 100, 1141. <https://doi.org/10.3097/LO.2025.1141>
4. Hainz-Renetzeder C., Pospisil K., Pachinger B. (2024). Grüne Energie, reiche Insektenwelt? Biodiversität in Freiflächen-Photovoltaik-Anlagen. *Zoll+ Landschaftsplanung und Landschaftsökologie* 44: 56-60.
5. Karner, K., Hainz-Renetzeder, C., et al. (submitted on 2 June 2026 to Environmental Science and Policy). Experts’ and stakeholders’ perceptions on biodiversity impacts of ground-mounted photovoltaic systems and related conservation measures for Austria.
6. Hainz-Renetzeder, C., Mikovits, C., Pachinger B., et al. (in preparation): Conflicts between nature conservation and photovoltaic expansion on high-value farmland: An Austrian case study of affected habitats (Working title)

7. Hainz-Renetzeder, C., Pachinger, B., et al. (in preparation): The importance of design and management of ground-mounted photovoltaics for arthropods (Working title)
8. Sposato, R., Klic, R., Hampl, N. (in preparation): Green Energy, Greener Habitats? Public perceptions of utility-scale photovoltaics in biodiversity landscapes (Working title)
9. Sposato, R., Klic, R., Plöchl, J., Scherhauser, P. (in preparation): Stepping out of the shadow - Social acceptance of Utility-Scale Photovoltaics (Working title)
10. Plöchl, J., Niederhofer, M., Scherhauser, P. (in preparation): Energy justice and social acceptance of ground-mounted PV systems. A comparison of cases in Austrian biosphere reserves (Working title)

2.6.2 Academic Theses, Other Publications, and Public Contributions

Factsheets and Policy Briefs:

1. Mikovits, Christian, Wiesenhofer, Florian (2025): Technisch-Ökonomische Modellierung des PV Freiflächenpotentials in österreichischen Biosphärenparks, BioPV Factsheet #1, Universität für Bodenkultur Wien, <https://doi.org/10.5281/zenodo.17880813>
2. Hainz-Renetzeder, Christa, Pospisil, Katharina, Neumayer, Hans, Pachinger, Bärbel (2025): Ergebnisse der Freilanderhebung und Empfehlungen zur Förderung der Biodiversität, BioPV Factsheet #2, Universität für Bodenkultur Wien, <https://doi.org/10.5281/zenodo.17881407>
3. Sposato, Robert, Klič, Rafaela, Hampl, Nina (2025): Umfrageergebnisse Gesellschaftliche Wahrnehmung von Freiflächen-Photovoltaikanlagen, BioPV Factsheet #3, Universität Graz, <https://doi.org/10.5281/zenodo.17881894>
4. Schiesser, Beatrix, Bittner, Karl, Baumgartinger-Seiringer, Mathias, Schauppenlehner, Thomas (2025): Ergebnisse der BioPV Laboratories, BioPV Factsheet #5, Universität für Bodenkultur Wien, <https://doi.org/10.5281/zenodo.17882086>
5. Mikovits, Christian, Hainz-Renetzeder, Christa, Schauppenlehner, Thomas, Bittner, Karl, Wiesenhofer, Florian, Pachinger, Bärbel, Sposato, Robert, Klic, Rafaela, Plöchl, Jana, Scherhauser, Patrick (forthcoming 2026): Integration der Ergebnisse. Kombination der technisch-ökonomischen, ökologischen und sozialen Aspekte, BioPV Factsheet #4, Universität für Bodenkultur Wien.
6. Plöchl, Jana, Niederhofer, Michaela, Scherhauser, Patrick (forthcoming 2026): Gerechtigkeits- und Akzeptanzfragen im Kontext von Freiflächen-Photovoltaikanlagen. Ergebnisse einer qualitativen Studie, BioPV Factsheet #6, Universität für Bodenkultur Wien.
7. Hainz-Renetzeder, C; Karner, K; Milchram, M; Petermann, J; Strohmaier, B; Tribsch, A; Weber, N. (2025). Fact Sheet #03: "Biodiversitätsverträglicher Ausbau von PV-Freiflächenanlagen" [pdf]; <https://www.biodiversityaustria.at/wp-content/uploads/2025/04/BD-Hub-Oe-Factsheet-03-Biodivfreundlicher-PV-Ausbau.pdf>.

Thesis:

1. Niederhofer, Michaela (2026): Energy justice in the context of ground-mounted photovoltaic systems in biosphere reserves, Master Thesis, BOKU University.
2. Bittner, K. (in preparation): Virtual Nature: Perception, Modelling, Processing, and Rendering of Vegetation and Biodiversity in Digital Experiences and Landscape Visualizations (Working title), BOKU University; cumulative dissertation including the published article <https://doi.org/10.14627/537770026>

Conferences and Workshops:

1. Hainz-Renetzeder, C; Baumgartinger, M; Bittner, K; Dworzak, V; Hampl, N; Mikovits, C; Pachinger, B; Plöchl, J; Schauppenlehner, T; Sposato, R; Scherhauser, P. (2024): Photovoltaics, Humans and the Biosphere: A transdisciplinary approach fostering Alpine resilience (BioPV). Veranstaltung: LANDSCAPE 2024 Agroecosystems in Transformation: Visions, Technologies and Actors. 17.09.2024 - 19.09.2024 | Ort: Berlin, Germany.
2. Pachinger, B; Pospisil, K; Neumayer, J; Kropf, M; Scherhauser, P; Hainz-Renetzeder, C (2024): Greenwashing oder Artenförderung? Insekten in PV-Freiflächenanlage. 90. Internationale Entomologentagung 2024, 08.11.2024 - 10.11.2024 Entomologische Arbeitsgemeinschaft am Biologiezentrum Linz, Linz, Österreich.
3. Pachinger, B; Baumgartinger, M; Bittner, K; Hainz-Renetzeder, C; Klic, R; Mikovits, C; Plöchl, J; Schauppenlehner, T; Sposato, R; Scherhauser, P (2025): Herausforderungen einer integrierten nachhaltigen Entwicklung bei PV-Freiflächenanlagen (BioPV). Vortrag bei den Tagen der Biodiversität 2025 – Gemeinsam aus der Biodiversitätskrise 25.02.2025 - 28.02.2025, Wien BOKU University, Zoologisch-Botanische Gesellschaft Österreich (ZOOBOT), Wien.
4. Klic, R; Hampl, N; Sposato, R (2025): Green energy, greener habitats. Exploring public perceptions of the balance between utility-scale photovoltaics and biodiversity conservation. Presentation at the ICEP – International Conference on Environmental Psychology 15.-18. Juny 2025, Vilnius, Lithuania.
5. Schauppenlehner, T; Bittner, K.; Baumgartinger-Seiringer, M; Hainz-Renetzeder, C; Scherhauser, P (2025): Using planning games and interactive visualisations labs for collaborative planning and local knowledge integration in the development of scenarios for ground-mounted photovoltaics in Austrian biosphere reserves, International Association for Landscape Ecology (IALE) in Bratislava, 2-5 September, <https://www.uk.e.sav.sk/doi/iale2025.pdf>.
6. Klic, R; Hampl, N; Sposato, R (2026): Green energy, greener habitats. Exploring public perceptions of the balance between utility-scale photovoltaics and biodiversity conservation. Presentation at the EnInnov, Symposium Energieinnovation 11.-13.02.2026, TU Graz, Österreich.

Teaching:

1. "Ground-mounted PV-Systems" as part of the interdisciplinary project course for 36 bachelor's students (Bachelor programme Environment and Bioresources Management at BOKU University) in the winter term 2023/24 & 2025/26
2. "Climate protection - Nature conservation; Expansion of open-space photovoltaics in conjunction with biodiversity protection thinking"; GIS-supported project (Bachelor programme Landscape Architecture and Landscape Planning) in the summer term 2024
3. "Climate and Energy Politics" (Bachelor programme Environment and Bioresources Management at BOKU University) in the winter term 2025/26 & summer term 2026

For media see section 3.3

2.7. Generated Data-Sets/Models/Tools

To make planning accessible and allow a wide range of people to interact with the trade-offs of PV planning, a custom toolkit for immersive landscape visualization and serious game development, the LandscapeLab, is employed. This toolkit aims to allow both experts and laypeople to plan virtual PV installations and get immediate feedback on the economic cost and value, the ecological impact, and the visual landscape impact. The findings and datasets from the techno-economic and the biodiversity assessment serve as the basis for these impacts; the LandscapeLab communicates them to participants and allows them to make specific decisions based on their personal evaluation of the various impacts and their regional knowledge.

LandscapeLab stages:

- Introduction of the participant and overview of project objectives, workshop goals, and procedures
- Baseline survey: an initial questionnaire captured participants' engagement with renewable energy and attitudes toward ground-mounted PV, along with demographics.
- Immersive 3D simulation game: two-phase process using PPGIS and VR enabling participants to engage in interactive scenario planning
- Reflection: recap and discussion of the key outcomes and insights
- Debrief and feedback questionnaire on the experience and learning outcomes

The LandscapeLab, based on previous works (Schauppenlehner et al. 2019, Schauppenlehner et al. 2020), has made significant advancements for allowing nuanced and parametric visualization of PV installations and to incorporate the complex game logic. These developments were embedded in the inter- and transdisciplinary research process of BioPV (cf. Figure 10).



Figure 10: Impressions from the case-study laboratories: Collaborative work on the interactive game board table (left), and immersive 3D experience using VR-glasses (right)

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- Schauppenlehner, T., Lux, K., Graf, C. (2019). Effiziente großflächige interaktive Landschaftsvisualisierungen im Kontext des Ausbaus erneuerbarer Energie – das Potenzial freier Geodaten für die Entwicklung interaktiver 3D-Visualisierungen. AGIT: Journal fuer Angewandte Geoinformatik 5: 172-8. <https://doi.org/10.14627/537669016>
- Schauppenlehner, T., Graf, C., Latosinska, B., Roth, M. (2020). Entwicklung einer neuen Schnittstelle für Mensch-Maschinen-Interaktion im Kontext raumbezogener partizipativer Prozesse. AGIT: Journal fuer Angewandte Geoinformatik 6: 13-22. <https://doi.org/10.14627/537698002>

2.8. Limitations and Uncertainties

In BioPV the following three methodological limitations should be discussed:

- The integration of ecological data into techno-economic modelling is dependent on consistent, up-to-date and reliable data for the impact assessment. If this prerequisite is met, areas can be defined in which priority expansion is possible, where win-win synergies can be established, and where further expansion is not compatible with nature protection. Unfortunately, these Austrian-wide consistent high-resolution data on

ecological values is not available for such a context, presenting a methodological limitation to keep in mind by interpreting the resulting priority and conflict areas.

- The final sample of interview partners for the analysis of social acceptance covered a wide range of backgrounds and interests, although it must be noted that women and younger participants (<30) were much harder to recruit and are thus underrepresented in our sample.
- By developing a technological framework for joint action, we have created several opportunities to collect data and contributions from a region. For low-threshold data collection, a prototype for a WebGIS (cf. Figure 11) was developed to collect zones for or against the expansion of ground-mounted PV at a low threshold at local or regional level. The advantage is that many people can be reached by using suitable communication channels. A disadvantage could be that the information content of this type of query is often low and requires greater effort for quality assurance (filtering out incorrect or meaningless data points).

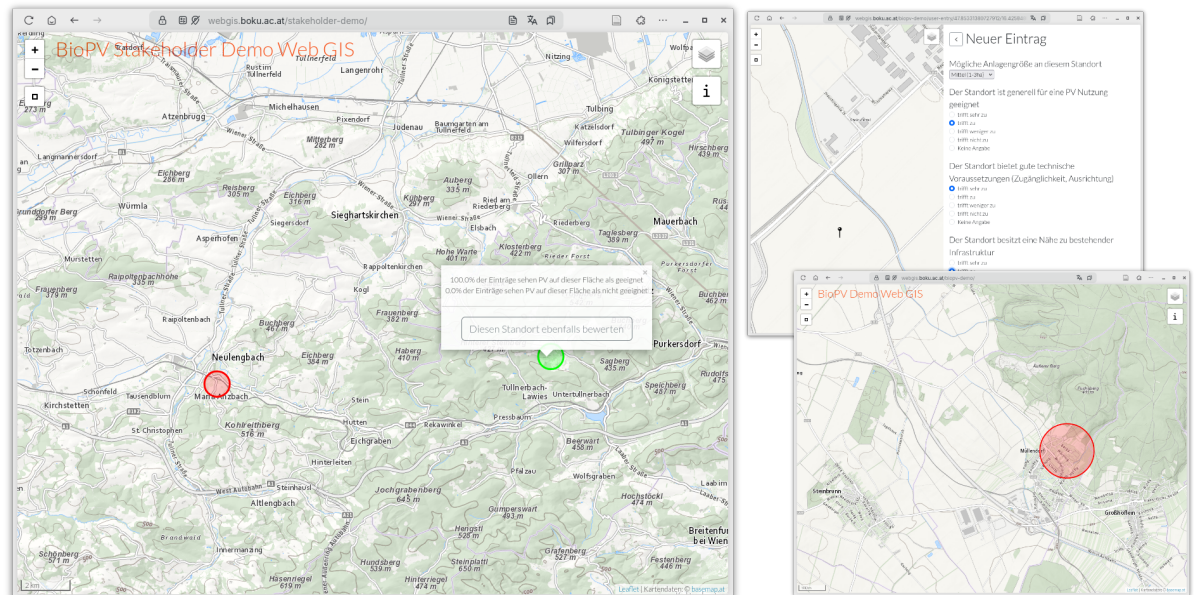


Figure 11: Prototype of the WebGIS application for collecting zones for or against the expansion of ground-mounted PV

3. Transdisciplinary Process Reflection and Social Impact

3.1. Concept and Goals of Initial Co-Design

BioPV's transdisciplinary process was based on the assumption that the inclusion of different stakeholders and their perspectives in the research process is essential for the production of useful and relevant knowledge. The knowledge generated through the project should reflect the needs of stakeholders and be evaluated for its feasibility in practice and transferability to other contexts. Additionally, by participating in the transdisciplinary process, stakeholders could identify with the project's outcomes and feel a sense of responsibility for their dissemination and implementation.

To achieve this transdisciplinary inclusion, an advisory stakeholder group was constituted at the start of the project. Communication and collaboration with this group was based on the following principles of transdisciplinary cooperation: (1) open and empathic communication at eye level; (2) open discussion of timelines and levels of participation (information - consultation - co-determination); (3) transparent documentation of the process and its results; (4) ensuring practical relevance and suitable dissemination formats of project results.

The advisory stakeholder group consisted of representatives from the biosphere reserves and climate and energy model regions (Klima- und Energiemodellregionen, KEM) studied in the project, the respective state administrations, companies and interest groups in the renewable energy sector, as well as non-governmental organizations focused on nature conservation and biodiversity. In total, the group comprised 24 members from the following organizations or institutions: Salzburger Lungau Biosphere Reserve and KEM Lungau; Wienerwald Biosphere Reserve Management GmbH; BirdLife Austria; Austrian Photovoltaic Association; Federal Ministry Economy, Energy and Tourism (BMWET), Section V/4: Renewable Energy Production; Energy and Environment Agency of Lower Austria (eNu); Renewable Energy Austria; EVN Naturkraft; International Commission for the Protection of the Alps (CIPRA); KEM Elsbeere Wienerwald; KEM Wein- und Thermenregion Südoststeiermark; Climate and Energy Fund; Municipal Administration of Lower Austria (Department of Nature Conservation, Department of Environmental and Energy Management); Municipal Administration of Salzburg (Energy Economics and Consulting Division); Austrian Chamber of Agriculture (Energy Division); Austrian Nature Conservation Association (Naturschutzbund); ÖKOBURO; Austrian Alpine Club; Environmental Federation (Umweltdachverband).

The core element of the transdisciplinary process were three stakeholder workshops, spaced out over the course of the project duration. The first meeting was held in March 2023 (project month 5) and focused on presenting an overview of the project, its methods and planned outcomes to the stakeholders, explaining BioPV's principles of transdisciplinary collaboration and planned activities with the stakeholder group, and collecting first insights and

perspectives from the stakeholders regarding GMPV. During the second workshop in February 2024 (project month 16), the techno-economic modelling of GMPV potentials in Austria was explained and participants were able to test the Labs' serious planning game and 3D visualization and provide valuable feedback. In addition, we collected stakeholders' insights on GMPV siting criteria for the techno-economic modelling and presented first results from the biodiversity fieldwork. The third workshop took place in May 2025 (project month 31) and was dedicated to present results across all three project dimensions (techno-economic, ecological and social), collecting stakeholders' ideas and needs for dissemination formats and materials, and exploring potential opportunities for exploitation of the results in collaboration with the members of the stakeholder group.

Next to the three stakeholder workshops, ongoing information on the state of the project was also an integral part of the transdisciplinary process. The stakeholder group received regular updates on the project's progress and news and was also contacted for consultations on specific parts of the project (for details see section 3.2).

In addition to the activities involving the stakeholder group, we worked even more closely with representatives of the three case study regions (both from the biosphere reserve management and the climate and energy model regions) to prepare and implement the empirical phases of the project and ensure coordination and local support. These key stakeholders supported the project team in communicating BioPV's goals and research activities within the regions, e.g. to other relevant organizations or municipal stakeholders. Their support was central to identify existing GMPV installations in the respective regions and finding suitable areas for the biodiversity fieldwork, contacting the owners of these sites for field access, finding interview partners for the walking interviews, disseminating the survey on the public perception of GMPV in the region, and organizing the Labs and recruiting participants. This close collaboration with local stakeholders, made possible through establishing a relationship of mutual trust right from the start of the project, was essential for the successful implementation of the project activities.

3.2. Ongoing Integration and/or Capacity Building

Ongoing exchange with the BioPV's stakeholder group and participation at different levels (information – consultation – co-determination) was an integral part of the project's work on all three dimensions of GMPV (techno-economic, ecological, and social). In addition to the three stakeholder workshops, stakeholder perspectives were integrated in the following ways:

Techno-economic modelling of the potential for ground-mounted PV systems in Austrian biosphere reserves

In addition to the siting criteria derived from the existing literature, the participants of the stakeholder workshops were also asked to provide input regarding the weighting of criteria. In the second stakeholder workshop, selected criteria were qualitatively assessed, including panel density (6–30 m²/kWp), PV system size (0.5 ha to >5 ha), and distance to settlements. The three most important results were (i) a preference for systems in proximity to residential areas, (ii) a tendency towards fewer large systems rather than many small ones, and (iii) a medium-to-loose panel density to enable biodiversity measures, and these preferences were considered in the techno-economic analysis via connection costs and scale effects.

Biodiversity promotion

In preparation for the fieldwork on the ecological dimension of GMPV, the stakeholder group – in particular the local and regional stakeholders – supported the project team by identifying existing installations and establishing contacts to landowners for access permissions. In the context of the literature research on existing recommendations for GMPV siting, management and monitoring, stakeholders also provided ideas for additional documents to include in the review. The group was further consulted on potential additional siting criteria and management measures that might be particularly relevant in biosphere reserves and previous experiences with measures for biodiversity promotion. Through an online survey, the stakeholders also provided insights and estimations on the effectiveness and feasibility of different biodiversity promotion measures identified in the literature. In the same vein, the stakeholders' perceptions of existing and potential additional monitoring practices were collected.

Analysis of social acceptance

The design of the survey and conjoint experiment to explore regional perceptions of GMPV was supported by a consultation of the stakeholder group regarding the usability and clarity of the survey questions, as well as additional inputs from the regional stakeholders regarding specific topics and themes that might be especially relevant in the biosphere reserve areas or the study areas more generally. Furthermore, the members of the stakeholder group provided ideas for potential attributes and attribute values for the conjoint analysis, based on inputs from the project team on the method and its purpose in the research design. The regional stakeholders, in particular, also supported the dissemination of the survey to gain additional participants.

Regarding the qualitative walking interviews, support from the regional stakeholders was invaluable to first reflect on the different actors and perspectives that would be important to include, and later to establish connections to suitable interview partners covering these different backgrounds and viewpoints. The regional stakeholders also provided valuable insights into local planning and policy practices regarding GMPV and attitudes towards GMPV installations, which helped to prepare the interviews by providing background information on the local context.

WebGIS and BioPV-Laboratories

The stakeholder group supported the development of the WebGIS software in two ways: First, the participants provided inputs on the kind of questions that should be asked when creating entries into the Web-GIS. This could

ensure covering different perspectives and interests regarding the siting preferences for GMPV. In addition, the software's clarity and usability were evaluated by the stakeholders to ensure that technical barriers do not hinder data collection.

Regarding the serious planning game and 3D landscape visualization, feedback and suggestions for improvement from the stakeholder group were collected during the second stakeholder workshop, where participants had the opportunity to test the software and discuss potential improvements. Key takeaways for the project team included the option to add visual screens in the form of hedges or fences around GMPV installations, the discussions around the representation of energy production and the game's goals, as well as ideas and suggestions for the inclusion of biodiversity indicators to cover ecological impacts of different siting and design choices for GMPV.

Finally, the regional stakeholders' support during the planning, participant recruitment and implementation of the Labs in the case study regions was of central importance, as the endorsement of locally connected actors helped motivate participants to join and build trust during the workshops.

Dissemination activities

The advisory stakeholder group supported the project team with several ideas and opportunities for dissemination, e.g. presenting the project results at organization-specific events and meetings, collaborating with research projects coordinated by some stakeholder group members, and ideas and opportunities for future collaboration on similar topics.

Additionally, several stakeholders participated in the project team's dissemination events (such as the energy cluster event and the webinar), e.g. by presenting regional perspectives on GMPV, serving as discussants on panels, or as regular participants contributing important questions and insights to these events.

3.3. Outreach/Social and/or Policy Impact

Since the start of the project, our research focus, ongoing activities and results have been documented on BioPV's webpage (<https://biopv.boku.ac.at/>), where they will remain available for the interested public, and future dissemination opportunities or publications will also be documented there (cf. Figure 12). The webpage is thus a core element of BioPV's outreach strategy.

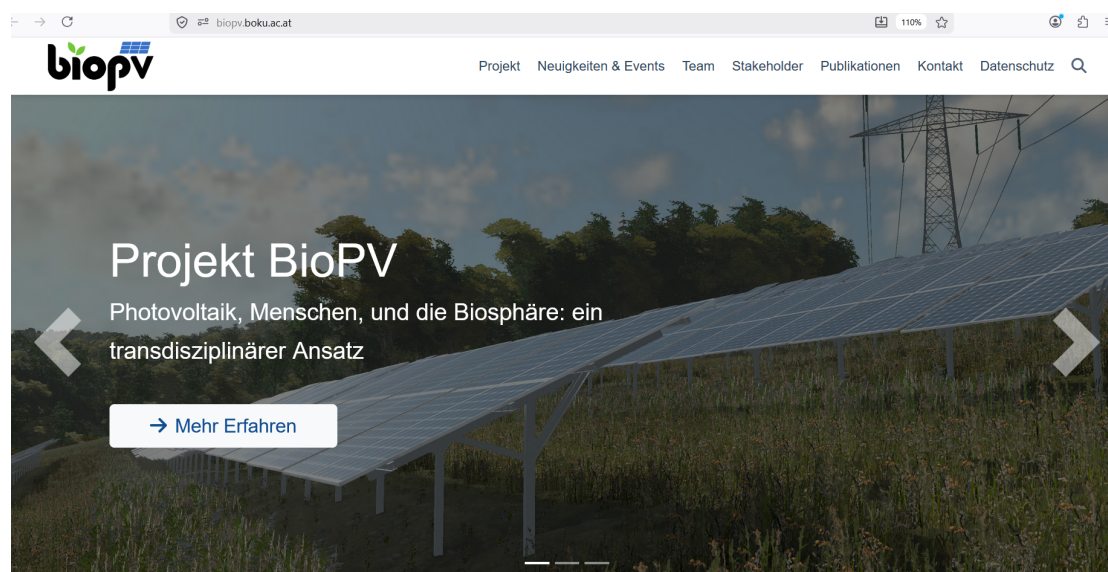


Figure 12: BioPV's webpage

Another central element was the advisory stakeholder group and the three stakeholder workshops held over the course of the project duration (described in section 3.1). The transdisciplinary setting enabled us to keep a diverse group of stakeholders informed of the project development and outputs, provided us with feedback and inputs for dissemination opportunities, and allowed the participating stakeholders to integrate BioPV's findings directly into their respective work.

Members of the project team also gave several interviews for media articles, as well as (co-)authoring own contributions:

- Bensa-Cruz, A. (27.02.2023): Solarstrom aus den Alpen: Was die ideale Photovoltaikanlage braucht. [futurezone.at](https://futurezone.at/science/solarstrom-photovoltaik-gebirge-berge-alpen-pv-pappel-karl-totter-patrick-scherhauser-biopv-boku/402341676).
<https://futurezone.at/science/solarstrom-photovoltaik-gebirge-berge-alpen-pv-pappel-karl-totter-patrick-scherhauser-biopv-boku/402341676>
- Projektteam BioPV (03/2023): PV-Freiflächenanlagen in österreichischen Biosphärenparks – eine inter- und transdisziplinäre Betrachtung. BOKU Magazin 1/2023, 35-36.
<https://www.yumpu.com/de/document/view/67690016/boku-magazin-1-2023>

- Grabner, K. (24.07.2023): Klimaschutz vs Naturschutz – Die Tücken der erneuerbaren Energie. Der Standard. <https://www.derstandard.at/story/3000000179520/die-tuecken-der-erneuerbaren-energie-klimaschutz-versus-naturschutz>
- Grobner, C. (17.09.2023): Das Artensterben im Schatten der grünen Energieträger. Die Presse. <https://www.diepresse.com/16402086/das-artensterben-im-schatten-der-gruenen-energetraeger>
- Hainz-Renetzeder, C., Huber, A., Seliger, C., Popp, S., Schinegger, R. (03/2024): Energiewende im Einklang mit der Natur? Die Notwendigkeit eines naturverträglichen Ausbaus erneuerbarer Energieträger. BOKU Magazin 1/2024, 12-15. <https://www.yumpu.com/de/document/view/68655908/boku-magazin-1-2024>
- Scherhauser, P. (26.08.2024): Photovoltaik in den Alpen. ÖAW interview. <https://www.oeaw.ac.at/news/photovoltaik-in-den-alpen>
- Wohlgenannt, L. (15.04.2025): Energieträger im Vergleich: Fossile sind schmutzig, schädlich, gefährlich und teuer. moment.at. <https://www.moment.at/story/energetraeger-vergleich/>

In addition, we had several opportunities to present BioPV's results at public and professional events to increase the project's outreach:

- Hainz-Renetzeder, C. and Schinegger, R.: „Das Spannungsfeld Klimaschutz & Naturschutz: Status Quo in Österreich.“, presentation at the BOKU-Energiecluster Event “Spannungsfeld Klimaschutz - Naturschutz: entweder, oder? Herausforderungen und Lösungsansätze für eine naturverträglichen Energiewende“, 13.6.2023 https://www.ots.at/presseaussendung/OTS_20230607_OT50019/klimaschutz-versus-naturschutz-entweder-oder-einladung-zur-veranstaltung-des-boku-energieclusters
- Schuppenlehner, T.: „Welche Flächenkonkurrenzen ergeben sich durch die Ausbauziele für PV und Wind 2030/2050?“, presentation at the BOKU-Energiecluster Event “Spannungsfeld Klimaschutz - Naturschutz: entweder, oder? Herausforderungen und Lösungsansätze für eine naturverträglichen Energiewende“, 13.6.2023 https://www.ots.at/presseaussendung/OTS_20230607_OT50019/klimaschutz-versus-naturschutz-entweder-oder-einladung-zur-veranstaltung-des-boku-energieclusters
- Hainz-Renetzeder, C.: „Klimakrise! Biodiversitätskrise! Die naturverträgliche Energiewende als Krisenintervention“, presentation at the BOKU-Energiecluster Event “Nachhaltige Energiezukunft“, 16.4.2024 <https://boku.ac.at/boku-energiecluster/veranstaltungen-und-rueckblick/16042024-nachhaltige-energiezukunft>
- Hampf, N.: Soziale Akzeptanz von PV-Freiflächenanlagen, presentation at VÖU Jubiläumstagung, 10.10.2024.
- Hainz-Renetzeder, C.: presentation of BioPV at the Wiener Umwelthanwaltschaft and Akademikersektion Alpenverein; 21.4. in Vienna
- Hainz-Renetzeder, C.: Ground mounted PV in biosphere reserves - Experiences from the scientific project „BIO PV“; presentation in the frame of the project meeting BiodivErSe; 22.04.2026 in St. Pölten.
- Pachinger, B.: Präsentation im Rahmen der Vorstellung von eNu-Pilotprojekt „PV-Sonneninseln“, 6.8.2025 in St. Pölten.

To present a synthesis of BioPV's findings towards the end of the project, we also organized a final event in collaboration with BOKU Energiecluster dedicated solely to the topic of ground-mounted PV. Insights from the techno-economic, ecological and social dimensions as well as the participatory planning labs were presented by BioPV's team members and subsequently discussed by a stakeholder panel, with contributions from several members of BioPV's stakeholder group. The event with the title “Licht und Schatten – Freiflächen-Photovoltaik im Spannungsfeld zwischen Landschaft, Mensch und Biodiversität“ (see <https://boku.ac.at/boku-energiecluster/veranstaltungen-und-rueckblick/21102025-licht-und-schatten>) took place in October 2025 and was very well-received, attracting participants from research, public and practice, as well as many online participants. The event was live-streamed on Youtube and can still be watched online (<https://www.youtube.com/live/F3n8rsQr74>), with the video having been viewed over 650 times by May 2026.

As an opportunity to present more in-depth findings for a professional audience, we further organized a two-hour online Webinar in December 2025. The webinar recording is also available online: <https://www.youtube.com/watch?v=hSmW9SpSIQA>.

Finally, to reach a non-scientific and -professional audience, together with some representatives of our advisory stakeholder group we created several social media posts explaining BioPV's findings for an interested lay audience (<https://www.instagram.com/p/DRUEI0RCJOL/>, <https://www.instagram.com/p/DSaNg4HiNnn/>, <https://www.instagram.com/p/DTIJEDQCBpC/>). The preparation of social media posts is still ongoing, and further posts are planned in the next months. Another future activity is the creation of an online photo gallery including photos taken in the context of the project to illustrate different PV designs, impacts on biodiversity, species found during the ecological fieldwork, etc. These photos will be published in a creative commons licence (CC BY NC 4.0) and available for use by the interested public and stakeholders.

3.4. Challenges, Lessons Learned and Reflection

Integration of ecological data into techno-economic modelling, planning games and 3D visualization

The lack of consistent high-resolution data on ecological values is not only a methodological limitation (see section 2.8) but also presents a challenge for inter- and transdisciplinary integration and complicates interpretation and communication within the project team and especially to stakeholders.

Another challenge in assessing biodiversity is the scale level. If a single GMPV system requires more space for an environmentally compatible design, this also means that more space is needed overall to achieve a defined energy output target. As a result, the overall pressure on land increases. The landscape ecological impact of the distribution and number of GMPV systems must also be considered on a regional scale. Migratory species in particular are severely affected by this fragmentation. This leads to complex challenges in the sustainable planning of this form of renewable energy expansion.

While data-driven approaches and comprehensive visualization tools make the impacts of GMPV more tangible and support active engagement, conveying ecological dynamics that are not easily visible or intuitive proved more difficult. The complexity of ecological aspects and the lack of immediate visual cues make them harder for stakeholders, especially laypersons, to grasp and to weigh against other criteria. In addition, there are regional differences in how the aesthetic and ecological value of the landscape is understood and prioritized, partly due to divergent land-use baselines.

Representation of different perspectives in interviews and collaborative planning

Despite efforts to achieve a balanced participant mix for both the walking interviews and the regional case-study laboratories, men were strongly overrepresented among both experts and lay participants. Contributing factors include the technical nature of the topic, the male-dominated fields of renewable energy, infrastructure planning, energy-related spatial planning, and, in many cases, regional and local planning and politics. This raises the question of how to navigate the tension between the goal of balance and the limited availability of female experts in the relevant sectors, given that repeated recruitment across multiple projects can place an undue burden on a small group of individuals. In case-study laboratories, the few female participants primarily came from the fields of nature conservation, regional management, or education. Among lay participants, women's continued predominance in care work may also result in higher male attendance at additional events held outside regular working hours. Overall, recruiting lay stakeholders proved more challenging than recruiting experts with a professional stake in the topic.

Lessons for inter- and transdisciplinary research

The preparation and execution of the BioPV Labs clearly demonstrated the importance of inter- and transdisciplinary collaboration in complex planning projects. In addition to techno-economic parameters, ecological impacts depend on numerous factors, which are also interpreted and understood differently depending on the region (e.g., the significance of the landscape). Therefore, intensive exchange within the project team was necessary to address these aspects comprehensively and to develop a meaningful application in terms of complexity and transparency. The participation of all disciplines in the workshops proved particularly important, as it allowed for expert answers to even complex questions on specific aspects, leading to very trusting discussions in the workshops. Additionally, (regional) stakeholders' inputs and support were invaluable throughout the project to ensure the inclusion of different perspectives and the smooth implementation of empirical fieldwork.

3.5. Continuation and Long-Term Impact

In terms of methodological development, the technological and methodological *LandscapeLab* framework made major advances in terms of data-driven visualisations and modifications in the field of GMPV. The interdisciplinary development opened a broad range of novel options for data integration and communication. This enables the project team to systematically utilize the framework within future projects and project partnerships. Furthermore, the BioPV Labs results will be incorporated into the BOKU Core Facility "Landscape Innovation Lab," which is up and running since January 2026.

Regarding the dissemination of the project results, several publications are planned based on BioPV's empirical work, and further dissemination in the scientific community, e.g. through conference presentations, is also planned by the project team. Additionally, dissemination activities for non-scientific actors will be pursued as and when opportunities arise, and the insights generated through the project will continue to be incorporated into the team members' teaching.

The fruitful collaborations with selected members of the stakeholder group have also led to further opportunities for cooperation and joint work on future projects. Further collaborations are already underway in the context of the research projects "Windplan" (FFG) and "TriLand" (ÖAW/ESS), and other stakeholders have expressed interest in collaborating again in future projects and even co-authoring funding applications.