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Some aspects of the impact of photovoltaic plants on the environment

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Abstract. Renewable energy sources (RES) play a key role in the global effort to tackle climate change and ensure a sustainable energy future. They are energy sources that are naturally renewable and have a minimal or zero carbon footprint. The main types of renewable energy sources include wind, solar (thermal and photovoltaic), aerothermal, geothermal, hydrothermal, ambient energy, tidal, wave and other ocean energy, hydroelectric power, biomass, landfill gas, sewage treatment plant gas and biogases (EC Directive 2018/2001). Large-scale photovoltaic power plants (PPPs) are being developed at a rapid pace and are set to use thousands or millions of acres of land worldwide. While the energy, economic and environmental impacts of PPPs are generally considered positive, large-scale deployment has negative impacts on non-urban areas. Specific impacts on soils and rural areas (e.g. permanent or temporary soil sealing conditions, complete or partial soil shading, land degradation, habitat fragmentation and loss of traditional agricultural practices) have been identified and require further investigation. The life cycle analysis of PPPs showed that they cannot be accepted as green technologies with zero emissions due to the potential negative effects on the environment. However, they are one of the most promising renewable energy sources, which emphasizes the need to search for sustainable models for their production, construction and operation.

Key words: solar plants, photovoltaic power plants, alternative energy sources, renewable energy, environmental impact.

Introduction

The rapid growth of the world population and the advancement of civilization have led to an exponential increase in the demand for energy. Fossil fuels are the main source of energy worldwide. However, greenhouse gases such as methane, carbon dioxide, and nitrous oxide, which are released in large quantities during the process of burning fossil fuels, are the main cause of climate change (Olabi & Abdelkareem, 2022).

Renewable energy sources (RES) play a key role in the global effort to tackle climate change and ensure a sustainable energy future. They are energy sources that are naturally renewable and have a minimal or zero carbon footprint. The main types of renewable energy sources include wind, solar (thermal and photovoltaic), aerothermal, geothermal, hydrothermal, ambient energy, tidal, wave and other ocean energy, hydroelectric power, biomass, landfill gas, sewage treatment plant gas and biogases (Directive (EU) 2018/2001). Large-scale photovoltaic power plants (PPPs) are being developed at a rapid pace and are set to use thousands or millions of acres of land worldwide. The environmental issues associated with the installation and operation phases of such facilities have not yet been comprehensively addressed in the literature (Turney & Fthenakis, 2011). In the last decade, as the area occupied by PPPs world-wide has increased, so has the number of scietific studies on their impacts (Klimentova-Nikolova et al., 2025).

Since photovoltaic (PV) energy contributes to the reduction of pollutant emissions, the spread of PPPs has been widely supported as a response to global climate change (Bergesen et al., 2014) in regions with optimal conditions for photovoltaic installations due to high and continuous solar radiation throughout the year (Espinosa & Krebs, 2014; Gunderson et al., 2015). Incorporating solar power plants on existing pasture or agricultural land provides an additional revenue stream for landowners and encourages diversification, providing income for years when agricultural productivity is low or for crops of relatively low value. Similar benefits have been demonstrated with the development of wind turbines on agricultural land (Holmes & Papay, 2011). Based on these ground-mounted facilities, photovoltaic structures are becoming a common infrastructure in the Mediterranean region and can contribute, at least indirectly, to various forms of environmental degradation, including land-scape deterioration, land take, soil degradation and loss of traditional arable land and biodiversity (Delfanti et al., 2016).

While the energy, economic and environmental impacts of photovoltaic facilities are generally considered positive, large-scale deployment has negative impacts on non-urban areas (Carullo et al., 2013; Naspetti et al., 2016). Land use for PPPs can compete with other land uses such as agriculture, forestry, or urbanization. It is therefore not surprising that much of the work on solar energy also addresses the issue of land use (Biswas et al., 2021). Specific impacts on soils and rural areas (e.g. permanent or temporary soil sealing conditions, complete or partial soil shading, land degradation, habitat fragmentation and loss of traditional agricultural practices) have been identified and require further investigation (Beylot et al., 2014; Hernandez et al., 2014; Koldrack et al., 2014).

Zhang et al. (2023) discussed the benefits and potential environmental impacts of implementing photovoltaic technology and provided recommendations for improving its sustainability. Although PV technology significantly reduces pollutant and greenhouse gas emissions, it also has negative environmental impacts. These include biodiversity and habitat loss, climate impacts, resource consumption, and disposal of photovoltaic modules. The production of photovoltaic system components and the recycling of their parts at the end of the power plant's life can use or generate toxic substances that pose potential risks to the environment and human health (Zhang et al., 2023).

The environmental and human health hazards of photovoltaics are reviewed by Nain & Kumar (2020), who focus on the potential carcinogenic effects, and by Kwak et al. (2020), who also found that the main materials used in solar cells, including lead, tin, cadmium, silicon and copper, are hazardous to human health if released into the environment.

Tawalbeh et al. (2021) examined the environmental impacts of photovoltaic systems from production to disposal, presenting a comprehensive analysis of these impacts and proposing new design solutions to mitigate them. Their study also compares the greenhouse gas emissions of photovoltaic solar systems with those of fossil fuels and suggests ways to further reduce the carbon footprint of photovoltaic systems. According to the authors, the harmful impacts of photovoltaic plants on the environment can be significantly reduced through careful siting, recycling, the development of new materials and optimized design (Tawalbeh et al., 2021).

A report commissioned by the Welsh Government examined in detail the impact of photovoltaic parks on agricultural land and soils (RSK ADAS, 2023). A study by Delfanti et al. (2016) examined the environmental degradation resulting from the expansion of photovoltaic parks in Italy, including landscape degradation, land take, soil degradation and loss of traditional arable land and biodiversity (Delfanti et al., 2016). A comprehensive overview of the possible impacts of photovoltaic systems located in open areas on nature and land use in Germany, the impact on specific habitats and animal groups and on the landscape, based on field studies in six selected solar parks, has been reported by Herden et al. (2009). The results have contributed to a better assessment of the impacts of PV systems, while at the same time providing guidance for spatial design as well as for minimizing and/or compensating for the impacts arising from them under German conditions (Herden et al., 2009).

In order to reduce dependence on fossil fuels and achieve climate neutrality as aimed at European Green Deal (EC, 2021), it is necessary to understand in which phases of the life cycle of photovoltaic panels negative impacts occur and which factors influence their intensity. These include, as main environmental impacts, land use, greenhouse gas emissions, emissions of hazardous substances, water consumption, noise and waste generated at the end of the life cycle of photovoltaic panels.

Based on the above mentioned, the aim of the present study is to summarize some aspects of the impact of photovoltaic power plants (PPPs), installed in non-urbanized territories, on the environment.

Materials and methods

We performed a literature search to gain an understanding of which type of impacts of the PPPs on environment have been recognized, discussed, measured through empirical data or modelling studies. The initial identification of scientific literature in the field was done by searching for articles in Scopus, Web of Science and Science Direct platforms (Petrova & Nikolov, 2023). The keywords searched were "photovoltaic power plants" and "solar power plants" + "impact on the environment" (first stage of the review process). A total of 141 matching articles were found, allowing access to the full text and downloading. The second stage included manual review of these articles and removal of duplicates, as well as screening of title, abstract and conclusion for relevance to the research topic, based on which 48 publications were excluded from the initial list. In third stage, the thematic relevance of the remaining 93 publications was examined and of these, only 77 publications were included in the final reference list, and 16 were removed.

Results and Discussion

Potential impacts can be traced throughout the whole life of a photovoltaic installation, from construction to decommissioning, and may have one or more potential environmental impacts with multiple potential ecological effects. Furthermore, the technology, size and location of the infrastructure can affect biota and the environment in different ways (Murphy-Mariscal et al., 2018).

The potential impacts of photovoltaic power plants on the environment can be summarized as follows: 1) during the production of PV panels; 2) during the construction of photovoltaic power plant; 3) during the exploitation; 4) during the decommissioning phase (Fig. 1).

Environmental impacts in the production phase of photovoltaic panels

When analyzing the life cycle of a photovoltaic power plant, it becomes clear that greenhouse gases emissions occur during the production of components, processing and transportation of materials, installation of the PV facilities, decommissioning, and dismantling, while during the operation of a PPP, there are no emissions (if we ignore the cleaning of the panels). Some authors have shown that CO_2 emissions for the production of photovoltaic systems vary from 14 to 73 g CO_2-eq/kWh, depending on the specific technology, the location of the power plant and the type of electricity used for production. The reported values for CO_2 emissions are approximately in the same range as for concentrated solar power technologies (8 to 90 g CO_2 eq./kWh). The variability is caused by different energy requirements during the manufacturing and assembly processes, as well as the raw materials used to produce photovoltaic modules (Bošnjaković et al., 2023).

Photovoltaic cells are made of different types of semiconductor materials. Some pollutants can be emitted during the production of photovoltaic system components and during end-of-life disposal. In addition to greenhouse gases (such as CO_2, CH_4, N_2O, SF_6), there are possible emissions of gases that create acidic compounds (such as SO_2, NO_x), particulate matter (such as dust), heavy metals (such as Cd, Pb) and organic compounds such as solvents. Perfluorocarbons (PFCs) are widely used in the electronics industry, e.g. in plasma cleaning of silicon modules, which also uses a number of harmful compounds, which may be released into the soil or groundwater if they are damaged or discarded (Bošnjaković et al., 2023).

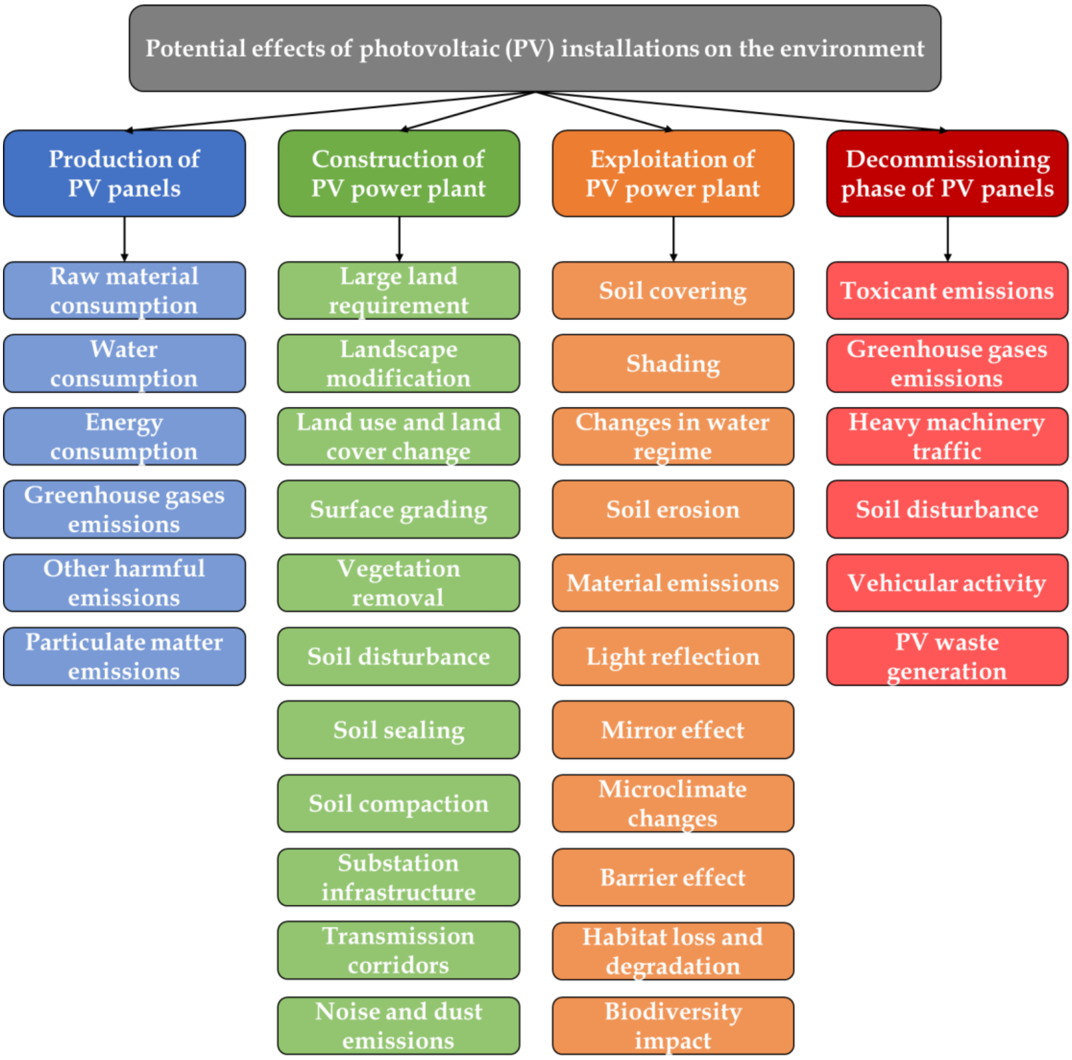

Fig. 1. Summary of the potential environmental impact of photovoltaic power plants.

Environmental impacts during the construction phase of photovoltaic power plants

The construction of a PPP involves operations that inevitably have an impact on soil and land use. When building PPPs, areas are sealed and built up through the construction itself or through the installed facilities. The intensity of the sealing can be different - complete construction in the area of the foundations or accompanying buildings (transformers), or partial, for example by covering the roads with gravel (Herden et al., 2009).

All construction phase activities involve traffic with installations/machinery throughout the site, possibly following access roads to parts of the site. Examples of equipment used include excavators and dump trucks for soil removal and storage, trenching machines, piling rigs and dump trucks for transporting cables, poles and panels.

Disturbance of soil layers, trampling, compaction occur during the construction phase, when heavy construction machinery (excavation, transport of materials) causes an impact on the soil as a result of its compaction or excavation. This is observed both during construction work (transport, storage, installation of modules) and during the installation of cables (Herden et al., 2009; Batey, 2009).

Deep soil removal is necessary to prepare the site base, access roads and tracks (where aggregates and geotextile membrane are used), foundations for inverters and substations. Some sites require removal of soil to a depth of up to 30 cm, i.e. usually the topsoil, but digging to this depth may mix some subsoil layers if not removed separately. Trenches created by a trenching machine will require removal of soil to a depth of typically up to 1.2 m (i.e. not only from the surface but also from deeper horizons) and a width of up to 0.75 m (RSK ADAS, 2023).

Disruption of the road network - The removal of large parts of the landscape can, for example, lead to impacts on local hiking trails. Such restrictions on recreational uses can be considered as impacts on the landscape appearance (recreational potential of landscapes) (Herden et al., 2009).

Environmental impacts during the exploitation phase of photovoltaic power plants

Soil covering – Due to the considerable distance between the modules and the ground, these soils cannot be classified as built-up, although this may disrupt or affect soil functions or habitats. A significant result is the shading of the areas under the panels, as well as the surface drying of the soils due to the reduction in the amount of precipitation under the modules. In addition, water flowing from the module edge can lead to soil erosion (Herden et al., 2009).

Shading – This is most pronounced with fixed modules, but even with them not all parts of the area are constantly or evenly shaded due to the movement of the sun. However, depending on the module areas, especially when the sun is low, relatively large areas remain partially in shade (Herden et al., 2009). In some contexts, the shadow effect of solar panels can be beneficial, for example, when used to preserve crops during heat waves and droughts (Barron-Gafford et al., 2016) or by providing shade and shelter for some arthropods (Suuronen et al., 2017) and bird species (Visser et al., 2019).

Change in the rain regime, respectively soil moisture - Covering the soil with PV panels leads to a decrease in the amount of precipitation (rain, snow, dew), which could cause surface drying of the soil (Klimentova-Nikolova et al., 2025). Thanks to capillary rise, the lower soil layers can be supplied with water, but not the surface ones. In case of snowfall, due to the shading effect of the panels, the areas below them will probably remain without snow cover, which also provokes a moisture deficit (Herden et al., 2009).

Soil erosion – When the ground is covered by large module surfaces, rainwater runoff can lead to soil erosion, especially during heavy rainfall, mainly in facilities on slopes and open soils where water does not absorb well (Herden et al., 2009).

Barrier effect - The territory of all photovoltaic parks is fenced for security and safety reasons, which leads to fragmentation and/or complete loss of habitat for small and large mammals (Herden et al., 2009; Murphy-Mariscal et al., 2018). This leads to both a smaller total habitat area and changes in the spatial configuration of the habitat (Berger-Tal & Saltz, 2019). Habitat fragmentation is associated with reduced species richness, edge effects, compromised ecosystem function and population isolation and reduced genetic exchange (Haddad et al., 2015; Fahrig, 2003).

Material emissions - Contamination of PV panels with dust, pollen and bird droppings has a negative impact on their performance, with losses reaching up to 11%. Covering the modules with anti-reflective synthetic materials reduces the ability of the surfaces to repel pollution. By placing the modules at an angle, pollution can be reduced to some extent, but at an inclination of the modules less than 10 degrees, cleaning by precipitation alone is approximately zero. In such cases, periodic cleaning of the facilities with water or with chemicals that run off into the soil is necessary (Herden et al., 2009).

The deployment of PPPs can also degrade habitats by altering water quality and quantity. Surface water flows are sometimes intentionally modified to reduce soil erosion around the infrastructure. This can affect downstream aquatic ecosystems and habitats by altering the flow of organic matter, nutrients, minerals and sediment. Chemical dust removers and herbicides used to maximize solar exposure of panels can increase runoff and affect the chemistry of waterways (Cameron et al., 2012; Grippo et al., 2014; Turney & Fthenakis, 2011).

Light reflection - The modules, as well as the supporting structures of the photovoltaic panels, reflect some of the light, which is why from a long distance they do not differ significantly from the sky, especially in strong light. In contrast to areas covered with vegetation, they appear as brighter objects in the landscape and can thus cause a disruption of the landscape appearance. An important aspect is the reflection in the infrared range, which can also lead to potential negative impacts on animals (Herden et al., 2009).

Mirror effect - Unlike reflection, in which scattered light does not carry information, the mirror effect is expressed in the reflection of visible parts of the environment on the glass surface. The mirror effect of the module panels is highly dependent on the selected material, with a stronger manifestation observed in thin-film modules (a thin carrier layer between two glass surfaces), especially in unfavorable light (Herden et al., 2009).

Heating of the modules and cables - The surface of the photovoltaic panels heats up strongly during prolonged sunlight, in which the temperature of the modules can reach up to 60°C, although it usually ranges in the range of 35°C-50°C. In photovoltaic parks of particularly large sizes, the heating of the modules can lead to an impact on the local microclimate, e.g. heating of the adjacent territory or convection (Wu et al., 2014; Armstrong et al., 2016). It can also affect flying insects by attracting them on cooler days. In extreme cases, injury or death of small flying animals is possible (Herden et al., 2009).

Habitat loss and degradation can occur during the construction, operation, and decommissioning phases of solar energy facilities. The construction of ground-mounted solar thermal and photovoltaic facilities may involve clearing vegetation and cultivating the surface to facilitate installation, prevent shading of the solar panels by vegetation or undulating terrain, and reduce the risk of wildfires on the site. During the operation phase, some photovoltaic plants apply herbicides, cover the ground with gravel, and mow frequently to manage vegetation around the solar panels (Turney & Fthenakis, 2011; Wilson et al., 2015; Tanner et al., 2014).

These construction and operational practices can lead to habitat loss and degradation, resulting in species mortality or displacement, which in turn can lead to a reduction in species richness and density (Murphy-Mariscal et al., 2018; Berger-Tal & Saltz, 2019). In addition to removing plant species, clearing and sorting can increase soil erosion and reduce the amount of organic carbon and nitrogen, which in turn can affect primary production by plants and food availability for wildlife (Sánchez-Zapata et al., 2016). Lambert et al. (2021) studied soil temperature and moisture, CO_2 emissions and vegetation under and outside the photovoltaic panels of three solar parks in the French Mediterranean. They demonstrated that physical, chemical and general soil quality indicators were lower in the PPP than in semi-natural land cover types (pine forest and shrubs). The results obtained clearly demonstrate that the clearing and cultivation of the soil surface during the construction of the solar park led to a strong deterioration of the physical quality of the soil, especially its structure

Various direct and indirect impacts on biodiversity can combine to cause cumulative impacts. Cumulative impacts include the combined impacts of a single renewable energy facility (e.g. habitat fragmentation and direct mortality), the combined impacts of multiple projects, either from the same sector or from multiple sectors in an ecosystem, landscape or migration route, and the combined effects of pressures over time. Cumulative impacts can be additive (i.e. the impact is equal to the sum of the individual impacts), synergistic (i.e. the cumulative effect is greater than the sum of the individual impacts), or antagonistic (i.e. the cumulative effect is less than the sum of its individual impacts) (Whitehead et al., 2017; IFC, 2017; Goodale & Milman, 2019).

The deployment of solar energy can affect the supply and access to ecosystem services. Potentially affected are supporting services such as soil formation and nutrient cycling, regulating services such as climate and hydrology, material services such as water and food supply, and cultural services such as recreational activities, aesthetic and spiritual values (Sánchez-Zapata et al., 2016).

In some contexts, through proper siting, design and management, solar facilities could enhance several ecosystem services while helping to combat climate change and meet energy needs (Randle-Boggis et al., 2020; Walston et al., 2021). For example, compared to agricultural land use before solar facilities were built in the Midwest of the United States, restoring and managing native grasslands can increase pollinator supply by 300%, carbon storage potential by 65%, sediment retention by more than 95%, and water retention by 19% (Walston et al., 2021).

Environmental impacts during the decommissioning phase of photovoltaic power plants

When the decommissioning phase is triggered at the end of the photovoltaic power plant's operational life, operations to remove the physical infrastructure begin. Access roads and tracks may require reinforcement to meet a standard suitable for heavy machinery. Traffic through and around the site is again increased as the panels, frames, inverter units and substations are removed. Cabling can be removed from the trenches and external cables dismantled. Access roads and building ties must be removed together with the aggregates and geotextile membranes used. Where the inverter units have been placed on an aggregate base or concrete base, this must also be removed (RSK ADAS, 2023).

Removing the metal beams is likely to be more problematic than their initial installation in most cases, as it is usually done with a 13-ton excavator and a vibrating driving/extraction device that removes one beam and then moves to the next (RSK ADAS, 2023). The removal of the metal beams is likely to be more problematic than their initial installation in most cases, as it is usually carried out with a 13-tonne excavator and a vibrating driving/extraction device, which removes one beam and then moves to the next (RSK ADAS, 2023). During the construction and decommissioning phases, there will be soil movement and on-site soil cultivation. During the commissioning, operation and decommissioning phases, there will be traffic with a range of machinery, including a bulldozer, a crawler excavator, a wheeled excavator, a hydraulic hammer and a rotary drilling rig, vibrating plates, which can lead to soil compaction. The main cause of compaction is the compressive forces applied to the soil by the wheels or tracks of the machinery (RSK ADAS, 2023). Hakansson et al. (1988) found that an axle load of 10 tons increased the bulk density of the soil to a depth of 50 cm. Compaction can be very persistent in the subsoil and possibly permanent.

Waste generation - According to the Report of IEA-PVPS (2018), PV panel waste will amount to 50,000 tons by 2030. In 2018, the organization collected over 27,000 tons of modules across Europe, which highlights the paramount importance of properly managing this waste and recycling the panels, which typically have a 25-30-year lifespan. However, some modules enter the waste stream earlier than expected due to damage during the transportation and installation stages, initial failures after start-up, technical and physical failures caused by harsh environmental conditions, and unexpected external factors, including natural disasters.

In a scenario of regular loss of PV panels, waste quantities will increase to 1.7 million tons by 2030 compared to 43,500 tons in 2016. An even more drastic increase to around 60 million tons can be expected by 2050. In a scenario of early entry of modules into the waste stream, the quantities by 2030 will be around 8 million tons and 78 million tons by 2050 (Report IEA-PVPS, 2024).

Conclusions

As a result of the systematic review and analysis of the scientific literature in the field of PPPs, the following conclusions can be drawn:

1) The life cycle analysis of photovoltaic power plants showed that they cannot be accepted as green technologies with zero emissions due to the potential negative effects on the environment.

2) However, they are one of the most promising renewable energy sources, which emphasizes the need to search for sustainable models for their production, construction and operation.

3) Evidence of adverse impacts on biodiversity from the construction, operation and decommissioning of solar and wind power facilities and power lines highlights the importance of taking biodiversity into account when expanding renewable energy.

4) In general, the impacts of photovoltaic power plants on the environment are direct and indirect, tangible and intangible, and the cumulative effect should also be taken into account.

5) Of the tangible impacts with the highest negative impact are fragmentation, isolation and loss of habitat for wild plants and animals, followed by changes in soil properties and functions.

6) Among the intangible impacts with the highest negative impact are heat release, soil shading, mirror effect, etc.

7) By effectively integrating biodiversity into energy system planning and appropriate policy combinations, governments can help ensure effective mitigation of these impacts and promote positive biodiversity outcomes in renewable energy projects.

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