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Field Validation of Satellite and Reanalysis Wind Resource Assessments: A Systematic Review

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ABSTRACT

Wind resource assessment increasingly relies on satellite observations, reanalysis and downscaled products, whose reliability depends on comparison with field measurements. This systematic review, reported following Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020, examined how such products have been validated in the field. Scopus and Web of Science were searched on 20 July 2026, which returned 125 records (105 after removing 20 duplicates). After keeping article records (n = 77) and screening titles and abstracts, 25 studies were included. A bibliometric description of the 105 unique records (1996 to 2026) is presented separately from the analysis of the 25 included studies. Classified by underlying data, four studies used satellite wind retrievals, two combined satellite data with reanalysis or models, eight used global or regional reanalysis, and eleven used downscaled or atlas products. In total, six studies (24%) involved satellite retrievals and 19 (76%) were reanalysis-based. Field validation relied on masts or towers (15 studies), weather stations (6), buoys (3), lidar (3), turbine records (2), and one anemometer campaign; eight studies combined two instrument types, and three abstracts did not specify the instrument. Validation designs ranged from a single mast to millions of records, and reported metrics were not uniform. Eight studies (32%) addressed single sites or areas up to about 1,000 km², and only two assessed a continuous area of that size. This review did not identify a unified, widely adopted procedure for validating satellite and reanalysis wind products. The IEC 61400-50 series and IEC 61400-15-1:2025, judged from their published scope descriptions, address measurement practice and site suitability reporting rather than product validation. We propose a reporting framework to improve transparency and comparability in future validation studies. Key limitations include restricting the search to two databases, single-reviewer screening, and data extraction limited to abstracts.

1. INTRODUCTION

Wind power continues to expand quickly. The Global Wind Energy Council reported a record 165 GW of new wind capacity in 2025 and a cumulative 1,299 GW at the end of that year [1]. Siting decisions in this expansion depend on estimates of the wind resource. Established practice obtains these estimates from measurement campaigns with meteorological masts and, increasingly, ground-based remote sensing instruments such as lidar and sodar [2-4]. Such campaigns provide reliable point records, but each campaign covers a limited footprint and takes time and resources to carry out.

To complement field campaigns, wind resource studies use remote data products, which can be grouped by their underlying data. Satellite retrievals, for example from synthetic aperture radar (SAR) and scatterometers, estimate near-surface winds, mainly over water. Reanalyses such as ERA5 and MERRA-2 assimilate observations, including satellite data, into numerical models to produce gridded long-term records [5, 6]; ERA5 has a horizontal resolution of about 31 km [5]. Downscaled products refine reanalysis to finer scales, for example, regional hindcasts such as NORA3, which downscales ERA5 with a 3 km nonhydrostatic model [7], and atlases such as the Global Wind Atlas, which is built from ERA5 with mesoscale and microscale modelling [8]. The terminology used for these products is not always consistent. For instance, the wind variables of the Photovoltaic Geographical Information System (PVGIS) tool are taken from ERA5 and ERA5-Land reanalysis [9], so data described as satellite data may in fact be reanalysis-based.

Whatever the product, its use for siting rests on evidence that it reproduces observed winds at the scale of use. A critical review has examined the uncertainties of reanalysis data used for wind resource assessment [10]. In a multi-country assessment, correction of reanalysis with the Global Wind

Atlas versions tested did not substantially improve, and in one case degraded, simulated wind power [11]. Less clear is how field validation is designed and reported across studies that cover satellite, reanalysis and downscaled products together, and at which spatial scales it is carried out, particularly for small geographic areas, where a single ERA5 grid cell can cover roughly 1,000 km² [5].

Standards address parts of this chain. The IEC 61400-50 series specifies wind measurement with masts and with ground-mounted remote sensing [3, 4], and IEC 61400-15-1:2025 defines a framework for assessing and reporting site suitability conditions, including the measurement and prediction of long-term wind characteristics at a site [12]. How far these documents cover the validation of satellite and reanalysis products is examined in this review and is not assumed.

This article reports a systematic review of studies that estimated wind resource from satellite, reanalysis, or downscaled products and compared the estimates with field measurements. It asks which products have been validated, how the validation was designed and reported, at which spatial scales it was done, and how reported practice relates to the IEC documents. Compared with the critical review in the study [10], which concerns reanalysis uncertainty, the present review also covers satellite and downscaled products, uses a documented systematic search, classifies products by their underlying data, extracts the validation design, and relates the results to spatial scale and to IEC documents. A bibliometric description of the wider literature is presented separately from the analysis of the included studies. The findings are intended to inform future work, including work on small areas in Peru, for which no case study is presented here.

2. METHOD

This study is a systematic review with a descriptive bibliometric component. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement [13] was adopted as the reporting guideline because it provides a structured way to document identification, screening, and inclusion. The subsections below describe the review questions, the search, the eligibility criteria, the selection process, the data extraction, and the bibliometric analysis.

2.1 Study design and review questions

The review addressed four questions. RQ1: Which remote data products have been compared with field measurements for wind resource assessment, when classified by their underlying data? RQ2: How were these field validations designed and reported, in terms of instruments, sites, heights, periods, and metrics? RQ3: At which spatial scales were they carried out, and how many addressed small geographic areas? RQ4: How do the reported practices relate to existing IEC documents, and which gaps remain?

Two analytical layers were used. The first is a descriptive bibliometric analysis of all 105 unique records retrieved. It was kept for the full set because it characterizes the publication landscape around the topic, including records that were later excluded from the synthesis, and it is interpreted separately from the second layer. The second layer is the extraction and narrative synthesis of the 25 included studies, which is the only basis for statements about the methods used in validation. Keyword structures from the bibliometric layer were not used to infer the methodological characteristics of the included studies.

2.2 Information sources and search strategy

Searches were run on 20 July 2026 in Scopus (Elsevier) and in Web of Science through the “All Databases” option of the institutional subscription, which includes the Web of Science Core Collection and other indexes available under that subscription. No language or date filters were applied. The search string combines four blocks with the AND operator (Table 1): wind potential terms, remote or reanalysis data terms, validation terms, and field measurement terms. It was applied to the title, abstract, and keywords (TITLE-ABS-KEY in Scopus and TS in Web of Science). Table 2 reports the search settings and the number of records.

Two features of the strategy affect its sensitivity. First, the string requires terms for both validation and field measurement, so studies that compared remote products with field data without using these terms in the title, abstract, or keywords would not be retrieved. Second, because the “All Databases” option depends on the institutional subscription, the number of records may differ at other institutions. No supplementary searches, such as citation chasing or a relaxed string, were performed, and therefore the recall of the strategy was not quantified.

Table 1. Search string by conceptual block (blocks combined with AND)

Block	Concept	Terms (Combined with OR Within the Block)
1	Wind potential	“wind energy potential”, “wind potential”, “wind power potential”, “wind resource assessment”, “wind resource potential”, “wind energy assessment”, “wind resource evaluation”, “wind energy evaluation”, “wind resource estimation”, “wind power assessment”
2	Remote or reanalysis data	satellite, “remote sensing”, ERA5, “ERA-Interim”, “ERA5-Land”, MERRA-2, CFSR, “NASA POWER”, reanalysis, “Global Wind Atlas”, GWA
3	Validation	validation, validate*, verification, “ground truth”
4	Field measurement	“field measurement*”, anemometer, “meteorological station”, “meteorological tower”, “met mast”, “meteorological mast”, “in-situ measurement*”, “ground-based”

Table 2. Search settings and number of records by database

Database	Fields	Filters	Search Date	Records
Scopus	TITLE-ABS-KEY	None	20 July 2026	42
Web of Science (All Databases option)	TS (Topic)	None	20 July 2026	83
Total				125

2.3 Eligibility criteria

Table 3 lists the criteria. They were applied in three steps: a document type filter, title and abstract screening, and full-text reading of the studies that passed the screening.

2.4 Study selection process

Records from both databases were merged with the Bibliometrix package and 20 duplicates were removed, which left 105 unique records (Figure 1). Records classified as Article or Research Article were kept for screening, and records of other types were excluded (reviews, data papers, conference and proceedings papers, books and chapters, and theses), which removed 28 records and left 77. Records tagged Article; Early Access (n = 12) were initially excluded together with the other non-final document types. Because publication status alone is not an eligibility criterion, they were re-screened against Table 3, and 77 met the criteria.

The titles and abstracts of the 77 records were screened against Table 3, and 52 were excluded because the abstract did not describe a remote data product compared with field measurements. The full texts of the remaining 25 studies were retrieved and read; none were excluded at this stage, so 25 studies were included in the synthesis. Screening, full-text assessment, and data coding were carried out by the first author, without independent duplicate screening. This is a limitation, discussed in Section 4.

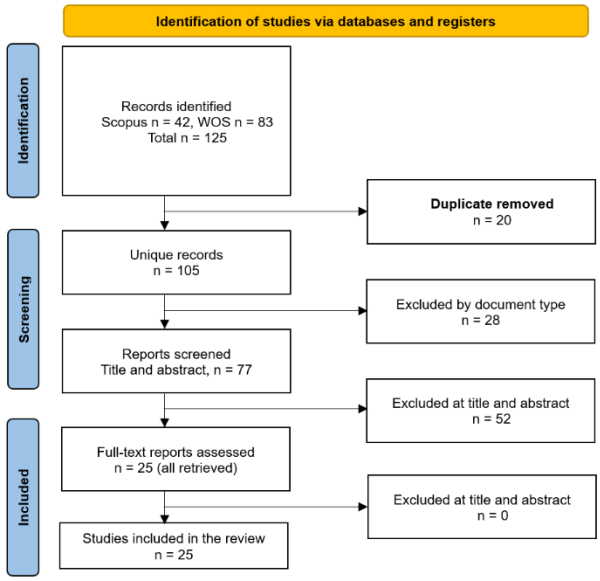

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram of record identification, screening and inclusion

Table 3. Inclusion and exclusion criteria

Criterion	Inclusion	Exclusion
Remote data	Wind speed or wind resource estimated from satellite-derived data, reanalysis, or downscaled products	Estimates based only on field data
Validation	Quantitative comparison of the remote estimate with field measurements from instruments (masts or towers, weather stations, buoys, lidar or sodar, turbine sensors)	Remote data used without comparison to field data; validation mentioned without describing the instrument, method or metrics
Publication type	Peer-reviewed journal article (Article or Research Article)	Reviews, data papers, conference or proceedings papers, books and chapters, theses and dissertations
Status, language and year	Any language and any year; Early Access records are not excluded on status alone	None on these grounds
Duplicates and access	Unique records with full text available	Duplicates between databases; full text not accessible (none in this review)

Table 4. Classification rules used for the included studies

Dimension	Categories and Assignment Rule
Remote data class	S: satellite wind retrievals (SAR, scatterometer, radiometer, or blended satellite wind products). M: satellite retrievals combined with reanalysis or assimilated into a model. R global: global reanalysis used directly or with statistical correction (for example, ERA5, ERA-Interim, MERRA-2, CFSv2, NCEP/NCAR R2) and products that redistribute them (PVGIS wind [9]). R regional: regional reanalysis with data assimilation (for example, COSMO-REA6, IMDAA). D: downscaled or atlas products obtained by dynamical or statistical downscaling of reanalysis or climate models (for example, Weather Research and Forecasting model (WRF) simulations, NORA3 [7], NEWA, Global Wind Atlas [8]). Each study was assigned to one class by the underlying data of the product used for the wind estimate, not by the terminology of the authors. Studies evaluating several products took the most processed class (D above R regional above R global). A reanalysis used only as a comparison reference for a satellite product did not change the class.
Field instruments	Mast or tower; weather station network; buoy or floating platform; ground-based or floating lidar; turbine sensors or turbine records; anemometer field campaign; not specified in the abstract. A study could use more than one type, so counts by type are unique studies per type and are not additive.
Role of field data	V: validation or comparison only. C: calibration, bias correction or training only. V + C: both.
Spatial extent	Site: a single location (mast, station, wind farm or turbine group, extent of a few kilometres). Multi-site: several separate locations compared point by point without mapping an area. Local area: a continuous area up to about 1,000 km², comparable to one ERA5 grid cell [5]. Regional: more than 1,000 km² up to subnational units and sea basins. National: the territory or maritime waters of one country. Global. In this review, a small geographic area is a site or a local area.

2.5 Data extraction and classification

For each included study, the following items were recorded: authors, year and journal; remote data used; remote data class; study area and spatial extent; field instruments and number of sites; measurement heights, period and temporal resolution; role of the field data; metrics reported; and main results. The

first author coded remote data class, instruments, role of field data, and spatial extent using the rules in Table 4. Where the label used by the authors could be ambiguous about the underlying data, the product was classified using the provider's documentation (Table 4).

Because heights, periods, temporal resolutions, and metrics were not comparable across studies, no meta-analysis was attempted, and no formal risk of bias assessment was applied. Results are presented as a narrative synthesis with counts of unique studies. Counts by instrument type are not additive because some studies used multiple instrument types.

2.6 Bibliometric analysis

The descriptive bibliometric analysis was run in Bibliometrix [14] through its Biblioshiny interface on the Posit Cloud platform, on the 105 unique records. Indicators included annual production, main information about the collection, a word cloud, a keyword co-occurrence network, and a thematic map. The search was run on 20 July 2026, so 2026 is an incomplete year, and the annual growth rate reported by Bibliometrix, which is computed between the first and the last year of the collection, is shown for completeness but is not interpreted as a trend.

Metadata were incomplete in the merged collection: the affiliation and Keywords Plus fields were missing in 79.05% and 83.81% of the records, respectively, and the reference count and international co-authorship indicators were not available. These indicators were marked as unavailable and were not interpreted, since missing fields are not genuine zero values. Keyword analyses used a merged keyword field that combines author keywords and Keywords Plus where available. The author keyword field (DE) contained 74 distinct keywords. The thematic map was built from the merged keyword field, and its clusters are interpreted only as descriptions of keyword associations. Keyword standardization followed these rules: author keywords and Keywords Plus were combined for each record in a single field (KW_Merged) with terms separated by semicolons; terms were not stemmed, and no thesaurus, synonym list, or stop-word list was applied, so that keywords were analysed as indexed by the databases. The keyword co-occurrence network included the 50 most frequent keywords, with a minimum edge frequency of 2 co-occurrences between two keywords, and its communities were identified with the Walktrap clustering algorithm. The thematic map used the 250 most frequent keywords, a minimum cluster frequency of 5 per thousand documents, one label per cluster, and the Walktrap clustering algorithm. All analyses were run in Bibliometrix version 5.0 through its Biblioshiny interface.

3. RESULTS

3.1 General landscape of the bibliographic collection

The collection of 105 unique records spans 1996 to 2026 and comes from 76 sources (Table 5). It involves 449 authors, with 4.64 co-authors per document, and three authors wrote single-authored documents. The mean citations per document are 20.91, and the mean age of the documents is 5.8 years.

Table 5. Main information about the bibliographic collection (105 unique records)

Indicator	Value
Timespan	1996 to 2026 (2026 incomplete, search run on 20 July 2026)
Sources	76
Documents	105
Authors	449
Authors of single-authored documents	3
Co-authors per document	4.64
Mean citations per document	20.91
Mean age of documents (years)	5.8
Annual growth rate reported by Bibliometrix	8.93% (endpoint-based, not interpreted)
Reference count	Not available
International co-authorship	Not available
Records with the affiliation field missing	79.05%
Records with the Keywords Plus field missing	83.81%

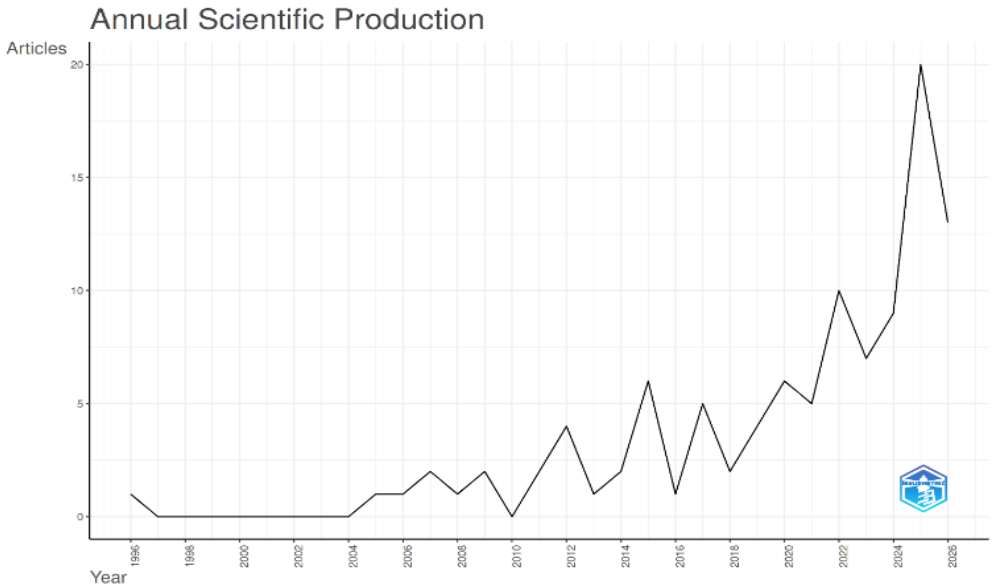

Figure 2. Annual scientific production of the 105 unique records (1996 to 2026; 2026 is incomplete as of 20 July 2026)

Annual production was low until about 2010 and increased afterwards, with the highest annual count in 2025 (about 20 records); 2026 is incomplete (Figure 2). The 8.93% growth rate reported by Bibliometrix is calculated between the first year of the collection (one record in 1996) and the last year (the incomplete 2026), over 30 yearly intervals. It is therefore sensitive to both endpoints and is not used here as a trend indicator. The reference count (0) and the international co-authorship value (0%) shown by Biblioshiny reflect missing metadata, not an absence of references or of collaboration, so both are marked as unavailable, and no inference about international collaboration is drawn.

3.2 Thematic structure of the bibliographic collection

The word cloud (Figure 3) is dominated by general terms such as wind power, wind energy, resource assessment, wind resource assessment, wind power density, weather forecasting, and offshore terms. ERA5, reanalysis data, and satellite data appear at lower frequencies, and validation terms such as model validation and bias correction appear at smaller sizes. The co-occurrence network (Figure 4) and the thematic map (Figure 5) describe how these keywords group. The thematic map shows clusters around wind power and weather forecasting, around wind turbines and atmospheric models, and around resource assessment, and a cluster of lower density that includes ERA5 together with wind resource assessment and wind energy.

These maps describe associations among keywords in a collection of 105 records, of which 80 were not included in the synthesis. They do not measure the quality of validation or whether validation procedures are standardized, and they were therefore not used to draw conclusions about the validation methods of the 25 included studies, which are analysed in the next sections.

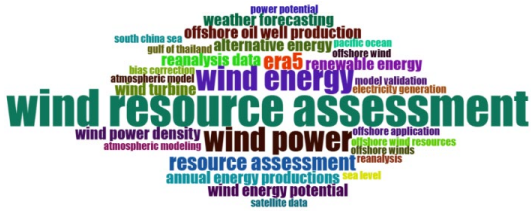

Figure 3. Word cloud of the keywords of the 105 unique records

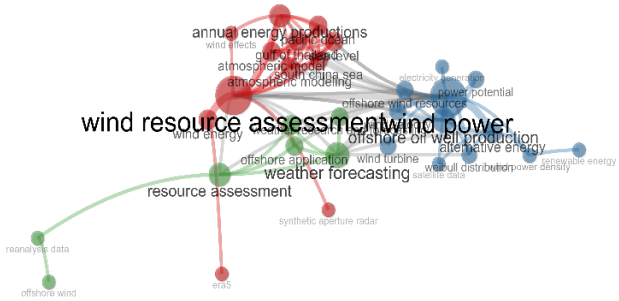

Figure 4. Keyword co-occurrence network

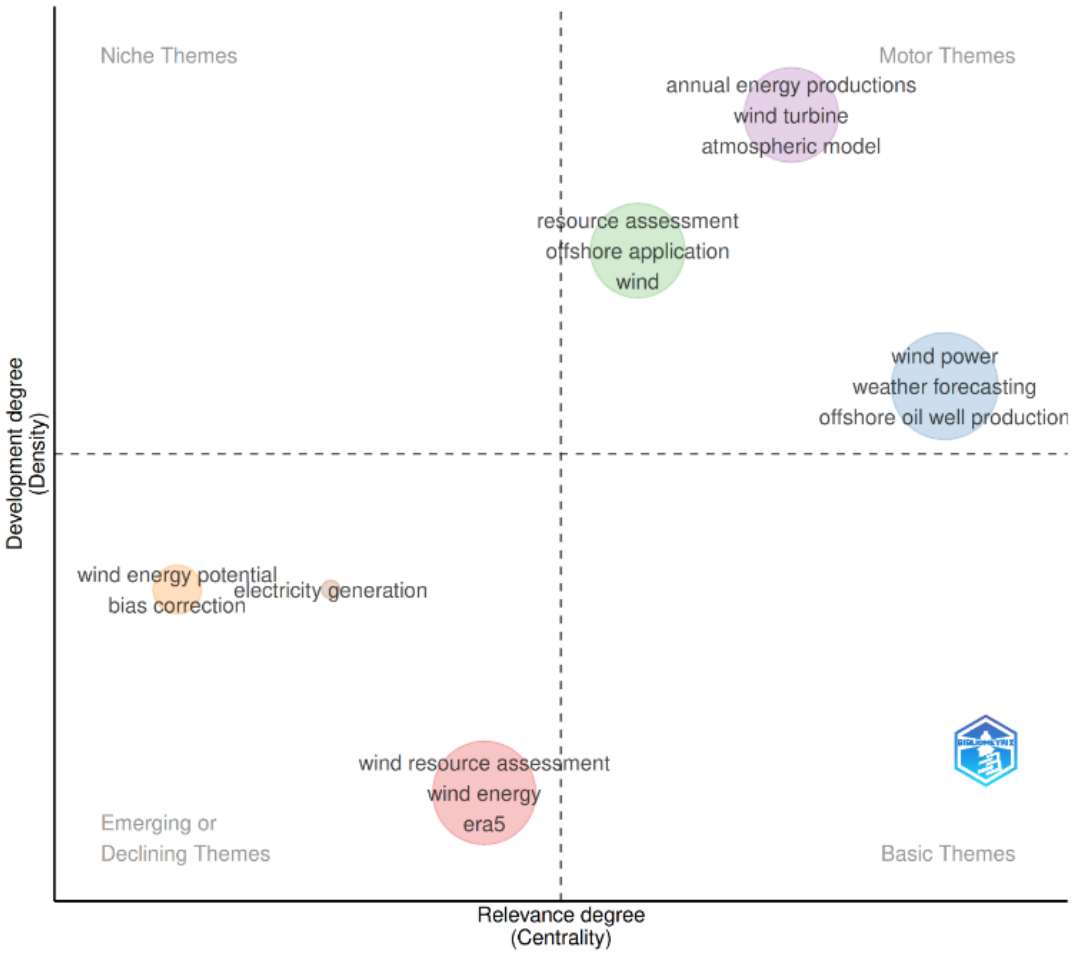

Figure 5. Thematic map of the keywords (density against centrality)

Table 6. Remote data, class, and study area of the 25 included studies

No.	Study	Remote Data Used	Class	Study Area	Extent
1	Condaxakis and Kozyrakis [15]	ERA5	R global	Wind farm siting position in a mountainous region, Greece	Site
2	Kumar et al. [16]	ERA5, IMDAA	R regional	Indian states, India	National
3	Fernández-González et al. [17]	WRF forced by ERA-Interim and GFS analyses	D	Alaiz mountain range, Spain	Local area
4	de Assis Tavares et al. [18]	ERA5, CFSv2, MERRA-2, WRF	D	Coast of Rio de Janeiro State, Brazil	Regional
5	Christiansen et al. [19]	C-band SAR (ERS-2, ENVISAT ASAR)	S	North Sea, offshore mast site	Site
6	Batablinlè et al. [20]	MERRA-2, CORDEX-Africa regional climate models (RCMs)	D	Togo	National
7	Dorrego Portela et al. [21]	MERRA-2, ERA5, Global Wind Atlas	D	Six tower sites, Mexico	Multi-site
8	Chang et al. [22]	SAR, ASCAT scatterometer, WRF with data assimilation	M	South China Sea	Regional
9	Soukissian et al. [23]	CERRA, New European Wind Atlas	D	Mediterranean Sea	Regional
10	Ami et al. [24]	PVGIS wind data (ERA5-based), described as satellite data	R global	Ningo-Prampram District (142 km²), Ghana	Local area
11	Peña-Sánchez et al. [25]	ERA5, Global Wind Atlas 4	D	Global	Global
12	Olczak et al. [26]	ERA5, MERRA	R global	One wind farm, Poland	Site
13	Ryu et al. [27]	ERA5, EMD-WRF	D	Southwest Sea of Korea (Hemosu-1 mast)	Site
14	Wang and Hsu [28]	Multi-satellite observations, Copernicus reanalysis	M	Taiwan and the Taiwan Strait	National
15	van Schaik et al. [29]	ERA5, ERA5-Land	R global	Princess Elisabeth Station, Antarctica	Site
16	Steinheuer and Friederichs [30]	COSMO-REA6	R regional	Hamburg weather mast, Germany	Site
17	Hadjipetrou et al. [31]	Sentinel-1 SAR (UERRA used as comparison)	S	Offshore areas around Cyprus	National
18	da Silva et al. [32]	BSW blended satellite winds	S	Coast of Ceará, Brazil	Regional
19	Komasilovs et al. [33]	NORA3	D	Four onshore locations, Latvia	Multi-site
20	Wei et al. [34]	ASCAT, QuikSCAT, WindSat	S	Jiangsu Province, China	Regional
21	Molyboh and Baltovskyy [35]	ERA5	R global	Azov region, two masts	Multi-site
22	Chancham et al. [36]	NCEP/NCAR R2, WRF, CFD	D	Gulf of Thailand	Regional
23	Gil Ruiz et al. [37]	ERA5, WRF	D	Caribbean region of Colombia	Regional
24	Anangapal and Victor [38]	ERA5	R global	Coasts of Gujarat and Tamil Nadu, India	Regional
25	Waewsak et al. [39]	Global reanalysis, mesoscale and microscale models	D	Gulf of Thailand	Regional

Note: The extent of Fernández-González et al. [17] is not stated in the abstract; it was classified as a local area from the description of a mountain range with several wind farms. CFD: Computational fluid dynamics; WRF: Weather Research and Forecasting model.

3.3 Remote data sources and study areas of the included studies

The 25 included studies were published between 2006 and 2026, and 17 of them (68%) were published in 2022 or later. Table 6 lists the remote data used in each study, its class, and the study area. Classified by underlying data, four studies used satellite wind retrievals (class S), two combined satellite retrievals with reanalysis or models (class M), six used global reanalysis (R global), two used regional reanalysis (R regional), and eleven used downscaled or atlas products (class D). Satellite data were therefore involved in six studies (24%), and four of them (16%) used satellite retrievals only, while 19 studies (76%) relied on reanalysis or on products derived from reanalysis.

This classification differs from one based on the terms used by the authors. Ami et al. [24] described their comparison data as satellite data, but the PVGIS wind variables are taken from ERA5 and ERA5-Land reanalysis [9], so the study was classified as reanalysis-based. The Global Wind Atlas, used by Dorrego Portela et al. [21] and Peña-Sánchez et al. [25], is built from ERA5 with mesoscale and microscale modelling [8], and NORA3, used by Komasilovs et al. [33], downscales ERA5 [7]; these studies were therefore classified as downscaled products. In the abstracts, satellite wind retrievals were used for coastal or offshore waters in all six satellite studies; Wei et al. [34] also assessed onshore areas, but the abstract does not state how the onshore estimates were obtained.

3.4 Field validation: Instruments, design and reporting

Table 7 summarizes the field validation of each study as stated in the abstracts. Twenty studies used field data only to validate or compare (V), two used them only to calibrate, correct, or train a method (C), and three used them for both (V +C) [25, 29, 35]. When the same observations are used to calibrate a method and to assess it, the independence of the validation is not guaranteed, and the abstracts of the C and V +C studies do not state whether independent data were held out.

Masts or towers were the most frequent reference (15 studies), followed by weather stations (6), buoys (3), lidar (3), turbine sensors or records (2) and one anemometer campaign (1); the instrument could not be identified from the abstract in three studies (Table 8). Eight studies used two instrument types, for example buoys with weather stations [18, 28] or lidar with masts [29, 33, 38]. Because a study with two instrument types is counted in two rows, the last three rows of Table 8 give unique studies.

The size of the reference varied widely. It ranged from one instrument at one site, such as the Hemosu-1 offshore mast

[27], the offshore mast in the North Sea [19], or the Hamburg weather mast [30], to 28 towers in the Gulf of Thailand [39], 13 offshore locations in the Mediterranean [23], and more than 18 million mast measurements and 8 million turbine measurements across six countries [25]. Several abstracts do not distinguish repeated observations at one site from independent sites. For example, the four anemometer heights of a single mast [17] give repeated observations at one site, whereas the six towers in Mexico [21] give six sites.

Table 7. Field validation characteristics of the 25 included studies, as stated in the abstracts

No.	Field Instruments and Sites	Heights, Period, Resolution	Role	Metrics and Main Result
1	A mast with short-term data (number of masts NR)	Mast heights NR; ERA5 record of twenty years	C	Measure-correlate-predict (MCP) with ERA5 and an uncertainty framework for energy yield; metrics NR
2	Ground-based observations at various locations (instrument NR)	Reanalysis period 2000 to 2020; heights NR	V	Statistical tests; ERA5 slightly better than IMDAA for wind; values NR
3	One mast with anemometers at 40, 78, 90 and 118 m	Period NR	V	Relative errors below 15% in wind speed for the best 12-member ensemble
4	Three buoys, one FPSO anemometer, seven inland weather stations	Heights and period NR	V	Metrics NR; annual energy production (AEP) differed among products near the coast
5	One offshore mast, North Sea	91 SAR scenes; winds of 2 to 15 m/s; mast height NR	V	Standard deviation about 1.1 m/s (in situ wind direction) and 1.3 m/s (SAR direction); negative bias of about 0.3 m/s for CMOD-IFR2; agreement within 15%
6	Ground-based observations (instrument NR)	Historical period 2001 to 2020; heights NR	V	MERRA-2: R^2 0.96, NSE 0.95, RMSE 0.35; three regional models: R^2 0.93 to 0.95, NSE 0.92 to 0.94, RMSE below 0.45
7	Six anemometric towers	80 m; period NR	V	Relative deviation of mean power density: ERA5 above 50% at five of six sites; MERRA-2 below 11% except 29.5% at one site; Global Wind Atlas 139.4% at that site
8	Seven coastal weather stations and a mast	Resource statistics at 100 m; period NR	V	Standard deviation 2.09 m/s (SAR) and 1.83 m/s (ASCAT); correlation 0.75 and 0.80
9	13 offshore locations (instrument NR)	Long-term; hourly and seasonal scales	V	Metrics NR; CERRA outperformed NEWA
10	Anemometer at several reference points (number NR)	10 m; period NR	V	t-test: no significant difference (p above 0.05) between ground and satellite data
11	More than 18 million mast measurements and 8 million turbine measurements, six countries	2002 to 2021	V + C	Mean capacity factor error 5.6% and Pearson correlation 0.844; mean error 0.6% for annual aggregated production
12	Nacelle sensors on six turbines of one wind farm	Hub height; hourly; 2019	V	Turbine wind speeds higher than ERA5 and MERRA; relative mean bias error of energy yield below 8% (ERA5, 3 MW turbines) and below 12% (MERRA, 0.8 MW turbines)
13	Hemosu-1 offshore mast	Nearby grid points; period NR	V	Errors quantified (values NR); shear, Monin-Obukhov length and Richardson number analysed
14	Buoys and ground weather stations (numbers NR)	NR	V	Buoy validation reported as confirming reliability (values NR)
15	Doppler wind lidar and vertical array anemometers at one station	Hub height estimates; period NR	V + C	Parameterized quantile mapping; AEP error reduced to 12%
16	Hamburg weather mast, five levels	10 to 250 m; hourly peak wind; period NR	C	Proper scores improved by up to 60% relative to climatology (method trained on mast data)
17	Five coastal weather stations	26-month Sentinel-1 series; 10-year UERRA series	V	Weibull distributions compared, overall agreement; values NR
18	Oceanic buoys and anemometric towers (numbers NR)	BSW at 10 m, 0.25 degrees, 6 hours	V	Accuracy verified; values NR
19	Masts and one lidar at four locations	NR	V	Correlation, distributions, wind roses and energy production compared; NORA3 more optimistic for energy at all locations; values NR
20	Meteorological stations (number NR)	Stations 2006 to 2014; satellite data 1999 to 2015	V	Metrics NR; offshore power density of 328 to 500 W/m²
21	Two nearby masts, one for correlation and one for validation	ERA5 at 100 m; training series 2009 to 2019; hourly forecasts 2020 to 2022	V + C	Metrics NR
22	13 coastal meteorological masts	Maps at 80, 100 and 120 m; period NR	V	Metrics NR
23	Ground stations (number NR)	WRF 9 km and 3 km nests; 15-minute output; power density at 100 m	V	Correlation, standard deviation, bias and Weibull distributions; WRF closer to observations than ERA5; values NR
24	Lidar and mast, offshore Gujarat and Tamil Nadu	NR	V	Correlation 0.949 and 0.958; negative mean bias error of 0.6 and 0.55 m/s
25	28 meteorological towers	Maps at 40, 80, 100 and 120 m at 200 m resolution; period NR	V	Metrics NR

Note: NR means not stated in the abstract. Studies are numbered as in Table 6. V: validation only; C: calibration or training only; V + C: both.

Table 8. Unique studies by field instrument type and remote data class

Instrument Type	Satellite Involved (S and M, n = 6)	Reanalysis-based (R and D, n = 19)	All Studies (n = 25)
Mast or tower	3	12	15
Weather station network	4	2	6
Buoy or floating platform	2	1	3
Ground-based or floating lidar	0	3	3
Turbine sensors or records	0	2	2
Anemometer field campaign	0	1	1
Instrument not specified in the abstract	0	3	3
Studies using one instrument type	3	14	17
Studies using two instrument types	3	5	8
Total unique studies	6	19	25

Note: the first seven rows add to 9, 24 and 33 assignments because eight studies appear in two rows. These totals equal the studies using one type plus twice the studies using two types (3 + 6 = 9; 14 + 10 = 24; 17 + 16 = 33).

Reported heights included 10 m [24, 32], 80 m [21], 100 m [22, 35], turbine hub height [26] and five levels between 10 and 250 m [30]. Periods ranged from one year of nacelle data [26] and a 26-month satellite series [31] to reanalysis records of twenty years [15]. Reported metrics included correlation coefficient and R^2 [20, 22, 38], standard deviation and bias of wind speed [19, 22], Root mean square error (RMSE) and Nash-Sutcliffe efficiency (NSE) [20], relative deviation of mean power density [21], relative error of annual energy production (AEP) [26, 29], capacity factor error [25] and, in one study, a t-test [24]. The compared variable therefore also varied, from wind speed to power density and energy yield. Procedures for matching the remote estimate to the field data, such as height adjustment, temporal averaging and spatial matching, are rarely described in the abstracts and could not be compared.

3.5 Remote data sources and field validation strategies

Table 9 classifies the studies by the extent of the assessed area, using the boundaries in Table 4. In this review, a small geographic area is a site or a local area, which places eight studies (32%) in that range. However, the six site studies are point assessments of one mast, station, or wind farm and do not map an area. Only two studies (8%) assessed a continuous area of up to about 1,000 km²: The assessed mountain range was validated using data from a single mast [17], whereas field measurements at multiple reference points within a 142 km² district were reported in this study [24]. Three further studies compared products at several separate locations without mapping an area [21, 33, 35].

Table 9. Included studies by spatial extent of the assessed area

Extent	Studies	Share	Studies (Reference Numbers)
Site	6	24%	[15, 19, 26, 27, 29, 30]
Multi-site	3	12%	[21, 33, 35]
Local area (up to about 1,000 km²)	2	8%	[17, 24]
Regional	9	36%	[18, 22, 23, 32, 34, 36, 37, 38, 39]
National	4	16%	[16, 20, 28, 31]
Global	1	4%	[25]
Total	25	100%	

Table 10. Scope of selected International Electrotechnical Commission (IEC) documents and their relation to the validation of remote wind products

Document	Published Scope (Summary)	Relation to Validating Remote Products
IEC 61400-50:2022 [40]	Overview of wind measurement options (masts, nacelle and spinner instruments, ground-mounted remote sensing, nacelle lidar); aims at consistent measurement and uncertainty assessment independent of the use case	Informs the quality of the reference field data; does not describe how satellite or reanalysis estimates are compared with them
IEC 61400-50-1:2022 [3]	Methods and requirements for instruments mounted on meteorological masts, nacelles and spinners; excludes remote sensing devices	Defines reference measurement practice for mast data; no procedure for validating remote products
IEC 61400-50-2:2022 [4]	Application of ground-mounted remote sensing technology (lidar and sodar)	Same, for lidar and sodar references
IEC 61400-50-3:2022 [41]	Use of nacelle-mounted lidars for wind measurements	Relevant to turbine-level measurement, not to zone identification
IEC 61400-15-1:2025 [12]	Framework for assessing and reporting site suitability conditions onshore and offshore: definition, measurement and prediction of long-term wind conditions, integration with turbine and plant characteristics, extremes, documentation and traceability	Gives a reporting and traceability framework for site wind conditions; from its scope description, it does not appear to prescribe how satellite or reanalysis products should be validated for the early identification of zones

Table 11. Proposed reporting framework for validating satellite and reanalysis wind products

Stage	What to Define or Report
1. Purpose and area	Decision supported; area extent in km² and its position in the scale of Table 4; criteria for high wind potential stated before the analysis (for example, classes of mean wind speed or power density)
2. Field reference data	Instrument type and conformity with the IEC 61400-50 series where applicable; number of independent sites; measurement heights; period and temporal resolution; data availability and quality control
3. Candidate remote products	Underlying data and processing level (satellite retrieval, reanalysis, downscaled product); spatial and temporal resolution and its size relative to the study area
4. Matching	Height adjustment method; time alignment and averaging; spatial matching (nearest cell or interpolation); treatment of land and sea masks
5. Independent validation	Data held out from any calibration; metrics for wind speed, distribution and power density (bias, RMSE, correlation, distribution comparison); sample size; results by site
6. Selection or correction	Product selection or bias correction informed by stage 5, followed by re-validation on independent data
7. Uncertainty	Uncertainty of the reference measurements and of the remote product, and its propagation to power density or energy
8. Classification	Application of the criteria from stage 1 to classify zones, together with the uncertainty from stage 7
9. Documentation	Traceable reporting of all items above, following the reporting logic of IEC 61400-15-1:2025 [12]

The district assessed by Ami et al. [24] is smaller than one ERA5 grid cell of about 31 km on a side [5], so any estimate for such an area from ERA5-based products rests on very few grid cells. This is the scale at which the question of resolution relative to area becomes most relevant.

3.6 Coverage of existing International Electrotechnical Commission documents and remaining gaps

Table 10 summarizes the scope of the IEC documents most related to the measurement and reporting aspects of the included studies. They were reviewed from their published scope descriptions, not from their full texts.

Based on these scope descriptions, the documents cover how field reference measurements are made and how site conditions are assessed and documented, but they do not appear to specify how remote products should be matched to those measurements or judged acceptable. The items that were not specified in the scope descriptions and that varied across the included studies are: matching in height, time and space; minimum duration and number of sites; metrics and acceptance thresholds; independence between calibration and validation data; and the relation between product resolution and the size of the area. The full texts of the standards were not reviewed; therefore, these inferences should be verified against the full documents.

3.7 Proposed reporting framework

Table 11 proposes a reporting framework for studies that validate satellite or reanalysis wind products in the field. It is built from the items that varied across the included studies and from the IEC documents above, and it is a proposal to be tested, not an established or validated procedure. Validation is placed before and during data selection and correction rather than at the end, because several included studies used field data to calibrate or correct products [15, 25, 29, 30, 35].

4. DISCUSSION

This review examined 25 studies that compared satellite, reanalysis, or downscaled wind products with field measurements. Its findings describe the studies identified through two databases and one search string, and they should not be read as a description of the whole field.

Regarding the remote products (RQ1), reanalysis-based products accounted for 19 of the 25 studies (76%), and satellite wind retrievals were involved in six (24%), all of them for coastal or offshore waters in the abstracts. The label “satellite data” can therefore hide the origin of the data: PVGIS wind variables come from ERA5 and ERA5-Land [9], ERA5 itself assimilates satellite observations [5], and the Global Wind Atlas and NORA3 are derived from ERA5 [7, 8]. Classifying products by underlying data, as done here, changed the satellite share from the 28% that a classification by authors’ terminology would suggest to 24%, and it is the reason why the title refers to satellite and reanalysis products together.

Regarding validation design (RQ2), the included studies differ in the instruments used, in the number of independent sites, in the role given to field data, and in the metrics reported (Tables 7 and 8). The compared variable also differs, from wind speed to power density, capacity factor, and energy yield. These differences matter because validation outcomes depend on the product, the site, and the variable. For example, turbine wind speeds in Poland were higher than ERA5 and MERRA values, which the authors attribute to a coarse grid that does not capture turbines placed at sites chosen for local potential [26]; relative deviations of mean power density in Mexico varied between products and sites, with ERA5 above 50% at five of six sites and MERRA-2 mostly below 11% [21]; and a related multi-country study found that correction with the Global Wind Atlas versions tested did not substantially improve reanalysis-based wind power [11]. Such results cannot be compared directly unless heights, periods, matching, and metrics are reported in a common way. In five studies, the field data were also used to calibrate or train a method [15, 25, 29, 30, 35], which raises the question of independent validation.

Regarding spatial scale (RQ3), eight studies (32%) addressed a site or a local area, but only two assessed a continuous area of up to about 1,000 km² [17, 24], and only one of them reports field measurements at several points inside the area [24]. A single-point validation shows how a product behaves at that point; it does not by itself show how well the product separates zones inside a small area. When the area is smaller than one ERA5 grid cell, which is the case for the 142 km² district in this study [24], the number of grid cells available to represent variation inside the area is very small.

Regarding existing documents (RQ4), the IEC 61400-50

series and IEC 61400-15-1:2025, judged from their published scope descriptions, address how reference measurements are made and how site conditions are assessed and reported (Table 10). The scope descriptions do not indicate a procedure for matching and judging satellite or reanalysis products against those measurements. The included studies also rarely state whether their reference measurements followed these standards, at least in the abstracts. Both observations need confirmation against the full texts.

These results support a cautious reading: this review did not identify a unified, widely adopted procedure for validating satellite and reanalysis wind products, but it cannot exclude that one exists outside the studies retrieved. The reporting framework in Table 11 is offered as a basis for discussion and for testing, including in small areas such as those of Peru. No Peruvian case study or field validation is presented here, and the application to Peru is a direction for future research.

Several limitations apply: First, only Scopus and Web of Science were searched, and the Web of Science query used the "All Databases" option, whose content depends on the institutional subscription. Second, the search string required both validation and field measurement terms, and no supplementary search was done to estimate its recall, so relevant studies may have been missed. Third, screening, full-text assessment, and coding were done by one reviewer without duplicate screening, and records tagged Early Access were treated as described in Section 2.4. Fourth, the descriptors in Tables 6 and 7 come from abstracts, so NR means only that an item was not stated there. Fifth, the bibliometric layer includes 80 records that were not part of the synthesis and have incomplete affiliation, keyword, and reference metadata. Sixth, product classes follow provider documentation and could be debated; the IEC documents were reviewed from scope descriptions only, and no risk of bias assessment or meta-analysis was performed. Finally, the search ended on 20 July 2026, so 2026 is incomplete.

5. CONCLUSIONS

This systematic review included 25 studies, selected from 125 records retrieved in Scopus and Web of Science, that compared satellite, reanalysis, or downscaled wind products with field measurements. The conclusions apply to those studies.

First, the bibliographic collection of 105 unique records shows more publications in recent years, with the highest annual count in 2025 and an incomplete 2026. This description is based on a corpus that includes records not eligible for synthesis.

Second, classified by underlying data, 19 of the 25 studies (76%) relied on reanalysis or on products derived from it, and six (24%) involved satellite retrievals, four of them (16%) without reanalysis. In the abstracts, the satellite studies concerned coastal or offshore waters.

Third, validation designs differed in instruments (masts or towers in 15 studies, weather stations in 6, buoys in 3, lidar in 3), in the number of sites, in the role of the field data (validation in 20 studies, calibration in two and both in three), in the metrics, and in the variable compared. This review did not identify a unified, widely adopted procedure for validating satellite and reanalysis wind products. The IEC 61400-50 series and IEC 61400-15-1:2025, judged from their scope descriptions, address measurement and site suitability reporting rather than product validation.

Fourth, eight studies (32%) addressed a site or a local area, and only two assessed a continuous area of up to about 1,000 km², one of them with field measurements at several points inside the area.

Finally, the reporting framework is proposed for testing. It asks future studies to state the area extent, the reference instruments and sites, the matching procedure, independent validation with common metrics, and the uncertainty. Testing it in small areas, including areas in Peru, is a direction for future research.

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NOMENCLATURE

AEP	Annual energy production
ERA5	Fifth-generation ECMWF atmospheric reanalysis
GWA	Global Wind Atlas
IEC	International Electrotechnical Commission
MCP	Measure-correlate-predict
MERRA-2	Modern-Era Retrospective Analysis for Research and Applications, Version 2
NR	Not stated in the abstract
NSE	Nash-Sutcliffe efficiency
PVGIS	Photovoltaic Geographical Information System
RCM	Regional climate model
RMSE	Root mean square error
SAR	Synthetic aperture radar
WRF	Weather Research and Forecasting model