

# 基于遥感与GIS技术的太阳能光伏潜力评估

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**摘要:** 光伏潜力评估是衡量特定区域太阳能资源可开发利用程度和光伏发电潜力的重要手段, 也是区域能源科学规划及合理利用的基础。为构建较为系统的光伏潜力评估框架, 帮助相关领域研究人员厘清评估流程并提供方法参考, 本文在系统梳理国内外最新光伏潜力评估研究成果的基础上, 深入分析了遥感与GIS技术在光伏潜力评估中的应用现状。研究内容涵盖从辐射数据获取、光伏布设适宜性区域评价/可利用面积确定(集中式/分布式光伏系统)、坡度坡向分析、阴影遮挡模拟到光伏潜力估算的各关键环节。在此基础上, 进一步对集中式和分布式光伏系统潜力评估流程进行归纳和整理。最后, 结合当前光伏应用新形势, 本文展望了遥感与GIS技术在未来光伏产业发展中的潜在作用, 以期对相关研究提供理论和方法思考。

**关键词:** 太阳能, 辐射评估, 集中式/分布式光伏系统, 光伏选址, 能源规划

**中图分类号:** P967/P2

**引用格式:** 陈旻, 张锴, 朱瑞. 2025. 基于遥感与GIS技术的太阳能光伏潜力评估. 遥感学报, 29(6): 2289-2303

Chen M, Zhang K and Zhu R. 2025. Photovoltaic potential assessment based on remote sensing and GIS. National Remote Sensing Bulletin, 29(6): 2289-2303 [DOI: 10.11834/jrs.20254355]

## 1 引言

近年来, 遥感与GIS技术在多时空尺度光伏潜力评估研究与应用中取得了显著成果(Zhu等, 2022; Zhang等, 2023; Zhang等, 2024a), 并有效支撑了光伏潜力评估精度与效率的提升。然而, 目前尚缺乏对遥感与GIS技术在太阳能资源评估、光伏布设适宜性区域评价及光伏潜力估算等方面的系统性梳理和总结。尽管已有研究综述了GIS技术在太阳辐射数据获取(Anselmo和Ferrara, 2023)、光伏布设适宜性区域评价(Choi等, 2019)、城市尺度建筑屋顶光伏潜力评估(Gassar和Cha, 2021)中的应用。但上述研究或仅关注建筑屋顶光伏系统, 或未能涵盖光伏潜力评估的完整流程。面向集中式和分布式光伏系统, 较为全面、系统的光伏潜力评估框架尚有待探索。

因此, 本文以光伏潜力评估流程为切入点, 旨在系统分析和总结集中式与分布式光伏系统潜力评估的关键步骤, 以期对相关研究提供一个清晰的参考框架, 并对未来遥感与GIS技术在光伏产业发展中的潜在作用进行展望。

## 2 基于遥感与GIS技术的太阳辐射数据获取

太阳辐射是指太阳向外发射的能量, 包括可见光、紫外线和红外线等各种电磁波及粒子流, 是地球维持生物活动和大气循环的主要能量来源, 更是太阳能光伏系统得以运转的关键核心(Zeng等, 2020)。受地球大气圈层影响, 入射到地表的辐照度主要包括直接水平辐照度(DHI)和直接法向辐照度(DNI), 二者的几何和称为全球水平辐照度(GHI)(Kumar等, 2020)。地球的自转、公

收稿日期: 2024-08-08; 预印本: 2025-05-06

基金项目: 国家自然科学基金可持续发展国际合作科学计划(SDIC)重点项目(编号: W2412152)

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转、地理位置及天气状况等多种因素会导致 GHI 在不同时间和地点存在显著差异 (Obiwulu 等, 2022)。因此, 为了获得精确的地表辐射数据, 需要结合多种观测和模拟手段。当前, 获取地表辐射数据的主要方法包括 (Liao 等, 2022): (1) 利用地面观测站点进行直接测量; (2) 利用卫星和航空遥感数据进行反演计算; (3) 基于气象参数和物理模型进行模拟; (4) 基于机器学习方法进行预测。

地面辐射观测站点覆盖范围有限且成本较高, 但数据精度高。通过地理空间插值等方法也可将观测数据扩展到较为广泛的区域 (Fathizad 等, 2017)。搭载辐射传感器的卫星能够捕获大气光谱影像, 反演得到高时空分辨率的地表辐射数据, 具备覆盖范围广、可连续监测等特征 (Letu 等, 2022)。数值模拟方法基于气象学和物理模型, 结合地表特征、大气成分、云量等参数, 对太阳辐射进行模拟和预测, 能够提供长期、连续的太阳辐射数据 (Guermoui 等, 2020)。此外, 机器学习也被用于处理气象遥感数据或通过结合气象参数驱动模拟地表辐射 (Lu 等, 2023)。目前, 将地面观测数据与卫星遥感数据及数值模拟方法结合, 通过再处理生成融合太阳辐射数据和基于气象参

数及机器学习方法进行预测是辐射数据产品主流生产方式 (Guermoui 等, 2020; Zhang 等, 2021)。上述方法不仅为太阳能资源表征提供了可靠手段, 还为光伏系统适宜性区域评价和高精度光伏潜力评估提供了坚实的数据基础。

目前已发布的部分辐射数据详见表 1。可见大部分辐射数据产品仅包含 GHI, 较少有包含 DHI 和 DNI 的数据产品。原因在于地面测量时, DHI 和 DNI 需要额外的设备和技术投入 (Cavaco 等, 2021); 基于遥感、气象数据和物理模型反演、模拟 DHI 和 DNI 时, 也需要借助复杂的辐射传输模型 (Zhang 等, 2024c)。尽管如此, 在大尺度农业光合有效辐射估算、城市规划建筑能耗估算、热岛效应评估等应用场景中, GHI 已能够提供必要信息支持决策和优化过程。此外, 部分研究在反演或模拟太阳辐射时, 由于缺乏气溶胶、云量等参数或受限于计算资源, 未能考虑大气层对太阳辐射的影响, 仅生成晴空辐射数据, 造成对真实气象条件下区域辐射强度的高估 (Al-Sanea 等, 2004)。因此, 在使用晴空辐射数据表征区域辐射资源时, 还需结合气象参数进行校正, 以使其符合真实天气条件下的辐射强度 (Xie 等, 2023)。

表 1 常见辐射数据描述  
Table 1 Common radiation data description

数据名称/ 发布机构	数据 格式	空间 分辨率	时间 分辨率	数据来源	覆盖区域	时间范围	数据类别	参考文献
CAMS	CSV/ netCDF4		1 min	物理模型	全球	2004 年—	GHI、DHI、 DNI	(Lefèvre 等, 2013)
CERES SYN1deg	Grid	1°	1 h	遥感数据	全球	2000 年—	GHI、DHI、 DNI	(Zhang 等, 2024c)
GEWEX-SRB	Grid	10—30 km	3 h	融合数据产品	全球	1983— 2017 年	GHI	(Zhang 等, 2014)
ISCCP-FD	netCDF4	280 km <sup>2</sup>	3 h	物理模型	全球	1983— 2009 年	GHI	(Zhang 和 Rossow, 2023)
SARAH-2	GeoTIFF	0.05°, 0.25°	每月平均	遥感再分析产品	欧洲、非洲、 亚洲	2005— 2020 年	GHI	(Gracia Amillo 等, 2021)
全球地表 太阳辐射数据	netCDF4	10 km	3 h	遥感再分析数据+ 物理模型	全球	1983— 2018 年	GHI	(Tang 等, 2019)
中国地表太阳 辐射数据	netCDF4	10 km	3 h	遥感反演+站点数据+ 物理模型	中国	1983— 2017 年	GHI	(Feng 和 Wang, 2021)
基于站点估算的 太阳辐射数据	.txt	—	每日	站点数据+物理模型	中国	1960— 2021 年	GHI、DHI、 DNI	(Tang 等, 2023)

3 集中式光伏潜力评估

太阳能光伏潜力评估是一个多层次、多维度

的分析过程, 主要包括物理、地理、技术、经济和市场潜力评估五个阶段 (Zhang 等, 2020)。当前基于遥感与 GIS 技术的光伏潜力评估主要关注于

物理和地理潜力，较少涉及技术、经济和市场潜力评估。集中式光伏是指安装在空旷用地，装机容量>5 MW 的光伏系统（Benalcazar 等，2024），其潜力评估主要分为2个阶段：光伏布设适宜性区域评价和光伏潜力估算。

3.1 光伏布设适宜性区域评价

集中式光伏系统布设需要考虑太阳辐射强度、地形地貌、土地利用/覆被、生态环境、地价、政策支持等多种自然和社会经济要素（Qiu 等，2022）。内陆水体及海洋浮动式光伏布设还需要考虑湖泊、水库水文特征及近海洋流、海面风浪等因素（Hooper等，2021）。因此，光伏布设适宜性区域评价是一个复杂的多层次决策过程。

遥感为光伏布设适宜性区域评价/选址提供了数据支撑，如DEM数据可以表征地面坡向坡度等属性信息，排除地表起伏较大且不易接收到太阳辐射的区域；土地覆被/利用数据可以筛选出未利用地或荒地等使用成本较低且对生态环境影响较小的区域。在此基础上，GIS基于空间分析和多准则决策MCDM（Multi-Criteria Decision Making）方法，综合考虑技术、经济、环境及社会等因素，评估不同区域光伏布设的适宜性（Wang等，2009）。MCDM适用于复杂决策环境，能系统地处理多重标准和不确定性，支持更全面和理性的决策过程（Scott等，2012）。MCDM包含多属性决策MADM（Multi-Attribute Decision-Making）和多目标决策MODM（Multi-Objective Decision-Making）两大类（de Souza等，2021）。

光伏布设适宜性区域评价领域广泛应用的是MADM方法。根据不同决策分析技术，MADM方

法一般分为成对比较法、优先级排序法、理想解距离法、基于交互的方法、基于效用的方法和混合方法6类（Yalcin等，2022），如图1所示。成对比较法主要通过确定各项准则的相对重要性来综合评估各个方案，常用的方法包括AHP（Analytic Hierarchy Process）、ANP（Analytic Network Process）和BWM（Best-Worst Method）等；优先级排序法则通过比较各备选方案的优越性来确定最佳方案，常用的方法有PROMETHEE（Preference Ranking Organization Method for Enrichment Evaluations）、ELECTRE（ELimination Et Choice Translating REality）等；理想解距离法通过计算决策选项与理想解和反理想解的距离，选择最接近理想解的选项作为首选，常见的方法有TOPSIS（Technique for order preference by similarity to ideal solution）、VIKOR（VlseKriterijumska Optimizacija I Kompromisno Resenje）等；如果决策问题中的标准或因素相互影响，通常使用基于交互的方法，代表性方法有DEMATEL（The Decision-Making Trial and Evaluation Laboratory）、GRA（Grey Relational Analysis）等；基于效用的方法通过将各备选方案在不同准则下的表现转换为单一的效用值来进行综合评价，主要有MAUT（Multi-Attribute Utility Theory）、SMART（Simple Multi-Attribute Rating Technique）和DEA（Data Envelopment Analysis）方法等；混合方法则结合多种单一决策方法，以弥补使用单一决策方法所带来的局限性，主要有AHP-TOPSIS、AHP-VIKOR等方法。然而，尽管单一决策方法在某些情况下可能不如混合方法有效，但当决策标准较为复杂时，混合方法会显著增加决策模拟的复杂性（Zoma和Sawadogo，2023）。

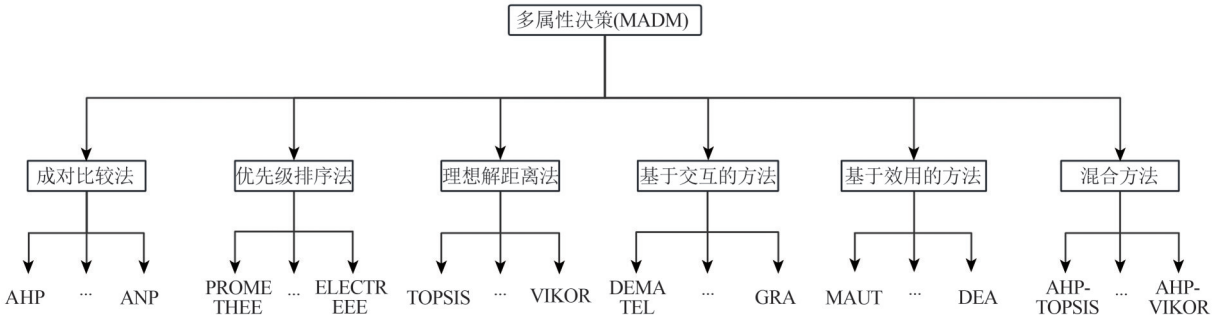


图 1 光伏布设适宜性区域评价的多属性决策方法及其分类  
Fig. 1 MADM method and classification for regional evaluation of PV deployment suitability



表2展示了MADM方法在光伏布设适宜性区域评价和选址中的应用案例。结合图1可以发现：在基于遥感与GIS技术的光伏适宜区域评估和光伏最佳选址研究中，AHP是应用最为广泛的决策分析方法之一（Wu等，2014）；太阳辐射强度被认为是适宜性区域评估最重要的标准，而受保护的

区域和水体被认为具有最高等级的限制性因素（Al Garni和Awasthi，2018）；随着这一领域研究的成熟，适宜性区域评价逐渐从单一决策方法转向混合方法，以提高分析的准确性和可靠性。未来研究应进一步优化混合决策方法，提升光伏布设适宜性区域评价和选址的科学性。

表 2 光伏布设适宜性区域评价案例  
Table 2 Photovoltaic siting suitability assessment cases

研究案例	研究主题	研究区域	方法	数据	决策标准
（张乾等,2018）	光伏电站布设适宜性评估	中国	AHP	辐射数据、DEM、路网、夜间灯光、土地覆被	太阳总辐射、日照时数的稳定程度、离路网、城镇的距离、坡向、海拔、土地利用
（赵振宇等,2023）	大型光伏电站选址	内蒙古自治区，中国	AHP-DEMATEL	DEM、气象数据、经济面板数据	辐射强度、日照时数、坡度、经济水平
（Rediske等,2020）	大型光伏电站选址	巴西	AHP-TOPSIS	水域、路网、土地利用、保护区、DEM	离道路、城镇、变电站、保护区等的距离，太阳辐射强度、坡向坡度
（Díaz-Cuevas等，2018）	光伏电站最佳选址	塞维利亚省，西班牙	AHP	DEM、路网、POI、自然保护区、土地覆被	太阳辐射强度、坡向坡度，离居民点、电网、路网等的距离
（Minaei等,2021）	光伏布设适宜性评估	呼罗珊—拉扎维省，伊朗	BWM	DEM、地质断层、气象数据、自然保护区、路网	离路网、河流、地质断层等的距离，坡向、日照时数、辐射强度、降水、温度和湿度
（Fard等,2022）	光伏电站选址	桂兰省，伊朗	模糊BWM	辐射数据、土地利用、DEM、路网、保护区	与城镇、居民点、主要道路、水源、保护区等的距离，太阳辐射强度、坡向坡度、未利用地或荒地以及风速、温度等
（Colak等,2020）	光伏电站最佳选址	马拉蒂亚省，土耳其	AHP	辐射数据、土地覆被、DEM、路网、居民区、输电线路	太阳辐射，离道路、河湖、居民区、输电线路的距离，坡向坡度

3.2 光伏潜力估算

集中式光伏系统物理潜力评估只需在适宜性区域评价或选址基础上，结合辐射数据进行空间化表征或统计即可（Yu等，2023）。地理潜力评估则要求进一步考虑适宜区域面积、光伏面板朝向及倾斜角度、阴影遮挡等因素，进行综合模拟和计算（Hafeznia等，2017）。集中式光伏系统在选址时就已充分考虑了地形地貌、坡向坡度等地表特征，光伏板最佳倾角和朝向也可以根据最佳布设区域进行计算（Jacobson和Jadhav，2018）。即便是单、双轴及自适应追踪式光伏系统，其光伏板朝向和倾角也可以基于当地纬度、太阳高度角、方位角等进行实时计算（Sidek等，2017）。同时，在设计光伏面板阵列时，还会综合考虑光伏板自身造成的阴影遮挡，并在光伏潜力估算时统一计算阴影遮挡损耗（Chen等，2019）。因此，集中式光伏系统光伏潜力估算中所需的各项参数均可基

于光伏布设适宜性区域评估结果及光伏阵列布局模式进行计算。此外，用以衡量特定土地面积上光伏系统有效转化太阳能为电能效率的土地转换系数也被用于估算集中式光伏系统潜力。该系数综合考虑了土地面积、光伏组件效率、安装方式和阴影影响等环境和技术因素（Yang等，2019）。

光伏适宜性区域评估或选址后，根据土地转换系数、投资规模、项目预算等，借助辐射评估模型或专用分析软件，就可以得出较为精确的光伏潜力评估结果。本文将集中式光伏潜力估算方法分为经验模型、物理模型及相关软件3类（Assouline等，2018a）。经验模型通常基于历史数据和经验公式，通过统计分析和回归模型预测光伏潜力（Antonanzas等，2016）。物理模型则考虑了太阳辐射、气象条件等因素，通过复杂的物理公式进行计算（Liu等，2023）。相关软件如PVGIS、SAM等，集成了经验和物理模型，广泛应用于光伏潜力评估中（Kumar等，2022）。借助这

些评估方法和工具，全球、大洲及国家尺度太阳能及光伏潜力评估已取得显著进展（表3），使得相关利益主体能够全面分析特定区域的光伏资源分布及其利用潜力，从而为决策者提供科学依据，支持可再生能源项目的规划和实施。

表 3 集中式光伏潜力评估方法及相关案例

Table 3 Methods and related case studies for centralized photovoltaic potential assessment

方法分类	研究案例	研究主题	研究区域	参数	研究内容
经验模型	(Wang 等, 2021)	基于土地资源变化的中国光伏发电潜力估算	中国	太阳辐射、土地转换系数、光伏组件效率	以人均 GDP、城市化率等指标预测 2020 年、2030 年建成区面积,推算未来适宜建设屋顶光伏面积,并预测电力产出
	(Hafeznia 等, 2017)	公用事业规模光伏潜力评估框架	Birjand 大坝, 伊朗	太阳辐射、可用土地面积、光伏组件效率	以 900 m <sup>2</sup> 区域光伏装机容量为 46.2 kW 光伏系统为标准,外推整个研究区内的光伏潜力
	(Právalie 等, 2019)	太阳能潜力评估	全球	全球尺度辐射数据	基于辐射数据进行空间统计分析,即辐射强度就是光伏潜力
物理模型	(Zhang 等, 2020)	太阳能潜力评估	中国	太阳辐射、土地覆被	基于土地覆被数据直接排除农、林、草等不适宜光伏布设的区域后,直接统计适宜区域内的太阳辐射总量
	(Ouchani 等, 2021)	大规模光伏潜力评估	摩洛哥	太阳辐射、可用土地面积、光伏组件效率	将研究区划分为格网,计算每个格网中的光伏潜力
	(Sreenath 等, 2021)	公用事业规模陆基太阳能光伏电站的 7E 分析	马来西亚	用地面积、产能需求、方位角和倾角、光伏组件效率等	基于 RETScreen 软件内置的气象、辐射数据及光伏系统参数等信息,模拟了其电力产量,并对其经济和环境性相关指标进行了评估
相关软件	(Fadlallah 和 Serradj, 2020)	确定最优光伏系统	苏丹	NASA 气象及辐射数据	基于多种光伏类型参数,借助 HOMER 模拟 21 个备选地址的电力产量,并结合经济参数,选定最佳布设地址
	(Obeng 等, 2020)	光伏发电技术可行性评估	UENR Nsoatre 校区, 加纳	气象及辐射数据,光伏系统各项参数	基于 PVsyst 软件模拟最佳布设方位和角度,模拟了研究区内每小时电力产出

从表3中可以看出，基于经验模型的光伏潜力估算过程相对简单，但无法考虑影响光伏系统效率的细节信息。基于物理模型的光伏潜力估算重点在于土地转换系数和光伏系统参数的确定。但以上两种方法较适用于光伏潜力的前期评估阶段，即评估区域内光伏潜力的总体丰富程度。而基于相关软件的评估结果则具有较高精度，其模拟结果与光伏系统实际电力产出具有较高的一致性（Omar 等，2024），其拓展模块更是对进一步评估光伏系统的经济及环境效益提供了便利。此外，软件内置的多种光伏材料、参数和型号为多种光伏布设方案的对比和优化提供了基础（Kumar 等，2021；Mohammadi 和 Gezezin，2022）。因此，基于相关软件的光伏潜力评估方法更适用于集中式光伏电站的规划和建设阶段。

4 分布式光伏潜力评估

分布式光伏系统通常指与建筑屋顶、立面、道路噪音屏障等基础设施相结合的光伏系统（Gil 等，2020）。由于其具有布设灵活、不占用额外空间资源，且电力生产与消费端临近，可以减少传输损耗等优势而到了广泛应用（Nadeem 等，2023）。分布式光伏系统潜力估算首先需要获取辐射数据，并明确可布设光伏板的基础设施面积、光伏板倾斜角度及方位信息。同时，还需要量化光伏板受周围地物的阴影遮挡影响。最后，基于评估模型或相关软件，综合考虑上述所有因素，得出光伏潜力评估结果。

4.1 可布设面积确定

分布式光伏系统可布设面积的测定仍存在较

大挑战 (Hong 等, 2017)。如建筑屋顶、立面、道路噪音屏障等, 可供布设光伏系统的面积较小且分布较为分散, 加之建筑风格、屋顶样式、噪音屏障类型等复杂多样 (Zhong 等, 2021), 即使在小尺度区域内, 也难以便捷获取其面积等属性信息 (Barbón 等, 2022)。目前, 获取建筑屋顶等基础设施可布设光伏板面积的方法主要有 3 类: (1) 基于实地测量、工程图件或借助 LiDAR 数据,

以获得精确的建筑 3D 属性特征; (2) 通过经验模型外推, 利用建筑或街区尺度的高精度数据及经验系数估算大尺度区域的可布设面积等信息; (3) 基于航空卫星影像、街景图像和多源地理信息数据, 通过机器学习模型识别和预测建筑屋顶、道路噪音屏障等。有关上述方法的分析及相关研究案例参见表 4。

表 4 分布式光伏系统可布设基础设施面积获取方法分类

Table 4 Classification of methods for determining deployable infrastructure area for distributed photovoltaic systems

方法	优势	劣势	参考案例
实地测量 工程图件、LiDAR	数据精度高, 可获取建筑 3D 属性特征。	耗时长、需要较高的人力和物力成本,工程图件和政府数据库获取难度大,LiDAR 数据成本高	(Wadhawan 和 Pearce, 2017; Yildirim 等, 2021; Hu 等, 2024)
经验模型	低成本、高效率。	推算结果精度高度依赖于初始数据和经验系数的准确性	(Ko 等, 2015; Jiang 等, 2020; Wang 等, 2021; Kutlu 等, 2022)
机器学习	适用于大尺度区域、 高效率。	实现成本高,精度易受训练样本质量、输入特征值和算法影响	(Gagnon 等, 2018; Qian 等, 2022a; Zhang 等, 2022b; Zhang 等, 2022c; 刘梦月等, 2023)

获得建筑屋顶面积、建筑高度、噪音屏障里程等属性信息后, 还需考虑其他结构因素的限制, 如建筑屋顶和立面的空调设备、通风管道、窗户和天线等 (Ren 等, 2023)。此外, 不规则的屋顶结构和噪音屏障也会限制光伏板的实际布设数量 (Aslani 和 Seipel, 2022)。这些因素使得分布式光伏系统可布设面积的精确测定变得更加困难 (Tian 等, 2024)。部分研究在获得建筑屋顶、立面、道路噪音屏障等基础设施面积后, 通常使用经验系数来排除因屋顶障碍物或其他限制性因素造成的无法布设光伏系统的区域 (Bódis 等, 2019)。此外, 也有部分研究基于高分辨率遥感影像和 LiDAR 数据, 结合深度学习方法识别并排除建筑屋顶障碍物。然而, 由于数据获取成本等因素的限制, 这些方法的适用范围仍然有限 (Zhong 等, 2022)。

4.2 坡向、坡度分析

不同朝向和坡度的屋顶接收到的太阳辐射总量差异显著。例如, 北半球高纬度地区北向屋顶因接收到的太阳辐射较少, 通常不适合布设光伏板 (Esfahani 等, 2021)。而朝南且具有一定倾斜角度的屋顶能够接收到更多的太阳辐射, 适合安装光伏板以最大化发电效率 (Han 等, 2022)。对于非平顶建筑而言, 光伏板布设应与建筑结构特

征相一致, 以确保结构安全性 (Formolli 等, 2022)。此外, 当前大部分研究仅能获取建筑基底面积, 但非平顶建筑的实际屋顶面积通常与屋顶坡度紧密相关 (Yang 等, 2020)。因此, 获取建筑屋顶坡向、坡度信息对于精确评估分布式光伏系统潜力亦非常重要 (Sun 等, 2022)。

除基于 DEM 直接计算研究区域坡向、坡度外, 其还可基于 LiDAR 点云、3D 建筑模型及工程图件等获取 (Jurasz 等, 2020)。此外, 部分研究还通过经验系数法, 根据建筑类别 (如民用、商业或工业类建筑) 来估算研究区内建筑屋顶的坡向和坡度信息 (Pan 等, 2022)。然而, 目前多数大尺度区域屋顶光伏潜力评估研究中, 都将建筑屋顶视为平顶, 忽略了坡向坡度属性, 以提高光伏估算效率 (Wang 等, 2022b; Zhang 等, 2023)。尽管近年来也有部分研究通过识别屋顶脊线、建筑物类型和屋顶类别等方法来获取建筑屋顶坡向和坡度等属性信息, 以期为屋顶光伏潜力评估等提供更精确的数据, 但相关研究成果仍处于探索阶段, 尚未在大尺度区域得到广泛应用 (Qian 等, 2022b)。

4.3 阴影遮挡模拟

分布式光伏系统主要利用现有基础设施, 其周围环境较为复杂, 容易受到邻近地物的空间遮



挡 (Liao 等, 2023)。例如, 建筑屋顶、立面和道路噪音屏障可能会被临近建筑和植被遮挡 (Zhang 等, 2024b), 高速路面可能会受临近山体的遮挡 (Zhang 等, 2022a) 等。因此, 在确定区域基础设施实际可布设面积后, 还需模拟该区域的动态阴影特征, 并在光伏潜力估算时量化其对光伏系统辐射接收的影响, 以有效提升光伏系统潜力评估精度。

参考相关研究 (Robledo 等, 2019; Vo 和 Laefer, 2019), 本文将基于遥感与GIS技术进行光伏潜力评估研究中的阴影分析方法分为: 经验系

数法、基于GIS软件的方法、光线追踪法和像素计数方法4类 (表5)。经验系数法通过借鉴以往研究中的阴影遮挡系数, 能够通过简单换算量化邻近地物遮挡影响 (Xu 等, 2021)。光线追踪法通过模拟太阳光线在空间中的传播路径来确定被遮挡区域, 适用场景较广 (Vo 和 Laefer, 2019)。像素计数法通过离散化建筑3D实体, 并分析其离散化单元是否被阴影遮挡而判定阴影区域, 适用于复杂城市环境和建筑 (Arias-Rosales 和 LeDuc, 2022; Wang 等, 2023)。

表5 光伏潜力评估中的阴影分析方法

Table 5 Shadow analysis methods in PV potential assessment

方法	内容	优势	劣势	工具或模型	参考文献
经验系数法	基于已有研究文献,通过历史数据和经验系数进行估算	简洁高效,可用于多种尺度的阴影分析	精度较差、无法体现空间差异	—	(Rodríguez等,2017;Xu等,2021;Muhammed等,2023)
基于GIS软件的方法	基于相关GIS软件工具及多分辨率DEM数据进行阴影分析	方法简单易用且计算量较小;DEM数据易获取;适宜较大区域分析	基于栅格数据的阴影分析,只能表示2D阴影区域	Hillshade SolarGIS Helioscope r.sun	(Cebecauer和Suri,2015;Hong等,2017;Jung等,2019;Li和Han,2022;Zhang等,2022a)
光线追踪法	通过模拟太阳光线在空间中的传播路径,模拟其与建筑物之间的交互,确定阴影区域	适用于不同精度要求和复杂场景的阴影分析	精细化建筑阴影模拟需要耗费较多计算资源	R_shadow Python_Pybdshadow PVsyst PV*SOL	(Hofierka和Zlocha,2012;Dorman等,2019;Singh,2020;Zhu等,2020;Zhang等,2024b)
像素计数方法	将3D建筑离散化为超点、三角网或体素等,再通过正射投影等方法判断、统计被遮挡的基本单元	精度高,适用于精细三维模型	数据成本、计算成本巨大,仅适用于建筑或街道尺度	—	(de Almeida Rocha等,2019;Arias-Rosales和LeDuc,2022;Narjabadifam等,2022;Liu等,2023;Xu等,2024)

当前, 全球及国家尺度建筑屋顶光伏潜力评估中, 或未考虑建筑阴影遮挡, 或仅用经验系数估算其对光伏系统辐射接收的影响 (Joshi 等, 2021; Wang 等, 2022a)。在城市尺度, 光线追踪法能够有效模拟3D建筑阴影特征, 从而精确评估建筑立面的光伏潜力。像素计数法能够提供3D建筑精细结构的阴影特征, 为光伏系统的优化设计提供依据, 但需耗费较大的计算资源。综上, 根据可获得的数据类型、评估区域、所需的评估精度及算力资源, 分布式光伏系统阴影遮挡模拟可以灵活选择不同的分析方法。

4.4 光伏潜力估算

分布式光伏系统潜力评估方法可分为经验模

型、物理模型及相关软件3类 (表6), 其特征在3.2节已详细阐述。经验模型只适用于概略性的潜力估算或资源评估, 若服务于政策性能源规划或产业性资源开发, 还需采用基于物理模型或相关软件的评估方法, 以提供更加精确的评估结果, 支持能源决策和产业布局优化。

物理模型所需参数主要有辐射数据、光伏板可实际布设面积、光伏板朝向、倾角及动态阴影遮挡区域等。太阳辐射计算公式如下 (Raptis 等, 2017):

$$GI_{\beta\gamma} = DBI_{\beta\gamma} + DI_{\beta\gamma} + RGI_{\beta\gamma} \tag{1}$$

式中,  $\beta$ 、 $\gamma$ 分别为光伏板的倾角和方位角,  $GI_{\beta\gamma}$ 为其接收的太阳总辐射。  $DBI_{\beta\gamma}$ 、  $DI_{\beta\gamma}$ 、  $RGI_{\beta\gamma}$ 分别为光伏板接收到的直射、散射和反射辐射分量。

表 6 分布式光伏潜力评估方法及案例  
Table 6 Distributed photovoltaic potential assessment methods and cases

方法分类	研究案例	研究主题	研究区域	数据	研究内容
经验模型	(Wadhawan 和 Pearce, 2017)	国家尺度噪音屏障光伏潜力评估	美国	噪音屏障里程及空间分布	人工标记加利福尼亚州 200 个噪音屏障位置及朝向, 计算其光伏潜力, 并基于噪音屏障里程与道路里程比例外推得到全美道路噪音屏障光伏总潜力
	(王思琪 等, 2021)	屋顶光伏发电潜力预测	上海	建筑屋顶面积	基于 PVsyst 模拟了单位面积上的屋顶光伏发电潜力, 然后对上海市部分区域建筑屋顶面积进行估算, 外推得到研究区光伏发电总潜力
物理模型	(Assouline 等, 2018b)	大规模屋顶光伏潜力评估	瑞士	3D 建筑矢量、辐射数据、DEM、DSM	考虑屋顶阴影遮挡、坡度坡向、光伏板倾斜角度, 基于机器学习和物理模型, 评估了瑞士建筑屋顶光伏潜力
	(Zhang 等, 2023)	屋顶光伏潜力评估	中国	气象数据、辐射数据、建筑屋顶面积	基于建筑屋顶可利用面积, 借助辐射数据及辐射估算模型, 评估了中国建筑光伏潜力; 根据电网排放因子进一步估算了屋顶光伏的碳减排效益
	(Wang 等, 2022b)	旧住宅屋顶光伏潜力评估框架	南京	ECMWF 辐射数据、建筑矢量数据	基于 BIGEMAP 与 GIS 识别建筑屋顶, 假设所有建筑屋顶皆为平面屋顶, 并考虑阴影遮挡影响, 确定光伏板可实际布置面积后, 基于物理模型估算屋顶光伏潜力
	(Bódis 等, 2019)	屋顶光伏潜力评估	欧盟	辐射数据、建筑矢量	基于欧盟建筑存量数据, 假设 60% 的建筑屋顶面积可用于布置光伏板后, 借助 PVGIS 软件估算了屋顶光伏潜力
相关软件	(陈子龙等, 2021)	建筑屋顶光伏潜力评估	广州	建筑矢量	考虑建筑屋顶阴影遮挡等因素, 得出广州市建筑屋顶可实际利用面积后, 基于 PVsyst 模拟了标准光伏组件模块的电力产量, 进而计算得到广州市建筑屋顶光伏潜力
	(Dey 和 Subudhi, 2020)	90 kW 并网光伏系统的设计、仿真和经济评估	Rourkela 国家理工学院, 印度	布置地址、光伏板方位角、倾斜角度	基于 PVsyst 设计、模拟了一个 90kW 的屋顶光伏系统, 并对其光伏电力产量和经济性进行了评估
	(Ahmed 等, 2022)	建筑屋顶光伏可利用性调查	NEDUET 校园建筑, 巴基斯坦	3D 建筑矢量、纬度、天空晴朗程度	基于 PV*SOL 内置光伏系统类型, 输入可用屋顶面积、气象参数和光伏板布置模式, 模拟了光伏发电潜力
	(Kutlu 等, 2022)	屋顶光伏技术潜力评估	安卡拉 17 栋建筑, 土耳其	建筑类别: 住宅、商业及工业, 屋顶坡度	基于 HelioScope 软件, 在确定屋顶可用面积及坡度后, 模拟了 5 种不同光伏组件类型的布置方式及电力产量
	(常建国和付梦菲, 2022)	基于 PVsyst 软件的屋顶光伏发电潜力研究	郑州市区单体建筑	建筑屋顶高度、面积	基于 PVsyst 计算光伏板最佳布置角度等信息模拟发电量, 并分析不同因素对屋顶光伏发电潜力的影响

目前适用于中国区域分布式光伏潜力估算的数据较为缺乏, 相关研究主要基于 CAMS 的晴空辐射数据进行 (Zhang 等, 2024b)。但晴空辐射数据需要基于相关气象参数进行校正。常用方法是通过每月晴、阴天天数的占比计算大气透射率等参数, 模拟大气层对太阳辐射的散射和反射作用 (Huang 等, 2008)。在气象模拟等精度要求较高的领域, 晴空辐射数据校正需要更多参数 (如大气

中臭氧、水汽含量、气溶胶等) 和更为专业的校正模型 (Zhong 等, 2016)。适用于分布式光伏潜力估算的软件主要有 PVGIS、PVsyst、PV\*SOL 和 HelioScope 等 (表 6)。除 PVGIS 适用于较大尺度外, 其余软件均以建筑尺度潜力评估为主。相较于经验和物理模型, 部分相关软件还内置了辐射数据、阴影分析、光伏板类型等数据和模块, 有效缓解了非专业领域研究者评估的难度, 提升了



光伏潜力评估效率。此外,上述软件还兼具精细化的系统布局优化及性能模拟等功能,可以进一步为光伏系统经济可行性评估、光伏电力并网及调度等提供支持(Rozmi等,2019)。

## 5 结 语

当前,国内外基于遥感与GIS技术的光伏潜力评估在辐射数据产品研制、光伏适宜性布设区域评价、光伏潜力评估等方面已取得了丰硕的研究成果:高精度辐射数据产品为区域太阳能资源的精确表征提供了基础;多尺度、多维度的光伏适宜性区域评价及选址方法已相对成熟。光伏潜力评估研究重心正在从大尺度的光伏布设适宜性区域评价和光伏资源评估调查,向小尺度精细化的分布式光伏系统潜力评估转移;正在从专注于2D平面、仅考虑部署面积的粗略评估,转向3D空间,综合考虑空间遮挡、朝向和倾斜角度等因素的精细化评估;正在从低层次的物理、地理潜力评估,向更高层次的技术、经济潜力评估转移。

尽管在高精度辐射数据产品研制方面已取得一定进展,但就空间分布和整体性而言,关于太阳辐射的可访问数据库还不够充分(Kumar等,2020)。此外,较少有研究考虑动态天气变化(如云层、降雨和气溶胶)对光伏系统发电量的影响。在分布式光伏系统潜力评估中,当前获取建筑屋顶坡向、坡度和模拟阴影遮挡影响的方法在精度和成本上仍无法满足大尺度评估的需求(Vo和Laefer,2019)。此外,遥感与GIS技术在多能源系统空间布设与优化、电力调度与供需分配及协同管理等方面的探索仍显不足。

未来研究首先需要开发更高时空分辨率且覆盖区域更广的辐射数据产品,以提高光伏潜力评估的精度。其次,应加强动态天气变化(如云层、降雨和气溶胶等大气条件的短期和长期波动)影响光伏系统发电量的相关研究,开发更精细的动态预测模型,进一步提高短期预测的准确性(Limouni等,2023)。同时,应加强光伏潜力评估中的跨学科集成,结合气象学、环境科学等领域的知识,利用大数据和机器学习技术,发展综合评估模型,全面评估光伏系统的经济、环境和社会效益(Mangiante等,2020)。最后,亦需探索遥感与GIS技术在光伏与储能系统、风能、地热能等多种能源系统耦合协调、优化调度等方面的潜

在作用,以促进能源系统高效、平稳运行(Cheng等,2022)。

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# Photovoltaic potential assessment based on remote sensing and GIS

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**Abstract:** Photovoltaic (PV) potential assessment is a vital method for evaluating the developable solar energy resources and PV power generation potential in specific areas. It serves as the foundation for scientific regional energy planning and rational utilization. Advances in remote sensing and GIS technologies have significantly enriched multi-scale, long time-series, high spatial and temporal resolution solar radiation data products. These advancements have also propelled the multidimensional potential assessment of both centralized and distributed PV systems. However, there is currently a lack of systematic review and summary of the application of remote sensing and GIS technologies in solar resource assessment, PV suitability area evaluation, and PV potential estimation. Although some studies have reviewed the application of GIS technology in acquiring solar radiation data, evaluating PV suitability areas, and assessing urban rooftop PV potential, these studies either focus solely on building rooftop PV systems or fail to comprehensively cover all steps of PV potential assessment. Consequently, they do not fully and clearly reveal the technical framework and research pathways for PV potential assessment. Furthermore, a comprehensive framework for PV potential assessment, addressing both centralized and distributed PV systems, remains to be explored. This paper systematically analyzes the current applications of remote sensing and GIS technologies in PV potential assessment, covering key steps from radiation data acquisition, PV suitability area evaluation/usable area determination (for centralized and distributed PV systems), slope and aspect analysis, shadow simulation, to PV potential estimation. It delves into how different methodologies and tools are integrated into each of these steps, providing a holistic view of the process. By summarizing and organizing the assessment processes for both centralized and distributed PV systems, this paper aims to provide a more complete technical framework for related research. This framework is intended to foster a comprehensive understanding and further development of the PV potential assessment field, helping to standardize methods and improve accuracy across different studies. Additionally, considering the current trends in PV applications, this paper explores the potential role of remote sensing and GIS technologies in the future development of the PV industry. It highlights how these technologies can support advanced applications such as integrating PV systems with other renewable energy sources, optimizing energy storage solutions, and improving grid management. By addressing these emerging areas, the paper seeks to underscore the ongoing and future importance of remote sensing and GIS in maximizing the efficiency and effectiveness of solar energy utilization, thus contributing to the broader goals of energy sustainability and carbon neutrality.

**Key words:** solar energy, irradiation data, concentrated/distributed photovoltaic (PV) systems, PV site selection, energy planning

**Supported by** the National Natural Science Foundation of China's Sustainable Development International Cooperation Science Program (SDIC) (No. W2412152)