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Evaluating Land Use Optimization for Renewable Energy Projects: Spatial Planning and Multi-Objective Siting for Utility-Scale Solar and Wind

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Abstract- Utility-scale solar photovoltaics and onshore wind are central to power-system decarbonization, yet land availability, cumulative environmental impacts, and community acceptance increasingly constrain project pipelines. These constraints are often amplified by inconsistent land-use reporting: a project's direct impact area (land physically disturbed or occupied) differs from its total project area (the broader boundary associated with spacing, buffers, and parcels), leading to mismatched interpretations of trade-offs. This paper synthesizes peer-reviewed evidence and agency guidance to develop a transferable framework for land-use optimization in renewable energy siting. The framework integrates (i) geospatial screening and suitability mapping (GIS-based multi-criteria decision analysis), (ii) multi-objective portfolio optimization (e.g., Pareto-efficient site sets), and (iii) planning and policy instruments that operationalize "low-conflict" development (e.g., designated development areas and program-level environmental assessment). Results emphasize that land-use intensity varies strongly by technology and by the metric used; consequently, planning outputs should report both direct and total areas with explicit definitions. The synthesis further shows how strengthened avoidance of high conservation-value areas, early integration of grid feasibility, and transparent benefit-sharing and participation mechanisms can reduce conflict without undermining deployment. The paper concludes with best-practice recommendations and an implementable roadmap for agencies and developers to embed spatial optimization into permitting and long-term land-use plans.

Keywords: renewable energy siting; land-use optimization; spatial planning; GIS; multi-criteria decision analysis; multi-objective optimization; utility-scale solar; onshore wind; mitigation hierarchy; social acceptance.

I. INTRODUCTION

Land is simultaneously an enabling resource and a binding constraint for utility-scale renewable energy. Unlike fuel-based generation, wind and solar must be located where resource quality, terrain, and grid interconnection are feasible; this geographic dependence concentrates development pressure and can intensify competition with agriculture, biodiversity conservation, cultural landscapes, and nearby residents (Wu et al., 2023; USDA ERS, 2024).

Land-use debate is frequently shaped by inconsistent metrics. For planning, permitting, and public communication, it is essential to distinguish between direct impact area—land physically occupied or disturbed by permanent infrastructure (e.g., panel arrays, turbine pads, access roads, substations)—and total project area—the broader land area associated with project boundaries, spacing, and buffers (Denholm et al., 2009; Ong et al., 2013). These measures imply different trade-offs: wind projects often have large total areas due to turbine spacing but small permanent footprints, while ground-mounted photovoltaic (PV) facilities tend to be more spatially contiguous.

This paper addresses land-use optimization for utility-scale solar (ground-mounted PV and concentrated solar power, where relevant) and onshore wind through an interdisciplinary lens that links geospatial decision support, optimization algorithms, evidence on documented impacts, and planning and regulatory mechanisms. The analysis is intentionally transferable rather than jurisdiction-specific: it is designed to be parameterized with local legal constraints, ecological priorities, and social values.

Contribution and novelty. The paper translates a fragmented siting literature into an implementable, end-to-end workflow that produces decision-relevant outputs. The contribution is threefold: (i) a standardized terminology and reporting template for land-use accounting (direct impact area versus total project area, with explicit denominators); (ii) an integrated technical workflow that couples GIS-based screening and suitability mapping with multi-objective portfolio optimization to generate transparent trade-off sets; and (iii) a governance mapping that connects technical outputs to spatial planning instruments and permitting processes (e.g., designated development areas, programmatic review, and the mitigation hierarchy).

Research questions. The paper is structured around four questions:

1) How can land-use impacts and conflicts for utility-scale solar and wind be characterized using consistent definitions and measurable indicators, and what are the primary drivers of conflict (Denholm et al., 2009; Ong et al., 2013; USDA ERS, 2024)?

2) What siting criteria and GIS-based methods are most robust for identifying low-conflict, high-yield sites, and which data limitations most strongly affect validity (Malczewski, 2006; Martínez-Gordón et al., 2021)?

3) Which optimization formulations and solution approaches are best suited for renewable siting portfolios, and how should objectives and constraints be structured for decision relevance (Deb et al., 2002; Dantzig, 1963)?

4) Which policy and regulatory mechanisms most effectively mainstream land-use optimization into planning and permitting, and what implementation roadmap follows (Directive (EU) 2023/2413; European Commission, 2024; Bureau of Land Management, n.d.)?

II. METHODS

This study is a structured synthesis rather than a single-location empirical siting model. The methodology integrates: (i) peer-reviewed literature on renewable siting, GIS-based multi-criteria decision analysis (GIS-MCDA), and multi-objective optimization; (ii) empirical land-use studies and documented environmental and socioeconomic impacts; and (iii) official datasets and planning guidance relevant to land-use optimization and permitting.

Standardized terminology and reporting conventions. Three terms are used consistently throughout:

- **Direct impact area:** land physically occupied or disturbed by permanent infrastructure (Denholm et al., 2009; Ong et al., 2013).
- **Total project area:** the broader boundary associated with spacing, buffers, and parcels; for wind, this can include land that remains available for other uses (Denholm et al., 2009; USDA ERS, 2024).
- **Land-use optimization:** a systematic process to identify sites (or portfolios of sites) that meet energy targets while minimizing conflict across environmental, social, and economic objectives—typically via GIS constraint screening, suitability modeling, and portfolio optimization (Malczewski, 2006; Deb et al., 2002).

Where land-use intensity is reported, the denominator is stated explicitly (e.g., acres per MW_AC for solar where the source uses inverter-based AC capacity, and hectares per MW for wind).

Analytical framework. The reference framework has two stages:

Stage 1 (spatial feasibility and suitability) harmonizes spatial datasets, applies legally prohibited or technically infeasible exclusions (fatal-flaw screening), and ranks remaining land using GIS-MCDA. GIS-MCDA provides a transparent structure for multi-criteria evaluation but is sensitive to weight selection and layer standardization—necessitating sensitivity analysis and uncertainty reporting (Malczewski, 2006).

Stage 2 (portfolio selection and trade-off analysis) delineates candidate site polygons from feasible land and selects portfolios that meet targets and constraints while balancing multiple objectives. Multi-objective evolutionary approaches such as NSGA-II generate Pareto-efficient trade-off sets when objectives conflict (Deb et al., 2002). Exact methods (e.g., mixed-integer programming) can be advantageous when strict constraints and network structure must be enforced and computational scale is manageable (Dantzig, 1963).

Objectives and constraints (illustrative). A decision-relevant formulation typically includes: maximize expected annual energy production; minimize ecological conflict; minimize social conflict; and minimize grid and access costs. Hard constraints represent legal prohibitions and engineering infeasibilities. Soft constraints penalize high-conflict areas that are not legally excluded, enabling scenario analysis under different policy settings (Wu et al., 2023).

Data sources and representative datasets. A minimum dataset library typically spans renewable resource layers (Global Solar Atlas; Global Wind Atlas), land cover/land use (e.g., ESA WorldCover), protected areas and conservation designations (e.g., WDPA), infrastructure layers, jurisdiction-specific planning layers, and socioeconomic layers used for justice analysis (World Bank Group / ESMAP, 2020; Davis et al., 2023; UNEP-WCMC & IUCN, n.d.; U.S. Department of Energy, 2023).

Data gaps and limitations. Common gaps include parcel ownership/lease constraints, high-resolution biodiversity layers, and grid hosting capacity or interconnection queue constraints. When detailed grid data are unavailable, early-stage analysis may approximate feasibility using distance-based proxies, with limitations disclosed (U.S. Department of Energy, 2022).

III. RESULTS

This synthesis produces a decision-support framework and a set of standardized reporting outputs suitable for planning and permitting.

Land-use metrics synthesis

A central result of the evidence base is that technology comparisons are only meaningful if land-use metrics are reported with consistent definitions.

Table 1 summarizes representative empirical values commonly used in planning discussions.

Technology	Metric definition	Representative value	Key interpretation for planning
PV (large utility-scale)	Total area (acres/MW_AC)	~7.9	Contiguous land footprint; strong potential for farmland competition in certain regions
PV (large utility-scale)	Direct area (acres/MW_AC)	~7.2	Disturbed/occupied land used as "direct impact" proxy
CSP (utility-scale)	Total area (acres/MW_AC)	~10	Higher total area than typical PV averages in NREL sample
Wind (modern projects)	Permanent direct impact (ha/MW)	0.3 ± 0.3	Small physical footprint per MW; direct disturbance concentrated in pads/roads
Wind (modern projects)	Total area (ha/MW)	34.5 ± 22.4	Large total area due to spacing; co-use often feasible but not universal
Utility-scale solar and wind (rural U.S., 2020)	Total footprints (acres)	Solar ~336,000; Wind ~88,000	National footprint is small share of farmland, but local hotspots create conflict

These values highlight two planning-relevant points. First, wind projects typically have small permanent direct impacts per unit of capacity but large total project areas due to spacing, which can allow continued agricultural co-use in many cases (Denholm et al., 2009; USDA ERS, 2024). Second, PV projects tend to have more contiguous footprints, making competition with prime agricultural land and other land uses more direct in certain regions (Ong et al., 2013; American Farmland Trust, 2022).

Solar land requirements also evolve with technology and design. Empirical updates show that PV power density increased substantially over the last decade of large-scale deployment, implying that siting analyses should update density assumptions and distinguish among configurations where these differences affect land-use outcomes (Bolinger & Bolinger, 2021).

Comparison of decision-support and optimization methods

Table 2 compares the main method families used across the siting literature and practice, from constraint screening through portfolio optimization

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Method family	Example methods	Typical decision variables	Strengths	Limitations / risk modes	Best use cases
GIS constraint screening	Exclusion masks, buffers, setback rules	Cell feasibility (0/1)	Transparent and fast; aligns with legal constraints	Can over-simplify; buffer choice drives outcomes	Early-stage fatal-flaw screening
GIS-MCDA suitability mapping	Weighted linear combination; AHP; TOPSIS; fuzzy variants	Suitability score per cell	Communicable; integrates diverse criteria	Weight subjectivity; compensability can hide fatal impacts	Candidate area identification and stakeholder dialogue
Exact optimization	MILP / integer programming	Build/no-build site selection; capacity allocation	Rigorous constraints; reproducible; interpretable	Computationally hard at high resolution; requires careful linearization	Portfolio selection with network constraints
Evolutionary multi-objective optimization	NSGA-II	Site set selection; weights implicit through Pareto search	Produces trade-off frontier; handles non-linearities	Requires calibration; results can be sensitive to encoding	Multi-objective siting portfolios where stakeholders choose trade-offs
Swarm/metaheuristics	PSO, genetic algorithms	Similar to evolutionary; often continuous	Flexible; good for complex search spaces	Less interpretable; convergence uncertainty	Micrositing/layout optimization or complex non-linear objectives

Representative dataset library for spatial optimization

Table 3 summarizes a core dataset library frequently used to operationalize the framework at planning scale.

Dataset class	Primary dataset examples	Typical resolution / cadence	What it enables	Notes on limitations
Solar resource	Global Solar Atlas GIS layers	Planning-grade; downloadable by country	Baseline suitability screening, PV potential mapping	Bankable assessments require site measurements/modeling
Wind resource	Global Wind Atlas; peer-reviewed GWA dataset	High-resolution global modeling; terrain-aware	Baseline wind screening and resource comparisons	Requires downscaling and local constraints for micrositing
Land cover	ESA WorldCover (10 m)	10 m; 2020/2021 products	Fine-grained land-use screening (cropland, forests, built-up)	Classification error; temporal mismatch with rapid land change

Dataset class	Primary dataset examples	Typical resolution / cadence	What it enables	Notes on limitations
Protected areas	WDPA	Updated regularly; global	Exclusions and conservation-weighted penalties	Protection status heterogeneity; local designations may not appear
Planning layers	Acceleration areas / designated priority zones	Jurisdiction-specific	Policy-aligned siting and permitting acceleration	Requires legal harmonization and updates
Equity/social layers	Disadvantaged community indices	Jurisdiction-specific	Justice-aware siting and benefit-sharing targeting	Ethical and legal sensitivity; careful governance required

Cross-jurisdiction mechanisms for operationalizing low-conflict siting

Table 4 synthesizes case examples illustrating how agencies embed spatial designation and program-level assessment to reduce conflict and uncertainty while maintaining environmental safeguards.

Case study	Mechanism	Optimization logic	Reported outcomes / lessons	Primary sources
California desert planning	Landscape-level plan integrating conservation + renewable siting	Pre-identify development focus areas and conservation designations	Intended to streamline renewables while conserving desert ecosystems; multi-agency governance	Bureau of Land Management DRECP pages; collaboration description
EU acceleration areas	Statutory designation of renewables acceleration areas with streamlined permitting	Mapping → designate areas with low expected impacts; plan-level mitigation	Deadlines and permitting timelines codified; emphasis on mapping tools and multi-use	Directive (EU) 2023/2413; European Commission guidance
U.S. public lands solar planning	Programmatic EIS and designated leasing areas	Identify high resource/transmission, lower conflict lands	Designated leasing areas and broader lands with potential; structured planning process	Bureau of Land Management solar planning
India solar parks	Government-supported “park” model with land and infrastructure provided	Reduce transaction costs and delays by pre-assembling land/clearances	Speeds development but can generate land contestation if safeguards weak	MNRE scheme documentation; peer-reviewed contestation study
Net-zero spatial modeling (Western U.S.)	High-resolution energy+land modeling with conservation scenarios	Compare siting portfolios under different protection constraints	Strong protections reduced conflicts and transmission needs with modest system cost premium	Wu et al. (2023)

IV. DISCUSSION

Land-use optimization for renewables is best understood as managing trade-offs among objectives that cannot be maximized simultaneously. Two features distinguish optimization-based approaches from ad hoc siting: they make trade-offs explicit through objective functions and constraints, and they produce reproducible decision artifacts that can be stress-tested and debated.

Trade-offs and how optimization reframes them

Energy yield versus ecological protection: high resource potential can overlap high conservation-value landscapes, and cumulative effects emerge where projects cluster. Evidence-based practice emphasizes the mitigation hierarchy—avoid, minimize, restore, offset—with avoidance prioritized for high-value biodiversity areas and protection status explicitly encoded in constraint layers (Kiesecker et al., 2009; International Union for Conservation of Nature, 2021; U.S. Fish and Wildlife Service, 2012). High-resolution energy–land modeling indicates that stronger conservation constraints can shift siting patterns and, in some cases, reduce system expansion needs such as new transmission, at relatively modest system cost premiums (Wu et al., 2023).

Speed of deployment versus legitimacy of process: permitting acceleration can reduce delays and financing risk, but if community engagement and equity are treated as secondary, opposition and litigation risk can increase. Social acceptance research highlights that community acceptance is distinct from broad socio-political support and depends on procedural fairness and perceived distributions of benefits and burdens (Wüstenhagen et al., 2007).

Operational mitigation versus generation value: operational measures, most clearly documented for wind curtailment, can reduce wildlife impacts but entail energy losses. Where feasible, optimization should treat mitigation parameters as decision variables to find efficient ecological outcomes with bounded production costs (Adams et al., 2021; Whitby et al., 2024).

National-scale metrics versus local hotspots: national land-cover studies can show small aggregate footprints, yet local concentration in particular counties or landscapes can create substantial agricultural, ecological, and socioeconomic impacts. This scale mismatch motivates cumulative impact screening, explicit treatment of prime farmland and culturally sensitive landscapes, and transparent local participation processes (USDA ERS, 2024; American Farmland Trust, 2022).

Best-practice recommendations

Standardize land-use accounting in planning and communication: report both direct impact area and total project area, define denominators, and state co-use assumptions. Conflating metrics can mischaracterize trade-offs and undermine trust (Denholm et al., 2009; Ong et al., 2013).

Institutionalize low-conflict spatial designation: designated development areas and program-level review approaches can front-load screening, reduce duplication, and improve predictability when coupled with credible safeguards and public participation (European Commission, 2024; Bureau of Land Management, n.d.).

Apply avoidance-first biodiversity rules: protected areas and sensitive habitat layers should be treated as exclusions or high-penalty zones, consistent with tiered wildlife guidance and biodiversity mitigation best practice (U.S. Fish and Wildlife Service, 2012; International Union for Conservation of Nature, 2021).

Update technology assumptions and differentiate configurations: solar power density and land requirements have changed with technology and design; siting models should update assumptions and avoid treating all project types as equivalent (Bolinger & Bolinger, 2021).

Use dual-use pathways where appropriate: agrivoltaics and compatible land management can reduce land-use competition in some contexts, but benefits should be evaluated with explicit agronomic and ecological performance criteria (Dupraz et al., 2011; Barron-Gafford et al., 2019; U.S. Department of Energy, n.d.).

Embed equity and benefit-sharing: integrate equity screening and benefit-sharing mechanisms into siting governance to strengthen legitimacy (O'Shaughnessy et al., 2022; U.S. Department of Energy, 2023; International Renewable Energy Agency, 2024).

Implementation roadmap

A practical roadmap for implementing land-use optimization at jurisdictional scale has six phases: governance and scoping; data build and baseline mapping; suitability modeling and scenario design; portfolio optimization and grid integration; permitting alignment and spatial designation; and monitoring and iterative updates (Malczewski, 2006; U.S. Department of Energy, 2022; U.S. Fish and Wildlife Service, 2012; Directive (EU) 2023/2413; Bureau of Land Management, n.d.; Wu et al., 2023).

V. LIMITATIONS

The paper provides a reference framework rather than a jurisdiction-specific siting model. Because regulatory thresholds, ecological priorities, and social tolerances vary by place, the framework emphasizes transparency, scenario analysis, and sensitivity testing rather than universal parameter values. Quantitative land-use values are reported as representative empirical benchmarks and should be updated as local technology mixes and design standards change.

VI. CONCLUSION

Land-use optimization for utility-scale solar and onshore wind is increasingly essential for scaling renewable deployment while reducing environmental and social conflict. The synthesis demonstrates that consistent land-use accounting—distinguishing direct impact area from total project area and stating denominators explicitly—is foundational to credible planning and communication. Technically, the most defensible pathway combines legal and engineering constraint screening, GIS-MCDA suitability mapping with sensitivity analysis, and multi-objective portfolio selection that makes trade-offs explicit. Governance mechanisms that operationalize low-conflict siting—such as designated development areas, program-level assessment, biodiversity avoidance rules, and transparent participation and benefit-sharing—enable faster, more legitimate deployment without treating environmental protection and social acceptance as afterthoughts (International Union for Conservation of Nature, 2021; Wüstenhagen et al., 2007; Bureau of Land Management, n.d.).

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