

## Development Potential of Solar Energy in the Southern and Central United States

Volodymyr Tanieiev<sup>12\*</sup>

<sup>1</sup> *SEO Promstroy LLC, Ukraine*

<sup>2</sup> *Light Solution LLC, United States*

\*Corresponding Author: Volodymyr Tanieiev, Email: [vladtanieiev@gmail.com](mailto:vladtanieiev@gmail.com)

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ARTICLE INFORMATION	ABSTRACT
<p><b>Article history:</b>            Published on 28<sup>th</sup> Jan 2026</p> <p><b>Keywords:</b>            Utility-scale solar photovoltaic            Technical potential            Solar resource assessment            Land availability            Regional analysis</p>	<p>An integrated regional assessment of utility-scale solar photovoltaic (PV) deployment potential is conducted for the southern and central United States. The analysis combines long-term solar resource indicators, land-use constraints, and representative techno-economic assumptions within a harmonized regional framework. The analysis shows that the southern United States exhibits higher annual generation potential (<math>\approx 1850</math> TWh) despite a lower deployable capacity (<math>\approx 950</math> GW) compared to the central United States (<math>\approx 1050</math> GW, <math>\approx 1750</math> TWh). While global horizontal irradiance (GHI) patterns indicate substantially higher resource intensity in the southern states, the application of spatial exclusion criteria reveals pronounced differences in land availability and spatial continuity between regions. Technical potential estimates, derived by applying uniform capacity density assumptions to suitable land areas, show that extensive contiguous land in the central United States can compensate for more moderate irradiance levels. As a result, the deployable capacity and potential electricity generation of the two regions converge once spatial constraints are explicitly considered. The analysis further indicates that declining utility-scale PV costs reduce the sensitivity of deployment potential to moderate regional differences in solar resource quality, increasing the relative importance of land availability and spatial structure. These findings challenge resource-only ranking approaches and demonstrate the value of integrated spatial assessments for evaluating large-scale photovoltaic deployment. By clarifying how solar resource characteristics and land availability jointly shape regional technical potential, the study provides a structured basis for regional energy planning and long-term solar deployment strategies.</p>

### 1. Introduction

The large-scale deployment of solar photovoltaic (PV) technologies has become a central component of contemporary energy system transformation. Among renewable energy options, utility-scale solar PV occupies a distinct position due to sustained cost reductions, modular scalability, and compatibility with existing power system infrastructures. Over the past decade, rapid growth in cumulative installed PV capacity has shifted research attention from questions of technological feasibility toward issues related to spatial deployment potential and system-level integration [1].

In the United States, the spatial distribution of solar PV deployment is strongly influenced by regional differences in solar resource availability, land-use patterns, and settlement density. Southern states are commonly associated with higher solar irradiance and favorable climatic conditions, whereas large parts of the central United States are characterized by extensive land availability and relatively low levels of competing land use. Previous studies indicate that these contrasting regional characteristics may result in comparable large-scale deployment potential despite substantial differences in solar resource intensity [2].

A substantial body of literature has examined solar PV potential using either resource-based assessments or techno-economic modeling approaches. Resource-oriented studies typically focus on spatial patterns of global horizontal irradiance (GHI) and related performance indicators, frequently identifying the southern United States as particularly favorable for PV deployment [3]. In parallel, techno-economic analyses document declining costs of utility-scale PV systems and their increasing competitiveness across a wide range of geographic contexts, including regions with moderate solar resources [4].

Assessments that emphasize a single dimension of deployment potential, however, may overlook critical spatial constraints. In particular, land availability has emerged as a key determinant of the scale at which utility-scale PV systems can be deployed. Empirical and modeling studies demonstrate that environmental protections, urban development, and competing land uses can

significantly reduce the amount of land that is technically suitable for large-scale PV installations, even in regions with high solar resource availability [5].

While the importance of land-use constraints is widely acknowledged, their combined effect with solar resource characteristics on deployable capacity and electricity generation remains insufficiently quantified at the regional scale. In particular, comparative assessments rarely distinguish between regions where high irradiance primarily drives generation potential and those where extensive land availability enables greater deployable capacity.

As a result, regions with moderate solar resources but fewer land-use constraints may exhibit large-scale deployment potential comparable to, or in some cases exceeding, that of regions with higher irradiance. Addressing this divergence requires an explicit comparison of resource-driven and spatially constrained potential within a consistent analytical framework.

Recent spatial analyses therefore emphasize the importance of integrated frameworks that jointly consider solar resource characteristics, land-use constraints, and techno-economic conditions when evaluating large-scale PV potential. Such approaches support more realistic estimates of deployable capacity and reduce the risk of systematic overestimation associated with resource-only assessments [6]. At the same time, the use of harmonized assumptions and transparent data sources is increasingly recognized as essential for ensuring comparability across regions and studies.

Against this background, the present study examines the technical and techno-economic potential of utility-scale solar PV deployment in the southern and central United States using an integrated spatial perspective. By combining solar resource data, land-use constraints, and representative cost benchmarks within a unified analytical framework, the analysis clarifies how different combinations of irradiance and land availability shape regional deployment potential.

The contribution of this study is threefold. First, it provides a regionally consistent comparison of solar resource characteristics based on long-term national datasets. Second, it incorporates land-use constraints to delineate technically suitable areas for utility-scale PV deployment without relying on fine-scale site-specific modeling. Third, it evaluates regional technical potential in relation to contemporary techno-economic benchmarks, enabling a balanced interpretation of resource-driven and spatial drivers. Together, these elements support a more nuanced understanding of regional contrasts in utility-scale solar PV potential and contribute to large-scale assessments of photovoltaic expansion in the United States.

## 2. Literature Review

The assessment of large-scale solar photovoltaic (PV) deployment potential has evolved significantly over the past two decades, reflecting both technological progress and the growing role of spatial and system-level considerations in energy planning. Early studies primarily focused on theoretical or physical resource potential, emphasizing the distribution of solar irradiance as the main determinant of photovoltaic feasibility. Such resource-oriented approaches typically relied on global or regional maps of global horizontal irradiance (GHI) to identify areas with the highest expected energy yields and frequently ranked regions according to solar resource intensity [3,9].

Subsequent research expanded this perspective by introducing techno-economic dimensions into solar potential assessments. These studies incorporated assumptions about system efficiency, capital costs, and performance characteristics in order to translate physical resource availability into economically meaningful indicators, such as levelized cost of electricity (LCOE) or cost-supply curves [4,11,12]. Empirical analyses of utility-scale PV deployment in the United States demonstrated that rapid cost reductions and technological learning have substantially improved the competitiveness of photovoltaic systems across a wide range of geographic contexts, including regions with only moderate solar resources [4,10].

At the same time, a growing body of literature has emphasized the limitations of resource-only and techno-economic approaches when spatial feasibility is not explicitly considered. Land availability has emerged as a critical constraint for large-scale renewable energy deployment, particularly for ground-mounted PV systems that require extensive contiguous areas [2,5]. GIS-based studies conducted by the National Renewable Energy Laboratory (NREL) show that environmental protection zones, urban development, water bodies, and competing land uses can reduce theoretical solar potential by several orders of magnitude once realistic exclusion criteria are applied [7,18,25].

Spatially explicit assessments further reveal that land-use constraints vary substantially across regions and may outweigh differences in solar resource quality. Regions with high irradiance often coincide with high population density, intensive agriculture, or protected ecosystems, leading to fragmented deployment opportunities and higher land-use conflicts [22,23,28]. In contrast, regions characterized by lower population density and more homogeneous land-use structures may retain extensive technically suitable areas, even if their solar resource levels are comparatively moderate [5,24].

This shift in analytical focus has led to the development of integrated assessment frameworks that jointly consider solar resource characteristics, land-use constraints, and techno-economic assumptions. Such approaches aim to estimate technical or economic potential rather than purely theoretical potential and are increasingly regarded as more relevant for energy system planning and policy analysis [6,26,30]. Comparative studies at both national and global scales consistently demonstrate that the interaction between resource quality and spatial availability plays a decisive role in shaping large-scale photovoltaic deployment potential [19,20,35].

Recent international literature further situates photovoltaic deployment within broader land-use and energy system dynamics. Concepts such as “energy sprawl” highlight that renewable energy expansion represents one of the major drivers of land-use change, with significant implications for agriculture, biodiversity, and spatial planning [28,36,38]. In this context, solar PV is increasingly analyzed not only as a technological solution but also as a spatial phenomenon embedded within complex socio-environmental systems [27,29,37].

Despite these advances, many existing studies remain either highly spatially detailed but limited in regional comparability, or highly aggregated but insufficiently explicit about land-use assumptions. As a result, the relative roles of solar resource intensity

and land availability are often difficult to disentangle, particularly in comparative regional analyses. This methodological gap is especially relevant for large countries such as the United States, where regions exhibit fundamentally different combinations of climatic conditions, settlement patterns, and land-use structures.

Against this background, the present study builds on the integrated assessment tradition by adopting a regional-scale perspective that explicitly separates and recombines solar resource characteristics and land-use constraints within a harmonized analytical framework. By focusing on the southern and central United States as contrasting regional cases, the analysis contributes to the literature by clarifying how different structural drivers shape deployable photovoltaic capacity at scale. In doing so, it complements existing high-resolution spatial studies with a conceptually transparent regional comparison that is directly relevant for long-term energy planning and strategic deployment analysis.

### 3. Methodology

#### 3.1. Study area and regional classification

The analysis considers two aggregated regions of the contiguous United States—the southern and central regions—selected to represent contrasting combinations of solar resource availability and land-use characteristics. The regional delineation follows a functional rather than administrative logic and is designed to support comparative assessment rather than state-level ranking.

The southern region encompasses states associated with higher annual solar irradiance and climatic conditions conducive to photovoltaic performance. In contrast, the central region comprises states characterized by more moderate solar resource levels but extensive land availability and comparatively lower population density. This form of regional aggregation is consistent with national-scale renewable energy assessments that emphasize the analytical value of grouping states into functionally coherent regions when evaluating large-scale deployment potential [7].

A schematic representation of the study area and regional classification is provided in Figure 1. The figure illustrates the conceptual regional delineation applied throughout the analysis and is not intended to define precise geographic boundaries or jurisdictional limits.



Figure 1. Study area and schematic regional classification of the southern and central United States used in the analysis.

\*The figure illustrates the aggregated regional delineation applied throughout the study and is intended to support regional comparison rather than to define administrative or jurisdictional boundaries. States included in the southern and central regions are highlighted, while states not included in the regional aggregation are shown in grey.

Source: author's representation based on regional groupings commonly applied in U.S. solar potential studies [7].

The regional classification illustrated in Figure 1 establishes the spatial framework for the subsequent analysis. By distinguishing regions with contrasting combinations of solar resource characteristics and land availability, this delineation enables a consistent comparison of deployment potential under harmonized assumptions. Building on this regional structure, the following subsection describes the solar resource datasets used to quantify irradiance patterns and provide a uniform basis for assessing photovoltaic performance across the study area.

#### 3.2. Solar resource data

Solar resource characteristics are quantified using long-term averages of global horizontal irradiance (GHI) derived from the National Solar Radiation Database (NSRDB). The NSRDB provides gridded solar radiation data for the United States based on a combination of satellite observations, atmospheric modeling, and ground-based measurements, and is widely applied in both academic research and energy system planning [3].

For the purposes of this study, regional solar resource conditions are represented using aggregated annual GHI indicators rather than high-resolution, site-specific values. This approach is consistent with the regional scale of analysis and avoids introducing a level of numerical precision that would not be meaningful given the spatial aggregation applied. Similar aggregation strategies

have been adopted in regional and continental-scale assessments to ensure coherence between data resolution and analytical scope [8].

The use of long-term average irradiance values allows for comparison between regions under representative climatic conditions while reducing sensitivity to short-term weather variability and anomalous years. This practice is well established in large-scale evaluations of photovoltaic potential, where the objective is to identify structural differences in resource availability rather than to optimize individual project locations [9].

At the same time, the aggregation of solar resource data implies that intra-regional variability is not explicitly resolved. While this limits the ability to capture localized extremes, it supports a transparent comparison between regions and aligns with the objective of assessing deployment potential at scale rather than site-level performance. Within this framework, solar resource indicators provide a consistent input for estimating relative photovoltaic performance across regions.

The aggregated solar resource metrics described in this subsection form the resource-related input for the technical potential assessment. In the following subsection, these resource indicators are combined with land-use constraints to delineate areas that are technically suitable for utility-scale photovoltaic deployment.

### 3.3. Land-use constraints and spatial exclusions

Land availability for utility-scale solar PV deployment is evaluated using a land-use exclusion framework that reflects commonly applied technical, environmental, and spatial constraints. Instead of relying on detailed parcel-level screening, the analysis adopts generalized exclusion categories that have been shown to provide a robust approximation of technically feasible siting conditions at regional and national scales.

Excluded land categories include urbanized and densely built areas, water bodies, protected natural areas, and other land uses typically regarded as incompatible with large ground-mounted photovoltaic installations. This exclusion logic follows well-established methodological approaches developed by the National Renewable Energy Laboratory and widely applied in U.S. solar potential assessments [2,5]. By applying consistent exclusion criteria across regions, the analysis avoids region-specific bias and supports direct comparison of deployment potential under harmonized assumptions.

The application of spatial exclusions substantially reduces the gross land area available for utility-scale PV deployment and highlights the role of land-use competition as a limiting factor. Even in regions with favorable solar resource conditions, environmental protection measures and existing land-use patterns can constrain the spatial continuity required for large-scale projects. Conversely, regions characterized by lower population density and more homogeneous land-use structures tend to retain larger contiguous areas suitable for deployment, despite more moderate solar resource levels.

Following the application of exclusion criteria, the remaining suitable land areas are aggregated at the regional level and expressed as total land area potentially available for utility-scale PV deployment. This aggregation emphasizes methodological transparency and comparability rather than spatial granularity. Such an approach is appropriate for regional-scale evaluation of deployment potential and avoids the false precision that may arise from highly resolved spatial analyses when applied outside a project-specific context [6].

Within this framework, suitable land area functions as the spatial constraint linking solar resource availability to deployable capacity. The quantified land availability therefore provides the spatial basis for translating aggregated resource indicators into estimates of installable capacity under uniform technical assumptions.

Suitable land identified through the spatial filtering process was translated into installable photovoltaic capacity using representative capacity density values for utility-scale PV systems reported in the literature. This approach enables a consistent conversion from technically suitable land area to potential installed capacity without relying on site-specific plant layouts.

Annual electricity generation was subsequently estimated by combining the resulting installable capacity with region-specific solar resource characteristics. Typical performance assumptions for utility-scale PV systems were applied to reflect realistic operating conditions and to ensure comparability across regions. This sequential conversion from land availability to capacity and generation provides a transparent basis for evaluating regional differences in large-scale PV potential.

### 3.4. Techno-economic assumptions

Techno-economic indicators are defined using representative assumptions for contemporary utility-scale photovoltaic systems deployed in the United States. Capital expenditure (CAPEX), system configuration, and performance parameters are informed by recent empirical analyses of installed projects and standardized benchmarking studies. The objective of this subsection is not to model site-specific project economics, but to establish a consistent techno-economic baseline suitable for regional-scale comparison.

Installed cost ranges and performance characteristics are derived from utility-scale PV market data reported by the Lawrence Berkeley National Laboratory and the National Renewable Energy Laboratory, which provide comprehensive empirical coverage of recent U.S. installations [4,10]. Levelized cost of electricity (LCOE) benchmarks are employed for contextual interpretation of deployment feasibility rather than for optimization of individual projects and are aligned with widely cited cost analyses used in comparative energy system studies [11].

To ensure internal consistency across regions, uniform techno-economic assumptions are applied throughout the analysis. This harmonization allows observed differences in estimated deployment potential to be attributed primarily to variations in solar resource availability and land-use constraints, rather than to region-specific cost or performance assumptions [12]. Such an approach is commonly adopted in comparative assessments where the focus lies on structural drivers of deployment potential rather than localized market conditions.

Key datasets and assumptions used in the analysis are summarized in Table 1.

Table 1. Key datasets and techno-economic assumptions used in the analysis

Category	Parameter	Description	Source
Solar resource	GHI	Long-term average annual global horizontal irradiance	[3]
Spatial scale	Aggregation level	Regional aggregation (southern vs central U.S.)	[7]
Land availability	Exclusions	Urban areas, protected land, water bodies	[2], [5]
PV system design	Capacity density	Typical utility-scale PV layouts	[5]
Economics	CAPEX	Representative U.S. utility-scale PV costs	[4], [10]
Cost benchmark	LCOE	Representative utility-scale PV LCOE benchmarks	[11]

Source: compiled by the author based on publicly available datasets and benchmark studies cited above.

Following the definition of techno-economic assumptions, the analytical framework integrates solar resource indicators and suitable land area to estimate deployable capacity under uniform system design conditions. This integration establishes the quantitative basis for evaluating regional deployment potential, which is examined in the following section through a comparative analysis of technical potential and spatial constraints.

4. Findings

4.1. Solar resource characteristics

Regional solar resource conditions constitute the primary empirical input for assessing the potential of utility-scale photovoltaic deployment. Long-term average global horizontal irradiance (GHI) reveals a persistent contrast between the southern and central United States, reflecting differences in latitude, prevailing atmospheric circulation, cloud cover patterns, and seasonal variability. These structural differences in irradiance regimes have been documented consistently across national and global solar resource assessments [3,13].

The southern region exhibits higher annual GHI levels and lower relative seasonal variability, resulting in more stable expected energy yields over the year. Such conditions are generally associated with improved photovoltaic performance metrics and contribute to lower levelized cost of electricity under otherwise comparable system assumptions [14,15]. Empirical analyses of U.S. utility-scale PV systems confirm that regions with higher irradiance tend to achieve higher capacity factors, although the magnitude of this advantage varies depending on system design and operating conditions [16].

In contrast, the central United States is characterized by moderate irradiance levels distributed over a large contiguous area. While peak GHI values are lower than in the southern region, the spatial extent of suitable irradiance supports deployment at scale when combined with appropriate system layouts. Several comparative studies emphasize that such spatially extensive, moderate-resource regions can sustain large aggregate generation volumes, particularly when land availability is not a binding constraint [9,17].

A schematic overview of the regional distribution of solar resource patterns is provided in **Figure 2**. The figure highlights relative differences between regions based on long-term NSRDB-derived indicators and is intended to contextualize aggregated resource metrics rather than to resolve site-specific variability.

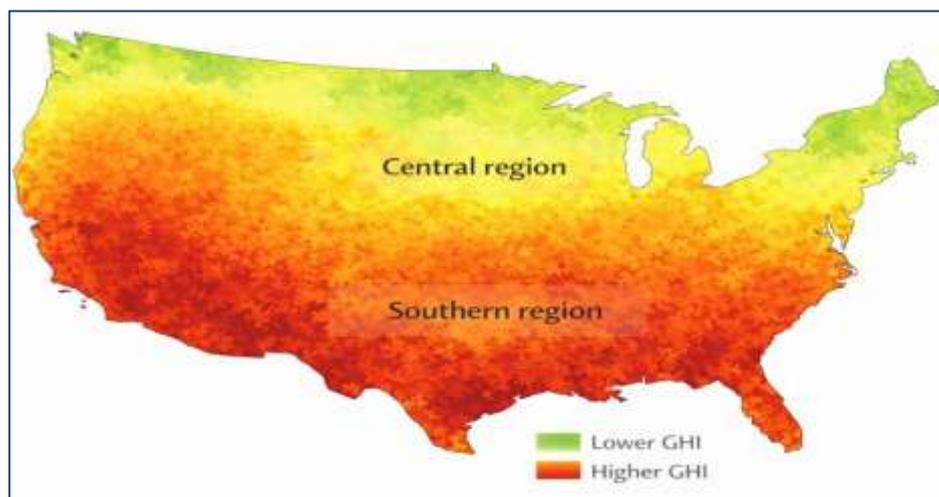


Figure 2. Schematic spatial distribution of solar resource across the contiguous United States.

\*Color shading illustrates the relative north-south gradient in long-term average global horizontal irradiance (GHI) patterns derived from NSRDB data. The figure is intended for regional contextualization of solar resource conditions rather than for site-specific or quantitative interpretation.

Source: author’s representation based on NSRDB-derived regional patterns [3].

Figure 2 reinforces that the advantage of the southern region lies primarily in resource intensity, whereas the central region benefits from the spatial continuity of moderate irradiance. This distinction is important because large-scale deployment potential

depends not only on local resource quality but also on whether favorable conditions are sufficiently widespread to support extensive project development [18].

Importantly, multiple studies caution against treating irradiance intensity as a sufficient proxy for deployment potential. Comparative global and regional analyses demonstrate that moderate solar resources, when combined with suitable land availability and system design choices, can yield generation outcomes comparable to those achieved in high-resource regions [9,19,20]. This observation is particularly relevant in the context of declining PV system costs, which have reduced the sensitivity of deployment feasibility to moderate differences in irradiance [21].

Taken together, the resource assessment confirms that both the southern and central regions possess solar conditions compatible with utility-scale PV deployment. However, the implications of these resource differences depend critically on how they interact with spatial constraints. The role of land availability and exclusion criteria therefore becomes central in determining the extent to which resource advantages can be translated into deployable capacity.

4.2. Land availability and technical constraints

Land availability constitutes a critical link between solar resource potential and deployable capacity for utility-scale photovoltaic systems. Even in regions characterized by favorable irradiance conditions, land-use constraints can substantially limit the scale, continuity, and spatial configuration of feasible installations. Conversely, regions with more moderate solar resources may partially offset lower irradiance through extensive land availability and reduced competition with other land uses.

The application of the land-use exclusion framework described in Section 2.3 reveals pronounced differences between the southern and central United States. In the southern region, suitable land areas are more frequently fragmented due to higher population density, intensive agricultural activity, and the prevalence of protected natural areas. Comparable patterns have been reported in multiple U.S. assessments, which show that land-use competition tends to intensify in regions combining favorable climatic conditions with higher levels of economic development [2,22].

Fragmentation of suitable land has important implications for utility-scale PV deployment. Large projects typically benefit from contiguous land parcels that support standardized layouts, simplified infrastructure, and economies of scale. Where suitable land is spatially fragmented, deployment may still be feasible, but project sizes are often smaller and development pathways more complex [23,24].

In contrast, the central United States retains extensive contiguous land areas that remain technically suitable for utility-scale PV deployment following the application of standard exclusion criteria. Lower population density, more homogeneous land-use patterns, and a greater prevalence of open land contribute to a substantially larger pool of technically suitable sites, despite more moderate solar resource levels. This spatial continuity enhances the feasibility of large-scale installations and supports deployment strategies that prioritize scale over peak resource intensity [5,25].

The comparison reveals a clear divergence between the two regions: higher solar resource intensity in the southern United States is associated with more fragmented suitable land, whereas the central region combines moderate irradiance with substantially larger contiguous areas suitable for deployment. At the regional scale, these spatial differences define the boundary conditions within which technical potential can be realized.

Table 2. Regional land availability and technical constraints for utility-scale PV deployment

Region	Solar resource level	Suitable land availability	Spatial continuity	Dominant limiting factors	Key references
Southern U.S.	High	Moderate	Fragmented	Urbanization, protected areas, agriculture	[2], [5], [22], [23]
Central U.S.	Moderate	Extensive	High	Lower irradiance, transmission distance	[5], [24], [25]

\*Note: Qualitative descriptors (High, Moderate, Extensive) reflect aggregated regional patterns derived from the applied land-use exclusion framework and long-term solar resource indicators rather than site-specific measurements.

Source: compiled by the author based on land-use exclusion frameworks and spatial analyses reported in the cited studies.

The patterns summarized in Table 2 underline the importance of explicitly accounting for spatial constraints when evaluating regional photovoltaic deployment potential. Without such considerations, regions with high solar resource intensity may appear disproportionately favorable, while land-abundant regions may be systematically undervalued. In practice, the balance between resource quality and spatial continuity plays a decisive role in shaping the scale at which utility-scale PV systems can be deployed.

By quantifying suitable land availability at the regional level, the analysis establishes the spatial boundary conditions required to translate solar resource indicators into estimates of deployable capacity. These spatial constraints therefore form the basis for the technical potential calculations presented in the following subsection.

4.3. Regional technical potential of utility-scale PV

The technical potential of utility-scale photovoltaic deployment is evaluated by jointly considering regional solar resource characteristics and the availability of suitable land identified through spatial exclusion analysis. This approach extends beyond theoretical or resource-only potential by explicitly incorporating spatial feasibility and system layout constraints, thereby providing a realistic upper bound for large-scale deployment under contemporary technological assumptions [7].

Applying uniform capacity density assumptions to the suitable land areas identified in Section 3.2 yields comparable overall deployment potential across the two regions, despite pronounced differences in solar resource intensity. In the southern United

States, higher irradiance results in greater expected electricity generation per unit of installed capacity. In the central United States, by contrast, the presence of extensive contiguous land areas enables deployment at a scale sufficient to compensate for more moderate resource conditions. Similar compensatory relationships between resource quality and spatial opportunity have been documented in previous large-scale assessments of photovoltaic potential [26,30].

These combined effects of resource intensity and land availability are reflected in the aggregated estimates of installable capacity and annual electricity generation presented in Figure 3, which juxtaposes regional outcomes under harmonized technical and spatial assumptions.

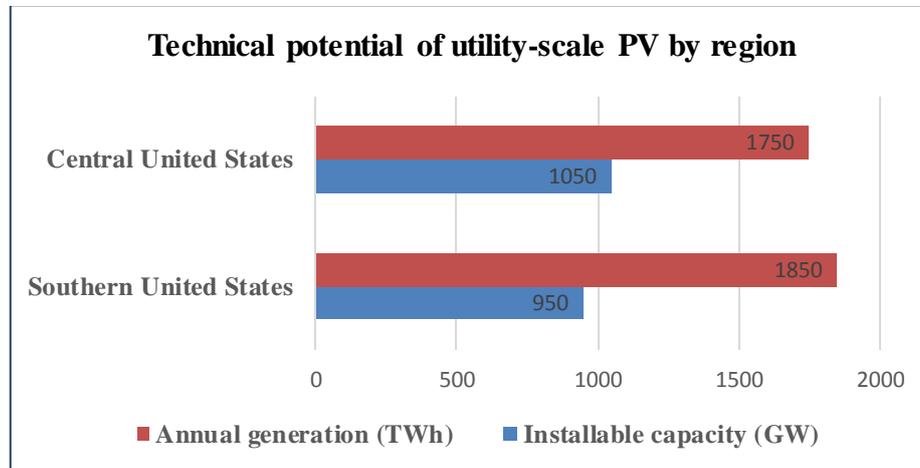


Figure 3. Installable capacity (GW) and annual electricity generation (TWh) estimated for utility-scale PV in the central and southern United States after applying land-use and technical exclusion criteria.

\*Values are indicative and shown on a common axis for comparative purposes.

Source: author's calculations based on NSRDB resource data and NREL land-use assumptions [7,5].

The comparison indicates that neither region exhibits a clear dominance once technical constraints are taken into account. In stead, deployment potential reflects a balance between higher solar resource intensity in the southern region and greater spatial opportunity in the central United States. This pattern is consistent with national-scale analyses showing that land availability and spatial continuity increasingly shape deployment outcomes as photovoltaic technology costs decline and system designs become more standardized [6,31].

At the scale considered here, the magnitude of estimated technical potential in both regions aligns with broader assessments of photovoltaic scalability. These results reinforce the view that utility-scale PV can contribute substantially to regional electricity supply under current technological conditions, even in areas that do not exhibit the highest resource intensity [1,32]. The findings further suggest that regional differences in deployment potential are less a function of absolute resource limits than of how effectively resource conditions can be translated into deployable capacity through spatial configuration.

Taken together, the technical potential estimates provide the quantitative foundation for assessing regional deployment prospects. To place these results in context, the following subsection examines how differences in resource–land interactions translate into broader patterns of regional opportunity and constraint.

#### 4.4. Interaction between solar resource and land availability

The regional results demonstrate that large-scale solar photovoltaic deployment potential cannot be adequately inferred from solar resource availability alone. Although the southern United States exhibits higher levels of global horizontal irradiance, this advantage does not translate proportionally into greater technical potential once land-use constraints are considered. Instead, deployable capacity emerges from the interaction between irradiance intensity and the spatial configuration of suitable land.

This interaction is quantitatively reflected in the contrasting capacity–generation profiles observed for the two regions, where higher irradiance and greater land availability contribute differently to overall technical potential. This outcome aligns with earlier assessments showing that land availability increasingly constrains renewable energy deployment in regions characterized by favorable climatic conditions and high levels of economic activity [2]. In such contexts, urban expansion, intensive agriculture, and environmental protection measures collectively limit the spatial continuity required for large-scale photovoltaic installations. As a result, regions with strong solar resources may exhibit fragmented deployment pathways despite favorable irradiance conditions.

By contrast, the central United States illustrates how moderate solar resource levels can support substantial technical potential when combined with extensive contiguous land areas. Previous studies emphasize that spatial continuity enables larger project footprints, more standardized system layouts, and improved economies of scale, partially compensating for lower resource intensity [5,24]. Empirical analyses of renewable energy deployment further suggest that contiguous land availability can be a decisive factor in determining achievable deployment scale over the long term [29,36].

Taken together, these patterns underscore the limitations of resource-based ranking approaches and highlight the need to explicitly incorporate spatial structure into assessments of photovoltaic deployment potential. Regions with slightly lower irradiance but greater land availability may offer more scalable deployment opportunities than resource-rich regions where land constraints

impose structural limits. This perspective is increasingly reflected in comparative assessments that emphasize land-use dynamics as a central determinant of renewable energy expansion [25,28].

#### 4.5. Comparison with previous regional and national assessments

At the national scale, estimates of technical potential reported in this study are consistent with the range of values documented in prior U.S. assessments of utility-scale photovoltaic deployment. GIS-based analyses developed by the National Renewable Energy Laboratory have repeatedly identified both the southern and central United States as major contributors to aggregate PV potential, while also demonstrating a strong sensitivity of results to land-use assumptions and exclusion criteria [7,26].

A distinguishing feature of many earlier studies lies in their emphasis on high spatial resolution. While such analyses provide valuable insights into site-level suitability, they often obscure the relative roles of solar resource quality and land availability by embedding both effects within detailed spatial outputs. The regional-scale perspective adopted here offers a complementary view by separating these structural drivers and enabling direct comparison between regions characterized by contrasting combinations of irradiance intensity and spatial opportunity. By contrast, the present study isolates these effects at the regional level, allowing the relative contributions of resource intensity and land availability to be examined explicitly rather than implicitly through spatial detail.

This analytical framing aligns with a growing body of work suggesting that conceptual clarity becomes increasingly important as renewable energy deployment scales up. Several studies argue that regional aggregation can reveal constraints and trade-offs that are less visible in highly resolved spatial datasets, particularly when the objective is to assess deployment potential rather than to identify specific project sites [30,31].

Evidence from international assessments further supports the relevance of these findings. Global analyses of photovoltaic potential consistently indicate that land-use constraints and spatial planning considerations play an increasingly decisive role as solar technologies mature and deployment expands beyond early high-resource locations [19,20,37]. From this perspective, the southern and central United States can be interpreted as illustrative cases of a broader global trade-off between resource intensity and spatial opportunity.

Recent spatially explicit studies also highlight the growing competition between large-scale photovoltaic deployment and other land-intensive uses, including agriculture, conservation, and infrastructure development. These interactions underscore the importance of integrated land-use planning frameworks that treat renewable energy deployment as part of a broader spatial system rather than as an isolated technological intervention [22,28,38]. Within this context, the results presented here reinforce the view that land availability should be treated as a central determinant of deployment potential rather than as a secondary constraint applied after resource assessment.

#### 4.6. Techno-economic context and implications for deployment

Recent techno-economic trends indicate that declining costs of utility-scale photovoltaic systems have reduced the sensitivity of deployment potential to moderate differences in solar resource quality. Empirical market data show that capital expenditures have converged across regions as system designs become increasingly standardized and supply chains mature, narrowing historical cost differentials within the United States [4]. Under these conditions, land availability and achievable project scale play a progressively larger role in shaping economic feasibility. In this context, the analysis does not aim to model project-level economics, but rather to clarify how spatial conditions condition the scale at which techno-economic feasibility can be realized.

Cost benchmark analyses further support this interpretation. Recent estimates of levelized cost of electricity indicate that utility-scale PV systems can achieve competitive cost ranges across a broad spectrum of irradiance conditions, provided projects can be deployed at sufficient scale [11]. As a result, regions previously regarded as marginal based on resource intensity alone may become economically attractive when extensive suitable land enables large installations and simplified infrastructure layouts.

At the same time, the distinction between technical potential and economically realizable deployment remains critical. While the present analysis identifies substantial technical potential in both regions, actual deployment trajectories will be influenced by system-level factors not explicitly captured here. Grid integration requirements, transmission availability, and regional market structures increasingly shape the pace and scale of solar expansion, particularly as penetration levels rise [40,41].

Studies of high-solar scenarios highlight that increasing photovoltaic shares introduce challenges related to temporal variability, curtailment, and infrastructure reinforcement. These system-level constraints do not negate the existence of technical potential but condition how, where, and at what rate it can be realized [42,43]. Consequently, regions with extensive land availability may retain an advantage by accommodating spatial flexibility in project siting and grid integration.

Despite these constraints, the scale of technical potential identified in this study suggests that utility-scale PV can play a central role in regional electricity supply portfolios. When combined with complementary technologies such as energy storage, flexible demand, and transmission expansion, the spatial characteristics highlighted here provide a robust foundation for long-term decarbonization strategies. The findings therefore point toward the importance of integrating spatial potential assessments with system-level planning to translate technical opportunity into sustained deployment.

#### 4.7. Methodological considerations and limitations

The interpretation of the results is shaped by several methodological choices embedded in the analytical framework. The use of aggregated regional indicators prioritizes conceptual transparency and comparability across regions, but necessarily abstracts from site-specific conditions that may influence individual project development. As a result, local factors such as micro-scale land-use conflicts, permitting processes, or detailed grid constraints are not explicitly resolved within the present analysis [12].

Uncertainty also arises from the treatment of land-use constraints. The exclusion criteria applied here follow established national-scale methodologies and support consistent comparison between regions, yet they remain generalized representations of complex and evolving land-use systems. Consequently, estimates of suitable land area should be interpreted as indicative rather than exhaustive, particularly in regions where land management practices and competing land uses are dynamic [25].

Finally, the analysis deliberately abstracts from policy incentives, regulatory frameworks, and market-specific conditions in order to focus on techno-economic potential under harmonized assumptions. While this approach facilitates structural comparison between regions, it does not capture policy-driven deployment pathways or infrastructure development strategies that can significantly influence realized capacity. The results therefore describe relative deployment potential rather than near-term development outcomes.

Taken together, these considerations highlight that the findings represent an upper-bound, comparative assessment of regional opportunity. The framework nonetheless provides a transparent basis for evaluating how solar resource characteristics and land availability interact, and it can be extended in future work to incorporate finer spatial resolution and system-level constraints.

#### 4.8. Synthesis

Across the preceding sections, a consistent pattern emerges in which neither solar resource availability nor land availability alone is sufficient to explain regional deployment potential. Instead, deployable capacity is shaped by how these factors interact under contemporary techno-economic conditions. Regions with high irradiance but constrained land availability and regions with moderate irradiance but extensive contiguous land exhibit comparable technical potential through different structural pathways.

This synthesis highlights that large-scale photovoltaic deployment is increasingly governed by spatial configuration rather than by peak resource quality. As system costs decline and design practices standardize, the ability to mobilize suitable land at scale increasingly becomes a defining constraint for utility-scale photovoltaic deployment. In this context, regional assessments that explicitly integrate resource, land-use, and techno-economic dimensions offer clearer insight into long-term deployment prospects than approaches based on resource ranking alone.

### 5. Conclusion and Recommendations

This work develops a regional-scale assessment of utility-scale solar photovoltaic deployment potential in the southern and central United States through the joint consideration of solar resource characteristics, land availability, and techno-economic conditions. By integrating these dimensions within a harmonized analytical framework, the analysis demonstrates that deployable capacity is governed by the interaction of spatial and technical factors rather than by solar resource intensity in isolation.

Higher levels of global horizontal irradiance in the southern United States translate into favorable system-level performance and higher expected energy yields. At the same time, these advantages are moderated by spatial constraints associated with land-use competition, population density, and the presence of protected areas. As a consequence, land suitable for large-scale photovoltaic deployment in the southern region is more fragmented and exhibits lower spatial continuity than would be inferred from irradiance patterns alone.

In the central United States, more moderate solar resource conditions coexist with extensive contiguous land areas that remain technically suitable after the application of standard exclusion criteria. This spatial continuity supports deployment at scale and enables project configurations that offset lower irradiance through economies of scale and simplified system layouts. Under uniform techno-economic assumptions, the resulting estimates indicate that the technical potential of utility-scale PV in the central region is comparable to that of the southern region despite differences in resource quality.

A central insight of the analysis is that regional technical potential converges once land availability is explicitly incorporated. This finding underscores the limitations of resource-only assessments and highlights spatial structure as a primary determinant of deployable capacity at scale. Regions that appear secondary when ranked solely by irradiance may therefore represent equally viable contexts for large-scale photovoltaic deployment under contemporary cost conditions.

From a techno-economic perspective, the results are consistent with broader evidence that declining capital costs and increasingly standardized system designs have reduced regional disparities in the economic performance of utility-scale PV systems. Under these conditions, land availability and spatial configuration increasingly shape deployment feasibility, while moderate differences in irradiance exert a diminishing influence. This shift has important implications for regional planning and investment strategies, suggesting that future deployment pathways may extend beyond historically favored high-irradiance locations.

The study further highlights the analytical value of regional-scale assessments that prioritize transparency and conceptual clarity. By aggregating spatial indicators and applying harmonized assumptions, the framework enables direct comparison between regions with contrasting characteristics while avoiding overinterpretation of fine-scale variability. Although such an approach does not replace project-level analysis, it provides a robust basis for identifying structural drivers of large-scale deployment potential.

Several limitations frame the interpretation of these findings. The analysis focuses on technical potential and does not explicitly incorporate grid integration constraints, transmission availability, or policy-driven deployment dynamics. In addition, generalized land-use exclusion criteria may not fully reflect recent changes in land management practices. Future research could extend the framework by integrating grid infrastructure models, energy storage deployment, and policy-sensitive scenarios to assess realizable deployment pathways under alternative system configurations.

Taken together, the results indicate that both the southern and central United States possess substantial potential for utility-scale solar photovoltaic deployment, realized through different combinations of resource intensity and spatial opportunity. Recognizing these regional contrasts is essential for developing balanced deployment strategies that maximize the contribution of solar PV to future electricity systems. By demonstrating the central role of land availability alongside solar resource characteristics, this study

contributes to a more grounded understanding of large-scale photovoltaic potential and supports informed regional and national energy planning.

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