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Land Use and Ecosystem Impacts of Solar Power Plants: A Case-Based Assessment from Türkiye

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A B S T R A C T

This study provides a multidimensional assessment of the land use and ecosystem impacts on Solar Power Plants (SPPs) in Türkiye, where solar investments have rapidly expanded due to high irradiation potential. While solar energy is a key pillar of the low-carbon transition, large-scale ground-mounted installations increasingly intersect with agricultural lands, rural livelihoods, and biodiversity hotspots. Drawing on regional case studies and national-scale trends, the research identifies spatial patterns of SPP development and highlights the socio-ecological risks associated with poor site selection. Key findings emphasize the need to balance energy generation with land conservation, ecosystem services, and social acceptance. The paper advances an integrative planning framework based on agrovoltaic systems, nature-based solutions, and GIS-supported decision-making. Rather than proposing a singular model, the study synthesizes best practices to guide strategic land use that minimizes conflict and enhances resilience. This work contributes to energy policy by reframing SPP investments as not only technological projects but also socio-environmental interventions, underlining the urgency of participatory, spatially just, and ecologically compatible energy transitions in Türkiye and beyond.

1. Introduction

The escalating global demand for energy and the intensifying efforts to combat climate change necessitate the widespread adoption of low-carbon energy sources. In this context, solar energy technologies have emerged as a critical pillar in achieving sustainability goals [1, 2]. Türkiye holds a strategic advantage in solar energy investments due to its geographical location and high annual solar irradiation [3, 4]. However, the environmental and socio-economic impacts arising from the utilization of this potential require comprehensive assessments,

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particularly in terms of land use and ecosystem balance [5, 6].

The primary aim of this study is to analyze, from a multidimensional perspective, the impacts of SPP investments on land use and their relationship with ecosystem integrity in Türkiye. The study addresses the spatial requirements of Solar Power Plant (SPP) projects, their effects on agricultural and natural areas, site selection criteria, levels of social acceptance, and nature-based solution proposals. Furthermore, through selected case studies from Türkiye, the local-scale implications of SPP developments are assessed, and policy recommendations are formulated to guide sustainable planning.

In the literature, increasing attention has been paid to the pressures exerted by SPPs on agricultural lands, pastures, and natural habitats, as well as their effects on microclimates, soil structure, and biodiversity. It has been shown that the installation of photovoltaic (PV) systems leads to habitat modification and changes in microclimatic conditions, which in turn affect plant and insect community structures [5, 6]. Additionally, PV installations have been found to significantly influence vegetation cover and soil properties, causing alterations in soil moisture, temperature, and biodiversity [7]. The rapid growth of solar energy investments in Türkiye further underscores the need for a more systematic evaluation of these impacts. Key research questions addressed in this study include the extent to which field implementations align with planning principles, and how a balance can be achieved between nature conservation, social acceptance, and energy efficiency.

In this regard, the study aims to provide not only a technical assessment but also a multidimensional analysis grounded in the axes of social, environmental, and spatial sustainability. By advocating for the integration of ecological sensitivities, the needs of local communities, and long-term land management strategies in the planning processes of SPP investments, this study seeks to offer a holistic contribution to energy policy development. It evaluate the rapidly expanding SPP investments in Türkiye not only in terms of their energy production capacity but also with respect to their multidimensional impacts on land use, ecosystem integrity, and rural socio-economic structures. The primary objective is to integrate findings from large-scale field implementations with ecological sensitivities, agricultural productivity dynamics, and social acceptance considerations in order to establish a sustainable planning framework for solar energy development. Beyond describing the current situation, the study advances innovative policy recommendations by highlighting the potential of agrovoltaic systems, nature-based solutions, and Geographic Information Systems (GIS)-supported decision-making tools. In doing so, it seeks to contribute to Türkiye's energy transition by promoting an approach that is environmentally responsible, socially equitable, and resilient in the long term.

2. Solar Power Plants and Land Use: A Conceptual Framework

Large-scale PV systems, particularly utility-scale SPPs, require extensive land areas for electricity generation. Ground-mounted PV facilities generally demand between 5 and 7 decares (approximately 2 to 2.8 hectares) of land per megawatt (MW) of installed capacity. This requirement varies depending on factors such as panel efficiency, slope, orientation, and the implementation of tracking systems. While fixed-tilt systems typically occupy less land, dual-axis trackers tend to require significantly more. Land requirements for SPPs fluctuate based on the type of plant, the technology employed, and regional geographical conditions. In particular, the amount of land needed per installed megawatt is a critical planning criterion for large-scale PV installations.

Initial estimates from the United States suggested that fixed-tilt PV systems required approximately 10 decares (around 4 hectares) per MW. However, these figures have been revised over time. According to the study conducted by Ong et al. [8], the average land requirement for fixed-tilt systems was calculated at approximately 7.5 decares per MW (roughly 3 hectares per MW). More recent data indicate that land-use intensity for fixed systems has decreased to as low as 0.35 Megawatt Direct Current (MWDC) per decare (approximately 2.8 decares per MWDC). This shift reflects the significant reduction in land required per unit of energy as a result of improvements in panel efficiency and more compact, optimized layout designs [9].

Under optimal conditions in Türkiye, each decare (1,000 m²) of land can support around 66 kilowatts (kW) of installed solar capacity. Accordingly, approximately 15 decares (1.5 hectares) are required for a 1 MW system [10]. However, these values are highly variable depending on panel type, layout configuration, terrain slope, orientation, and shading conditions [11]. The land requirement for fixed-tilt PV systems exhibits considerable variation due to the combined influence of technological and geographical factors. Current literature underscores that significant land savings can be achieved through the adoption of advanced, space-efficient installation designs enabled by technological advancements.

The areas selected for SPPs installations are typically low-productivity or underutilized lands, such as marginal agricultural areas, arid zones, and abandoned industrial sites. This preference is primarily driven by the goal of preserving fertile agricultural lands [12]. However, in practice, some SPP projects have been established on high-yield agricultural land, resulting in land-use conflicts and a reduction in ecosystem services [13]. Such land-use decisions, particularly when the balance between food production and energy generation is not adequately considered, pose significant risks to rural development and long-term environmental sustainability. To support more informed land-use decisions, it is crucial to implement planning frameworks based on agricultural land classification and to guide energy investments accordingly [13].

Additionally, agrivoltaic systems—integrated photovoltaic solutions designed to reduce land-use conflicts—enable simultaneous agricultural and energy production on the same plot of land, offering a holistic approach to land-use optimization [12]. This approach represents a significant innovation, especially for strategies aimed at simultaneously addressing food security and energy demand.

Land use in solar energy development should be evaluated not only in terms of energy production but also in light of its multidimensional impacts on agricultural productivity, ecosystem services, and rural development. In recent years, the increasing use of agricultural land for SPP projects has raised concerns regarding food security and land-use conflicts. For instance, in China, the allocation of high-quality farmland to solar energy projects has led to declines in agricultural output and emerging threats to food security [14]. To mitigate such issues, agrivoltaic systems have been developed to enable integrated agricultural and energy production on the same land. These systems create a synergistic land-use model by allowing agricultural activity to continue alongside energy generation [15].

Similar practices have begun to emerge in Türkiye as well. For example, the province of Konya, with its expansive flat terrain and high solar potential, has become a particularly attractive region for SPP investments. However, the impacts of such projects on agricultural land must be carefully evaluated [16].

Spatial planning in SPP investments must consider a broad spectrum of interrelated factors, including environmental sustainability, economic efficiency, and social acceptability. Within this framework, criteria such as solar irradiance potential, topography, existing land use, biodiversity, and infrastructure accessibility should be carefully evaluate. In particular, technical elements such as land slope, risk of shading, and proximity to transmission lines are critical determinants of system efficiency [17].

From an environmental perspective, the preservation of biodiversity, impacts on water resources, and risks of soil erosion are key concerns. To minimize ecological degradation throughout the project lifecycle, environmental oversight should be integrated into all phases—from site selection to construction and operational stages [18].

At the socio-economic level, meaningful involvement of local communities and a comprehensive assessment of social impacts are essential to ensuring long-term success. In renewable energy investments, public acceptability should be regarded as an equally significant consideration alongside technical and economic factors in decision-making processes [19]. Similarly, planning efforts should aim to balance localized socio-economic benefits with regional carbon reduction targets [20].

In SPP planning processes, land requirements, which vary by installation technology, play a pivotal role. Fixed-tilt photovoltaic systems, tracking PV technologies, and concentrated solar power (CSP) systems each have distinct spatial demands (see Table 1). The table shows that utility-scale PV and CSP systems require significantly larger land areas per unit of energy generated compared to rooftop PV, emphasizing the importance of careful site selection in land-scarce regions. These variations constitute critical parameters for investors and policymakers, not only in terms of economic performance but also in evaluating environmental impact. Therefore, technology selection is a strategic decision that influences not only energy output but also land sustainability. Land-use intensity has become one of the primary inputs in environmental and social impact assessments for solar projects [21].

Table 1. Land requirements by solar energy technologies [21]

Technology type	land requirement (hectare/MW)	Notes
Photovoltaic (Fixed Tilt)	3.2	Common fixed

		systems
PV (Tracking)	2.8	More efficient with tracker
CSP	3.6	Cooling systems may be required

To reinforce the comparative perspective, it is important to evaluate utility-scale PV systems in terms of land-use intensity (hectares per MW) across different regions. Comparative evidence from the United States, Europe, and China—drawing on studies such as Ong et al. [8] and van de Ven et al. [21]—offers a broader framework for understanding spatial requirements at the international level (Figure 1)

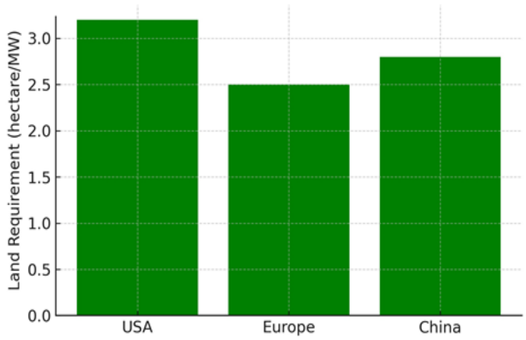

Figure 1. Land-Use Intensity of Utility-Scale PV in USA, Europe, and China (adapted from van de Ven et al., [21])

The increasing share of solar energy in electricity generation directly contributes to a rise in land use. According to the study by Van de Ven et al. [21], when the share of solar power in electricity production increases from 26% to 79%, the proportion of total land use rises from 0.5% to 2.8%. This non-linear growth trend underscores the necessity of evaluating energy policies in conjunction with principles of spatial sustainability. Figure 2 illustrates the increase in land use corresponding to the growing share of solar energy in electricity generation.

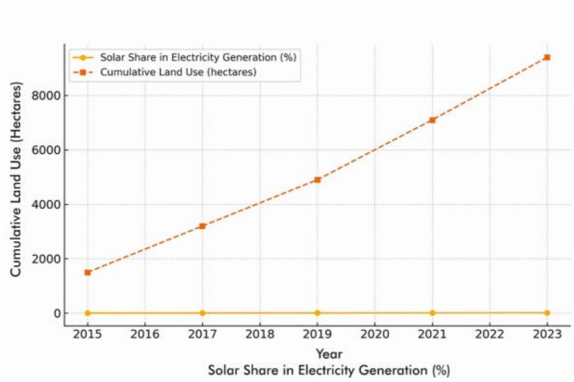

Figure 2. Land use increase associated with the growing share of solar power in electricity generation [21]

Solar energy development needs to be driven by a land use strategy that balances energy efficiency with agricultural productivity and ecological integrity. Prioritizing agrivoltaic systems and low-productivity land can reduce land use conflicts and increase sustainability.

3. Ecological and Social Risks

While SPPs offer low-carbon, environmentally friendly energy generation, their implementation may also give rise to significant ecological and social risks. Particularly in rural and natural areas, SPP projects can directly affect local socio-economic structures, land-use dynamics, and ecosystem services [5, 22]. Despite their clean energy credentials, projects implemented in these sensitive regions may disrupt existing human-environment relations and intensify socio-ecological vulnerabilities [23].

SPPs established in biodiversity-rich yet ecologically fragile regions can lead to habitat fragmentation and exert irreversible impacts on local flora and fauna. In particular, installations in semi-arid and rural landscapes may disrupt wildlife corridors, resulting in ecological isolation. This poses a serious threat to endangered species by reducing genetic diversity and increasing the risk of population collapse [24]. Infrastructure developments such as road construction and expansive panel arrays can compromise ecological integrity by shrinking habitats and increasing species extinction risks [5, 22].

Moreover, mechanical grading, soil compaction, and excavation works involved in SPP infrastructure construction reduce soil water retention capacity, decrease permeability, and heighten erosion risks

[6]. The use of heavy machinery and increased human activity during the installation phase alters ambient noise levels and disrupts biophysical conditions, inducing stress responses in bird species and soil invertebrates and often leading to displacement [5].

The shading effect produced beneath solar panels also causes significant microclimatic changes by altering soil moisture, temperature, and vegetation cover [25]. The visual impact of SPPs is another key concern; large-scale panel installations in natural and rural landscapes may disrupt scenic continuity, reduce aesthetic value, and adversely affect areas with tourism potential [6].

The spatial concentration of SPPs can also result in cumulative environmental impacts, such as the overuse of water resources, ongoing habitat degradation, diminished ecosystem services, and the potential exceedance of a region's ecological carrying capacity [22].

On the social dimension, insufficient inclusion of local populations in project processes may jeopardize the livelihoods of small-scale farmers and rural communities, potentially leading to social tensions. Such dynamics undermine the social acceptance of energy investments and foster growing distrust toward projects labeled as “green” [26]. For SPP projects to succeed in the long term, not only technical feasibility but also principles of social justice and ecological balance must be upheld. In this regard, the integration of Strategic Environmental Assessment (SEA) approaches into the planning processes of SPP projects is considered essential for enabling a more comprehensive analysis of cumulative impacts.

In regions with a high concentration of SPP developments, opaque land allocation procedures exacerbate perceptions of social injustice and threaten the foundations of social sustainability. Communities dependent on agriculture and livestock are indirectly affected, as disruptions to production patterns and reductions in rural employment have been observed. Over time, these investments tend to normalize the use of agricultural lands for energy production, contributing to speculative increases in land prices [27].

The lack of public participation in the planning of SPP investments undermines social acceptance and intensifies resistance behaviors. In certain regions of Türkiye, projects have been met with protests, legal disputes have arisen, and public trust has deteriorated [28]. This underscores the need to evaluate energy investments not only on technical and economic grounds but also in terms of their social legitimacy. Research indicates that public attitudes toward such projects are shaped not solely by perceived economic benefits but also by cultural connections to the land. Solar developments implemented in areas with traditional uses or symbolic meanings are often perceived as not merely economic but also cultural intrusions [29, 30].

In Türkiye, the limited adoption of agrivoltaic systems and the absence of regulatory support for such integrated practices have further intensified the disconnect between the energy and agricultural sectors [31]. This disjunction highlights the urgent need for strategic land management approaches.

Taken together, these issues suggest that SPP investments should be assessed not solely in terms of their energy generation potential but also through the lenses of social justice, ecosystem integrity, and rural development objectives. Land-use decisions must be approached holistically, accounting for biodiversity, soil fertility, water cycles, and public consent. Ultimately, energy policies must be aligned with the principles of social and environmental sustainability. While solar power offers environmental benefits, its spatial footprint poses significant socio-ecological risks. Long-term success depends on integrating biodiversity protection, social equity, and public participation into every stage of planning.

4. Land Use Trends in Solar Power Projects in Türkiye

Türkiye’s solar energy potential is remarkably high due to its geographic location and climatic characteristics. However, the regional distribution of this potential varies significantly depending on a range of factors. The geographical dispersion of SPPs across Türkiye is influenced by variables such as solar irradiation hours, land structure, and investor preferences. The Central Anatolia, Aegean, and Mediterranean regions have emerged as key hubs for solar investments due to their high solar potential and favorable land conditions.

The Central Anatolia Region, with its vast plains and extended sunshine duration, is particularly attractive for SPP development. Notably, the provinces of Konya, Kayseri, İzmir, Ankara, and Manisa stand out in terms of installed capacity. In contrast, although the Southeastern Anatolia Region possesses high solar irradiation potential, its solar investment levels have lagged behind due to intensive agricultural activities and investor inclinations [32].

Similarly, the Aegean and Mediterranean regions have experienced a significant concentration of SPP investments, driven by their advantageous solar exposure and land suitability. The provinces of İzmir, Manisa, and Antalya host several major solar energy projects. While Southeastern Anatolia has traditionally underperformed in solar investments despite its high potential, recent years have seen a noticeable increase in project activity in the region. The Eastern Anatolia and Black Sea regions, on the other hand, have been less preferred for SPP development due to rugged terrain and limited sunshine duration. However, with continued technological advancements and supportive incentive policies, the expansion of solar investments in these regions is anticipated [32].

SPP projects are generally implemented on lands with low productivity or in idle conditions, such as non-agricultural areas, marginal farmlands, and unused industrial zones. However, in some instances, highly productive agricultural lands have also been utilized for SPP development, leading to land-use conflicts and losses in ecosystem services [33]. A diverse range of land types is selected for SPP installations in Türkiye, and this distribution is a critical parameter in assessing both the environmental and economic impacts of solar projects.

While the majority of SPPs are concentrated on marginal agricultural lands or underutilized industrial areas with limited productivity, projects are also established on rangelands and dry farming fields. Nevertheless, such practices often entail various environmental and regulatory challenges [10, 34, 35]. The most commonly used land types for SPP installations and their associated characteristics are presented in Table 2. According to the data, degraded, arid, and industrially unused lands are the most preferred locations for solar installations, minimizing conflicts with agriculture and biodiversity.

Table 2. Most Common Land Types for Solar Power Plant Installations [36]

Land type	Description
Marginal agricultural lands	Low productivity lands unsuitable for agriculture. Most preferred areas for solar plant installations.
Pasture lands	Grazing lands for livestock. Installation requires special permission.
Dry agricultural lands	Areas cultivated without irrigation. Certain restrictions apply for solar plant installations.
Forest lands	Areas with forest status. Installation is generally prohibited or highly regulated.
Industrial and vacant lands	Unused or industrial lands outside residential areas. Suitable for solar installations.

In Türkiye, factors such as land slope, aspect (orientation), and elevation play a critical role in the site selection of SPP projects. For instance, plateau areas in Central Anatolia with low slope gradients are among the most preferred locations for solar plant installations. These areas not only offer favorable terrain but also benefit from high levels of solar irradiance, which contributes to enhanced system efficiency [37].

Site selection for SPPs involves multiple criteria such as solar radiation levels, distance to transformer stations, topography (slope and aspect), land use type, and proximity to roads, rivers, fault lines, and residential areas [38].

SPP projects in Türkiye are subject to evaluation under the Environmental Impact Assessment (EIA) Regulation. Projects with an installed capacity of 1 MW or more are required to undergo the EIA process. Within this framework, it is mandatory to obtain documentation verifying that the project area qualifies as non-agricultural land, as well as an official certificate of EIA exemption [33].

To minimize the environmental impacts of these projects, a comprehensive site selection process must also take into account criteria such as solar potential, topography, existing land use, biodiversity, and access to infrastructure [38]. These environmental considerations form an integral part of sustainable project development in the solar energy sector.

Spatial patterns of SPP development in Türkiye reflect a strong correlation between topography, solar potential, and land-use decisions. However, prioritizing degraded and underutilized lands remains essential to avoiding conflicts with agriculture and rural livelihoods.

Among European countries, Germany, Spain, Italy, and the Netherlands stand out with the highest installed solar capacities. Although Türkiye currently lags behind these countries in terms of capacity, it possesses significant potential to strengthen its position in the region (Figure 3).

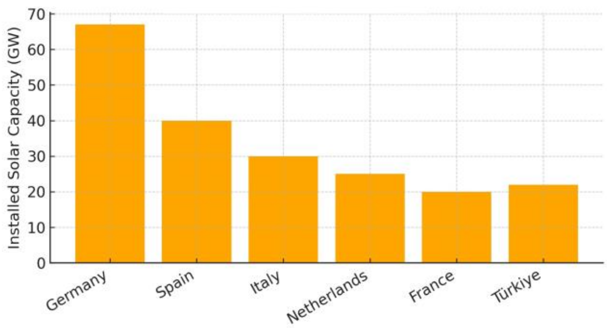

Figure 3. Solar Power Capacity in Selected European Countries (adapted from International Renewable Energy Agency (IRENA) [2])

5. The Current Status and Impacts of Solar Power Plants in Türkiye

Sustainable energy policies implemented in response to the global climate crisis have positioned solar energy as a clean, renewable, and economically viable source. With an annual average of 2,737 hours of sunshine and 1,527 kWh/m² of solar radiation, Türkiye ranks among the most advantageous countries in Europe for solar energy generation [39]. Consequently, solar energy investments have rapidly expanded across the country, playing a strategic role in the national energy transition.

As of the end of April 2025, Türkiye's total installed electricity generation capacity has reached 118,668 MW. Of this capacity, 18.7%—approximately 22,200 MW—is derived from solar energy. In line with the Ministry of Energy and Natural Resources' 2035 targets, this capacity is projected to increase to 53 Gigawatt (GW) [40].

To illustrate Türkiye’s seasonal solar energy potential, Table 3 presents monthly average global solar radiation and daily sunshine duration data. This table illustrates that the southern and southeastern regions of Türkiye consistently receive the highest levels of solar radiation and sunshine, reinforcing their strategic importance for future investments.

Table 3. Monthly average global solar radiation and sunshine duration in Türkiye [41]

Month	Avg. global radiation (kWh/m²/day)	Avg. sunshine duration (hours/day)
January	1.31	3.2
February	2.17	4.5
March	3.31	6.4
April	4.61	7.5
May	5.76	9.0
June	6.25	10.6
July	6.28	10.8
August	5.74	9.7
September	4.88	8.0
October	3.46	6.2
November	2.03	4.3
December	1.28	2.9

SPP investments generate significant environmental and social impacts, particularly in relation to site selection and land use. Case study analyses reveal that large-scale projects, in particular, affect agricultural production, water resources, and ecosystem services. Karapınar SPP (Konya), the largest solar energy investment in Türkiye, has an installed capacity of 1,350 MW and covers an area of 20 million square meters. Satellite imagery and GIS analyses indicate that the project has resulted in the loss of agricultural land, habitat fragmentation, and increased pressure on groundwater resources [42].

Table 4, compiled using the Energy Atlas database and publicly available energy reports, presents the distribution of installed solar capacity by province in Türkiye. The data highlights that provinces such as Konya, Ankara, and Gaziantep have the highest installed capacities, reflecting their favorable topography, high solar potential, and developed infrastructure networks. Figure 4 provides a visual representation of this data. The regional concentration of SPP investments varies according to factors such as solar irradiation duration, infrastructure accessibility, and land suitability. The visual distribution shows a clustering of solar power plants in Central Anatolia and the Aegean region, aligning with areas of high solar radiation and large expanses of flat, underutilized land.

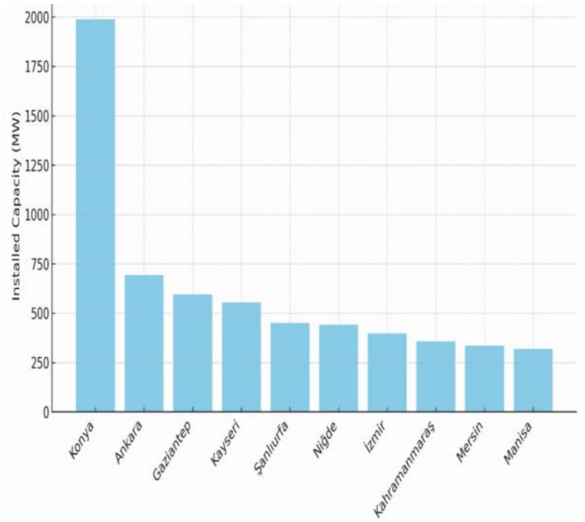

Figure 4. Distribution of installed solar power capacity by province in Türkiye [18].

Table 4. Distribution of installed solar power capacity by province in Türkiye [18]

Province	Installed capacity (MW)
Konya	1990
Ankara	694
Gaziantep	595
Kayseri	555
Şanlıurfa	451
Niğde	442
İzmir	398
Kahramanmaraş	358
Mersin	335
Manisa	319

Osmaniye province has emerged as one of the pioneering regions for SPP investments due to its high solar irradiation levels and the prevalence of barren lands with limited agricultural productivity. In a GIS-based study conducted by Nacar [27], a land use analysis was performed comparing pre- and post-installation conditions of completed SPP parcels. The results revealed irreversible alterations in pasturelands and natural vegetation, leading to increased erosion risks and losses in local biodiversity.

Although SPP projects in Elazığ have generally been established on arid lands with low agricultural value, evidence suggests that they have impacted the region's hydrological balance. Reports indicate that surface water resources previously used for irrigation by local communities have been redirected or depleted, and there has been a noticeable decline in public acceptance of these projects [43].

In Niğde, unlicensed small-scale SPP projects have been implemented primarily to meet the energy demands of agricultural irrigation systems. However, in some cases, agricultural lands have been permanently converted into energy infrastructure zones. This transformation is noted as a potential long-term threat to food production [27].

In Şanlıurfa, SPP investments have been predominantly developed on lands owned by irrigation cooperatives. While these installations demonstrate high efficiency, they have also led to land-use conflicts between agricultural production and energy generation activities [44].

SPP projects located within the Lake Van basin carry distinct environmental significance. Situated near protected archaeological and natural sites, these installations have raised concerns over visual pollution, habitat loss, and disruptions to ecosystem integrity [22].

SPPs in Korkuteli and Elmalı (Antalya) benefit from strong solar radiation, ensuring high energy efficiency. However, their placement on the Taurus Mountain foothills may disrupt local microclimates, posing risks to the region's sensitive ecosystems [45].

The integration of photovoltaic systems with green roof applications has the potential to reduce both building energy consumption and the urban heat island effect compared to bare roof surfaces. Experimental findings by Chen et al. [46] demonstrated that PV–Green Roof combinations significantly lowered hourly air temperatures and mitigated the temperature rise observed on bare roofs, limiting the difference to approximately 4 °C on sunny days.

Rooftop solar applications, developed in cooperation with industrial and municipal entities, are particularly widespread in industrial zones such as Ankara and İzmir (Aliağa). These systems provide sustainable solutions to meet urban and industrial electricity demand [39].

Some other noteworthy SPP projects across Türkiye include:

Kızıldere SPP (Denizli–Aydın): This project integrates a hybrid energy model with geothermal facilities, serving as a model for the combined use of renewable energy sources [36].

Başkent SPP (Ankara): Developed in partnership with the municipality and organized industrial zones, this plant supplies electricity for urban consumption while generating public revenue.

İzmir Aliağa SPP: Located in an organized industrial zone, this facility meets industrial electricity demand through rooftop photovoltaic panel installations [47].

Mersin SPP Projects (Tarsus, Silifke): Established near agricultural lands, these installations have led to land-use conflicts between energy infrastructure and agricultural production [48].

Case studies demonstrate that solar investments in Türkiye should be evaluated within a broader framework that includes not only energy production but also spatial planning, agricultural policy, water management, and environmental protection. These studies reveal the dual nature of SPP impacts: while advancing renewable energy goals, they also introduce localized environmental and social challenges. A region-specific and participatory planning approach is crucial for ensuring equitable outcomes.

6. Recommendations and a Roadmap for Sustainable Solar Power Plant Planning

The rapid expansion of SPPs in Türkiye necessitates the adoption of sustainability-oriented land-use strategies. SPP planning that safeguards socio-ecological balance requires a comprehensive policy approach encompassing alternative site selection, the implementation of integrated models, the promotion of participatory processes, and the integration of nature-based solutions. With the acceleration of Türkiye's energy transition policies, a significant increase in the number of SPPs has been observed. However, this expansion has simultaneously intensified land-use pressures and triggered competition among natural and economic resources. Planning SPPs with environmental sustainability in mind requires a holistic approach that balances energy potential with ecological resilience, agricultural protection, and social justice [49].

Long-term success in SPP deployment depends not only on technological efficiency but also on site selection practices that avoid disrupting ecosystem services, alignment with land-use planning principles, and investment decisions that are responsive to community needs [50]. In this context, the prioritization of idle or low ecological value lands located outside environmentally sensitive and biodiversity-rich areas yields more favorable outcomes in terms of both environmental protection and social acceptance [51].

One of the key challenges in Türkiye's solar planning process is the lack of inter-sectoral coordination. Without ensuring coherence among energy, environmental, agricultural, and urban development policies, the contribution of SPP investments to sustainable development will remain limited. Therefore, national strategies designed for energy projects must be integrated with spatial planning, climate adaptation, and rural development policies [41]. Site selection for SPPs should not rely solely on technical feasibility but must also account for environmental carrying capacity and social sensitivities. Instead of targeting agricultural lands and biodiversity-rich areas, priority should be given to degraded or idle lands in proximity to industrial zones [50].

Rather than conducting a direct spatial analysis, this study draws on existing GIS-integrated methods, including Analytic Hierarchy Process (AHP) and Fuzzy Logic, to frame a conceptual understanding of spatial planning challenges in solar power development. These tools are discussed in a theoretical context to illustrate their potential for enhancing environmental decision-making. Although this study does not directly employ GIS-based multi-criteria decision-making tools such as AHP, Fuzzy Logic, or TOPSIS, these methods are extensively reviewed and discussed to demonstrate their relevance and applicability to sustainable solar site selection. The methodological references provided aim to inform future research and planning frameworks in Türkiye's solar energy landscape.

The sustainability of SPP projects is directly linked to appropriate site selection. This process should not be limited to technical factors such as solar irradiation duration, slope, or infrastructure accessibility; it must also incorporate environmental and social dimensions, including the preservation of natural habitats, continuity of cultural landscapes, and disaster risk mitigation. Geomorphologically sensitive areas—such as those prone to landslides, floods, or erosion—should be carefully assessed, as they pose long-term investment risks [34].

A sustainability-focused approach to land selection aligns with the principle of land sparing, which aims to spatially separate land designated for production from land designated for conservation. Within this framework, ecologically low-value areas such as abandoned mining sites, unused industrial zones, or saline and barren soils are recommended for solar development [5]. This strategy not only prevents pressure on natural ecosystems but also reduces the potential for socio-spatial conflicts in land use.

To support multi-criteria decision-making processes in renewable energy investments, the integration of GIS, remote sensing technologies, and

AI-assisted modeling is strongly recommended. In the sustainable planning of SPPs, spatial decision support systems are playing an increasingly critical role. GIS-based multi-criteria analysis (MCA) methods have proven to be valuable tools in identifying environmentally optimal sites for solar installations [52, 53].

Studies conducted in various regions of Türkiye demonstrate the effectiveness of combining GIS with multi-criteria decision-making (MCDM) techniques such as the AHP, Fuzzy Logic, and TOPSIS. In a case study focused on wind energy siting in Kastamonu province, AHP was used to assign criterion weights, while Fuzzy Logic facilitated suitability analyses. This methodological integration offered decision-makers a more objective and systematic evaluation framework [54]. Similarly, a school site selection study conducted in Ankara utilized AHP and TOPSIS integrated with GIS to evaluate alternatives and identify optimal locations [55].

GIS-based MCDM methods strengthen the objectivity of site selection for solar power plants by enabling the comprehensive evaluation of technical, environmental, and economic factors. The findings of Nassar et al. [56] demonstrate that integrating criteria such as land use, slope, solar irradiance, and grid accessibility with geospatial data allows for the identification of the most suitable locations. In this context, the institutionalization of GIS-MCDM approaches as a mandatory component of planning processes would contribute to safer, more efficient, and environmentally responsible investment decisions at both local and national scales.

GIS provide a vital platform for visualization and analysis by enabling the simultaneous evaluation of multiple factors such as solar irradiation duration, land slope, aspect, land use type, and ecological protection zones [57]. In particular, the AHP offers a scientific basis for decision-making by assigning relative weights to criteria. In practice, the integration of AHP and GIS in Türkiye has yielded effective results not only in terms of technical suitability but also in enhancing environmental sustainability.

For instance, in a study conducted in Manisa province, AHP and Fuzzy Logic methods were integrated with GIS to determine the most suitable areas for SPP installations. The analysis revealed that approximately 14.5% of the province's territory was classified as highly suitable, with these zones predominantly located in plains and plateau regions. Moreover, siting SPPs away from high-productivity agricultural lands presents a significant advantage in terms of environmental sustainability [53]. Such systematic approaches also contribute to increased transparency in local government planning processes and help mitigate land-use conflicts.

The AHP-Objective Hierarchy (OH) approach developed by Dinçer et al. [58] underscores the importance of methodological standardization in solar power plant site selection. By reducing the influence of subjective assessments, this method optimizes hierarchy matrices based on expert judgments and ensures that decision outcomes are more reproducible. In GIS-based multi-criteria decision-making processes, the use of predefined criterion weights minimizes subjectivity in weighting procedures and enhances the reliability of the results. The application carried out in the Konya region demonstrated that the outcomes of conventional AHP and AHP-OH diverged, providing evidence that standardized methodologies can yield more consistent and reliable results in site selection.

In recent years, hybrid techniques such as Fuzzy AHP and Entropy Weighting have also been integrated with GIS. These approaches are particularly valuable in reducing uncertainty and enhancing objective data analysis during decision-making processes. As a result, energy planning can effectively account not only for economic and technical parameters but also for social and environmental sensitivities.

Agrovoltaic systems, which allow for simultaneous agricultural and energy production, offer a critical solution for the preservation of fertile agricultural lands. These integrated models support sustainable food production while creating additional space for energy generation. Successfully implemented in countries such as Germany, France, and Japan, the expansion of such systems in Türkiye would benefit from the development of supportive policy mechanisms [59].

Agrovoltaic systems represent an innovative approach that integrates traditional solar energy practices with agricultural activity on the same land, thereby addressing both food and energy security. Elevated panel structures used in these systems provide shading, which can enhance photosynthetic efficiency in crops under water stress conditions [60]. This contributes to the continuity of agricultural production in Mediterranean climate zones, where drought risk is particularly high.

Beyond productivity gains, agrovoltaic systems also offer additional income streams for farmers. Research has shown that these models provide non-agricultural revenue sources for farmers, leading to the creation of new energy-related employment opportunities in rural areas. This multifunctional structure offers economic diversification and resilience, especially for small and medium-scale producers.

Analyses conducted in Türkiye demonstrate that agrivoltaic systems—by integrating agricultural production and energy generation on the same land—hold significant potential for advancing sustainability. However, the lack of a comprehensive legal framework currently presents a major barrier for investors. A well-defined regulatory framework and incentive scheme coordinated between the Ministry of Agriculture and Forestry and the Ministry of Energy and Natural Resources is essential to expanding these systems [61].

Involving local communities, civil society organizations, and ecosystem experts in the design phase of SPP projects has been shown to enhance social acceptance and reduce conflicts. Under ecological balance criteria, project planning must integrate elements such as habitat integrity, species diversity, and landscape continuity [6]. These considerations should form the basis of EIA procedures. Minimizing the environmental and social impacts of SPPs requires not only technical analysis but also a multi-stakeholder and inclusive planning process. Particularly in rural areas, the active involvement of local communities and knowledge holders enhances the legitimacy and ecological compatibility of project implementation [26]. Participation should go beyond simple consultation and involve communities directly in decision-making processes, thereby ensuring alignment between local values and investment planning.

In ecologically responsible SPP planning, not only designated nature conservation areas but also potential habitat corridors, migratory bird pathways, and microecological thresholds should be taken into account. The literature has noted that large-scale solar developments can disrupt landscape integrity, creating fragmentation effects particularly for highly mobile species [24]. Therefore, the preservation of ecological corridors should be a key planning priority. Moreover, EIA processes for SPP investments should not be limited to documenting environmental impacts but must also include mitigation mechanisms and the integration of nature-based solutions. An effective EIA process should adopt an interdisciplinary structure involving not only environmental engineers, as well as ecologists, sociologists, and landscape planners. This holistic approach would support the development of more resilient energy systems aligned with sustainable development goals.

Finserås [62] emphasizes that renewable energy projects should not be evaluated solely in terms of energy generation but also in relation to broader sustainable development objectives, such as ecosystem restoration and biodiversity conservation. The study highlights the importance of integrating nature-based solutions (NbS) into environmental and energy law to achieve these goals. It further stresses that regulatory frameworks, including renovation and land-use permitting processes, should prioritize nature-compatible measures such as habitat restoration, soil health, and water management. Moreover, the research concludes that the legal framework for the energy transition must incorporate clear public interest criteria for NbS and ensure that compliance with these standards can be effectively monitored.

In SPP planning, nature-based solutions such as green infrastructure, native vegetation restoration, and soil conservation practices should be prioritized. These practices contribute to the preservation of carbon sink capacities and the continuity of local ecosystem services [63]. The European Union’s “Nature-Compatible Energy Transition” strategy, which seeks to integrate energy policy with environmental and climate change agendas, offers a valuable policy framework that Türkiye could adopt as a model [64].

The necessity of nature-based site management and ecological monitoring in solar power plants is supported by evidence of bird community responses to habitat quality. A large-scale study by Copping et al. [65] demonstrated that solar farms managed with mixed habitats provided higher bird abundance and species richness than both simply managed solar farms and surrounding agricultural land, while also offering important habitats for threatened farmland bird species. Structural heterogeneity, including features such as woody vegetation, hedgerows, and diverse flowering ground cover, was closely associated with these positive outcomes. These findings indicate that wildlife-friendly management practices can enhance ecological sustainability and contribute to broader conservation objectives.

To mitigate the environmental impacts of SPPs and safeguard ecological integrity, the integration of NbS into planning processes has become increasingly critical. Nature-based approaches offer multifaceted benefits such as habitat design compatible with energy generation, biodiversity-enhancing landscape restoration, and natural water management practices [66]. These measures not only reduce environmental risks but also strengthen the climate resilience of local communities.

Among the nature-based practices applicable to SPP sites, establishing pollinator-friendly vegetation beneath solar panels and utilizing these areas as bee pastures has gained prominence. This approach enhances ecosystem services while simultaneously generating economic value through local beekeeping activities [67]. Furthermore, on sloped terrains susceptible to erosion, the application of natural terracing and biotechnical soil stabilization techniques can prevent land degradation while extending the operational lifespan of solar infrastructure.

International energy planning frameworks increasingly advocate for nature-based solutions not merely as complementary measures but as central components of strategic planning. Policies issued by International Union for Conservation of Nature (IUCN) and United Nations Environment Programme (UNEP) emphasize that ecosystem-based planning forms a foundational pillar of long-term sustainability in energy investments [68]. In Türkiye, promoting these approaches through legal mandates and incorporating them into EIA requirements would ensure that the transition to green energy is ecologically resilient.

To ensure spatial justice in SPP development, it is recommended that mandatory GIS-based analytical processes be implemented, prioritizing degraded land based on soil quality, and encouraging local-level energy partnerships to strengthen public engagement in investment decisions. The land selection process for SPPs must be guided not only by technical feasibility but also by comprehensive spatial sustainability principles. In this context, making multi-layered GIS analyses a legal requirement in pre-investment stages is considered a strategic necessity for environmental protection, settlement balance, and the continuity of agricultural production. This would allow for the identification of sites that are not only high in solar potential but also low in ecological and social risk, thereby minimizing overall project impacts.

Protecting fertile agricultural lands from energy development has become an urgent priority to prevent conflict between sustainable energy policies and food security. As such, degraded, unproductive, or abandoned lands should be designated as priority investment zones. In doing so, a balance between energy generation and ecological integrity can be achieved, enabling energy projects to proceed under a socially cohesive, low-conflict land-use paradigm.

In rural regions where SPPs are implemented, consideration must extend beyond technical feasibility to include community sense of ownership and participation in decision-making processes. For this reason, the development of small-scale energy cooperatives and partnership models involving direct community participation is strongly recommended. This would transform energy generation from being a purely economic activity into a socially grounded mechanism that fosters local ownership and contributes to regional prosperity.

Sustainable SPP development requires a paradigm shift—from purely technical site assessments to holistic, GIS-informed, and community-inclusive planning. Integrating nature-based solutions and agrovoltaic systems is key to achieving long-term ecological and social resilience.

7.Conclusion and Recommendations

This study has evaluated the impacts of SPPs on land use and ecosystems in Türkiye through a multidimensional approach. While SPP investments contribute to environmentally friendly energy production through low carbon emissions, they also lead to significant transformations in both social and ecological systems within the areas where they are implemented. In particular, the occupation of agricultural lands, pasture areas, and natural habitats by solar projects introduces serious risks such as land-use conflicts, the degradation of ecosystem services, and loss of biodiversity.

The case studies discussed—Osmaniye, Elazığ, Niğde, Şanlıurfa, Van, Antalya, Kızıldere, Başkent, İzmir, and Mersin—demonstrate that SPPs exhibit diverse dynamics in terms of site selection, social acceptance, land use, and environmental impacts. These variations underscore the critical importance of regional context and local participation in solar energy planning. Especially promising are agrovoltaic systems, which integrate agriculture and energy production, offering a viable solution to enhance ecological sustainability while protecting the livelihoods of local communities.

The findings indicate that land selection processes must be evaluated not solely based on technical suitability but also in conjunction with variables such as environmental carrying capacity, soil fertility, water cycles, visual impacts, and public acceptance. Ensuring sustainable SPP development requires mandatory use of GIS and multi-criteria decision methods, prioritization of degraded lands thro While this paper does not present ugh soil quality assessments, and the establishment of community-based energy partnerships.

Considering the average lifespan of solar panels of approximately 25–30 years, a substantial volume of panel waste is expected to emerge globally in the coming decades. Uncontrolled disposal of these panels poses significant risks to ecosystems and human health, particularly due to the potential leaching of toxic elements such as lead, cadmium telluride, and selenium into soil and groundwater [69]. Moreover, the rapid growth of panel waste is likely to place additional pressure on landfill capacity, thereby exacerbating environmental burdens. Recycling processes are therefore of strategic importance, not only for mitigating environmental impacts but also for recovering valuable materials such as glass, aluminum, silver, silicon, and rare metals for reintegration into the circular economy [70]. Current technologies, including mechanical separation, thermal treatment, and chemical processes, enable the recovery of 80–90% of materials [71]. In the European Union, PV modules are subject to mandatory recycling under the Waste Electrical and Electronic Equipment (WEEE) Directive, while similar regulatory frameworks have also been developed in Japan and the United States [72]. In Türkiye, the development of specific legislation, financial incentive mechanisms, and technological infrastructure is critical to effectively manage the future volume of panel waste. Accordingly, the integration of PV module recycling into national energy policies should be regarded as an essential component of a sustainable energy transition.

The proposed policy framework for Türkiye emphasizes the prioritization of degraded, underutilized, and low-productivity lands; the promotion of agrovoltaic practices; the integration of nature-based solutions into planning processes; and the active participation of local communities in decision-making mechanisms. Through this comprehensive approach, it will be possible to simultaneously achieve renewable energy targets and maintain socio-environmental balance.

While this paper does not present an original application of spatial modeling techniques, it synthesizes findings from recent studies to propose an integrated framework for future energy planning. Further empirical research involving multi-criteria decision analysis tools is recommended to operationalize the planning strategies discussed herein. Most existing studies focus primarily on the technical or economic feasibility of solar power plants. In contrast, this study makes an original contribution to the literature by addressing solar energy development in Türkiye as a socio-ecological phenomenon. By integrating regional case studies with national land-use trends, the research highlights dimensions that have been relatively underexplored in the literature, such as cumulative ecosystem risks, issues of spatial justice, and the implications for rural livelihoods. Furthermore, the proposal to incorporate agrovoltaic models, nature-based solutions, and GIS-based decision support processes as strategic tools to minimize land–energy conflicts strengthens the innovative aspect of this work.

This multidimensional approach not only synthesizes existing best practices but also redefines solar energy investments as socio-environmental interventions rather than purely technological projects. The study provides novel insights into how renewable energy transitions can be made more spatially just, ecologically resilient, and socially inclusive, while simultaneously offering a forward-looking roadmap for policymakers and stakeholders.

For future research, the development of comprehensive environmental modeling tools to monitor the long-term ecological impacts of SPP projects is of critical importance. In this context, there is a need for advanced scenario-based studies supported by spatiotemporal data analytics to track the effects of solar installations on habitat fragmentation, soil moisture balance, microclimate alterations, and biodiversity. Furthermore, systematic testing of agrovoltaic systems—still not widely adopted in Türkiye's conditions—should be conducted to evaluate their performance in terms of agricultural productivity, energy efficiency, and water use. Such studies would provide concrete evidence of this integrated model's potential contribution to rural development.

In addition, qualitative research focusing not only on the technical and environmental aspects of SPPs but also on their cultural and social dimensions should be prioritized. Local communities' relationships with nature, traditional land-use practices, and the symbolic meanings attached to landscapes significantly influence the social acceptance and long-term success of energy projects. Therefore, participatory socio-cultural impact assessments are essential for developing strategies that enhance both social cohesion and environmental sustainability of solar energy investments.

Future research should aim to: (i) develop models for long-term monitoring of ecological impacts from SPPs, (ii) analyze agrovoltaic systems' performance under local conditions, and (iii) investigate community perceptions and socio-cultural dimensions of solar projects. These efforts would help ensure that Türkiye’s energy transition is grounded not only in installed capacity but also in social well-being and ecological resilience.

In line with all these recommendations, Türkiye’s energy transition should be built upon a foundation that prioritizes not merely the expansion of installed capacity but also the principles of social welfare, environmental integrity, and ecological resilience. This approach will enable the redesign of energy systems in a manner that is not only efficient for today but also just, inclusive, and nature-compatible for future generations.

For the sustainable expansion of solar power plants in Türkiye, it is essential to restrict the use of highly productive agricultural lands and to direct investments towards low-yield, degraded, or non-agricultural industrial areas. In planning processes, the mandatory application of GIS-based multi-criteria decision-making methods, consideration of environmental carrying capacity, and implementation of strategic environmental assessment are strongly recommended. Furthermore, the integration of agrovoltaic systems and nature-based solutions into the legal and institutional framework will provide long-term benefits for both energy generation and agricultural sustainability. Ensuring the active participation of local communities in decision-making processes and promoting small-scale energy cooperatives will strengthen social acceptance and reduce potential conflicts during investment phases. Collectively, these recommendations contribute to an energy transition in Türkiye that is not solely focused on capacity expansion but is instead grounded in ecological integrity, social equity, and rural development.

Nomenclature

AHP	Analytic hierarchy process
CSP	Concentrated solar power
EIA	Environmental impact assessment
GIS	Geographic information systems
GW	Gigawatt
IRENA	International renewable energy agency
IUCN	International union for conservation of nature
kW	Kilowatts
MW	Megawatt
MWDC	Megawatt direct current
MCA	Multi-criteria analysis
MCDM	Multi-criteria decision-making
NbS	Nature-based solutions
OH	Objective hierarchy
PV	Photovoltaic
SPP	Solar power plant
SPPs	Solar power plants
SEA	Strategic environmental assessment
UNEP	United nations environment programme
WEEE	Waste electrical and electronic equipment

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