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Review article

Energy droughts and climate change risks in renewable energy systems: A critical global review of compound risks, system vulnerability and mitigation strategies

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ABSTRACT

Extreme weather events and climate change increasingly affect the performance and reliability of renewable energy systems, posing significant challenges to the global clean energy transition. Despite the growing body of research on climate impacts across individual renewable-energy technologies, current knowledge remains fragmented across regions, technologies, and assessment methodologies, highlighting the need for a comprehensive synthesis of renewable-energy droughts and their future evolution under climate change. This critical review examines how climate variability and extreme events influence solar, wind, and hydropower systems, with particular emphasis on renewable-energy droughts and the indicators used to assess them, including the standardized renewable energy production index and capacity factor-based thresholds (e.g., 10% and 5%). Regionally, Europe experiences frequent winter wind droughts, with extreme events reducing energy production by more than 50% in southern regions, while solar droughts may affect up to 24% of days annually in northern Europe. In China, autumn wind droughts can persist for up to 15 days, and solar shortages may affect up to 63% of winter periods, increasing risks to grid stability. North Africa also exhibits pronounced wind and solar drought vulnerability, whereas hydropower systems worldwide are increasingly affected by hydrological droughts and altered river-flow regimes. Hybrid renewable-energy systems, energy storage, and stronger grid interconnections can substantially improve resilience to renewable-energy droughts. The review further shows that renewable-energy drought risks generally intensify under higher-emission climate scenarios, underscoring the need for standardized assessment frameworks, integrated climate-resilient planning, and greater consideration of socio-economic factors to support adaptation and future energy-system resilience.

1. Introduction

The transition to low-carbon energy systems has accelerated in recent years. This trend has been reinforced by increasing greenhouse gas emissions and intensifying international pressure to curb global warming, under agreements such as the Kyoto Protocol, the Paris Agreement and the Glasgow Climate Pact (UNFCCC, 1997, 2015, 2021). Renewable energies, in particular solar, wind and hydropower, are key to achieving decarbonisation and are also essential for the long-term sustainability of energy systems. Rapid technological progress,

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reduced deployment costs and policy support have enabled a significant expansion of these systems on a global scale over the past decade (IEA, 2021).

However, the development of these systems does not mean that they are no longer dependent on weather and climate conditions. Conversely, the efficiency and reliability of renewable-energy systems remain highly dependent on meteorological conditions. Events such as heat waves, prolonged droughts, dust storms, floods, frosts, and large-scale atmospheric circulation anomalies can disrupt energy production by altering solar radiation, wind fields, water availability, and infrastructure stability (Feron et al., 2021). Furthermore, climate change is expected to modify not only the intensity but also the frequency of these events, introducing additional uncertainty into the planning and operation of renewable-energy systems (Dutta et al., 2022).

In recent years, one of the major challenges in assessing the reliability of renewable energy has been a phenomenon known as an energy drought. This occurs when energy production remains below normal for a relatively long period due to adverse weather conditions, affecting one or more renewable sources simultaneously. In Europe, persistent atmospheric blocking patterns have repeatedly caused winter wind droughts (Bloomfield et al., 2021), while prolonged cloud-cover anomalies have reduced solar-energy production across parts of northern Europe (Kapica et al., 2024). Similarly, studies from Asia and North America demonstrate that sustained reductions in wind speed or solar radiation can place considerable stress on electricity-system reliability and grid stability (Kapica et al., 2024).

Hydropower is also vulnerable to these fluctuations, although the path of impact is different from that of wind and solar. Changes in precipitation, snowmelt timing, evapotranspiration, and river-flow regimes directly influence hydropower generation capacity (van Vliet et al., 2016). More recent studies further demonstrate that climate change is expected to alter hydrological regimes across Asia, leading to regionally contrasting impacts on future hydropower potential (Kim et al., 2022). In addition, when multiple climate extremes occur simultaneously, declines in renewable-energy production are no longer confined to a single technology, increasing the risk of supply shortages in interconnected power systems.

A review of the existing literature reveals that research remains highly fragmented. Most studies focus on a single renewable-energy technology rather than evaluating interactions among multiple renewable resources (Bloomfield et al., 2021). Others primarily assess climate impacts within individual regions without considering broader global patterns (Feron et al., 2021). Consequently, integrated assessments that simultaneously evaluate extreme weather events, long-term climate variability, renewable-energy droughts, and future climate projections across solar, wind, and hydropower systems remain relatively scarce (Dutta et al., 2022). Recent research by Kapica et al. (2024) demonstrated that large-scale atmospheric circulation patterns can simultaneously affect multiple renewable-energy resources. Similarly, Kim et al. (2022) showed that compound climate extremes can influence future hydropower potential through changes in regional hydrological regimes. Furthermore, Bloomfield et al. (2021) introduced one of the earliest standardized frameworks for assessing renewable-energy droughts, whereas Otero et al. (2023) highlighted the lack of methodological consistency arising from different indicators, threshold criteria, and temporal scales. van Vliet et al. (2016) investigated future hydropower responses to climate change, whereas Fournier et al. (2023) and Jin et al. (2024) evaluated future solar and wind resources using different datasets and modelling frameworks. Consequently, direct comparisons among renewable-energy technologies remain limited.

Based on these research gaps, the present study provides a critical and comprehensive review of the impact of climate variability and extreme weather events on renewable energy systems globally. This research pursues three main objectives: first, to examine how climate variability and extreme events affect the operational performance and resilience of solar, wind, and hydropower systems; second, second, to synthesize and critically evaluate the methods used to define and quantify renewable-energy drought across different regions; and third, to evaluate forward-looking estimates of renewable energy potential under different climate scenarios, with the aim of identifying emerging risks and opportunities for long-term energy security. By synthesizing global and regional evidence, this review clarifies the risks that climate change poses to renewable energy systems. By synthesizing global and regional evidence across renewable-energy technologies, climate drivers, renewable-energy drought indicators, and future climate projections, this review provides an integrated framework for understanding climate risks and supporting climate-resilient renewable-energy planning.

The remainder of this review is organized as follows. Section 2 describes the literature search methodology and compares the present review with previous review articles to highlight its incremental contribution. Section 3 synthesizes current knowledge on renewable-energy droughts, climate and weather drivers, future climate projections, mitigation and adaptation strategies, and remaining research gaps. Finally, the concluding section summarizes the principal findings, discusses the limitations of the current evidence base, and outlines priorities for future research and climate-resilient renewable-energy planning.

2. Search methodology

2.1. Literature search

The study was based on an extensive search of scientific literature. The main focus was on studies published between 2019 and 2025, but some older sources were also included in the review where necessary to complete the discussion, especially on a global scale. In selecting sources, an attempt was made to ensure that the regional coverage was as broad as possible and that the review was not limited to just a few regions.

The main part of the selected sources was from among articles published after 2019 in reputable scientific journals. The primary criterion for journal quality was their SJR (Scimago Journal & Country Rank) ranking, with most sources selected from Q1 and Q2 journals. However, the selection of sources was not limited to this framework. In three cases, exceptions were made: first, when an older study, despite its publication date, was of particular scientific importance to the topic at hand; second, when a highly relevant article had been published in Q3 or lower-level journals; and third, in the case of scientific reports, books, legal documents, and standards-related documents that were directly relevant to the topic, regardless of the year of publication. To identify relevant studies, Google Scholar, Web of Science, and Scopus databases were used. The search strategy was based on different combinations of keywords; These included: "wind and/or solar drought", "solar energy*", "wind energy*", "hydropower*", "extreme weather events*", "climate change", "future projection*", "wind speed", "solar radiation*", "rainfall", "precipitation", "energy generation*" and "renewable energy source*". At the end of this process, over 100 relevant references were selected for inclusion in this review.

For geographical synthesis, studies explicitly described by the authors as global assessments were classified under the *Global* category. In contrast, comparative studies investigating more than one geographical region were assigned to each relevant regional category included in the analysis. Consequently, a study comparing locations in Africa and North

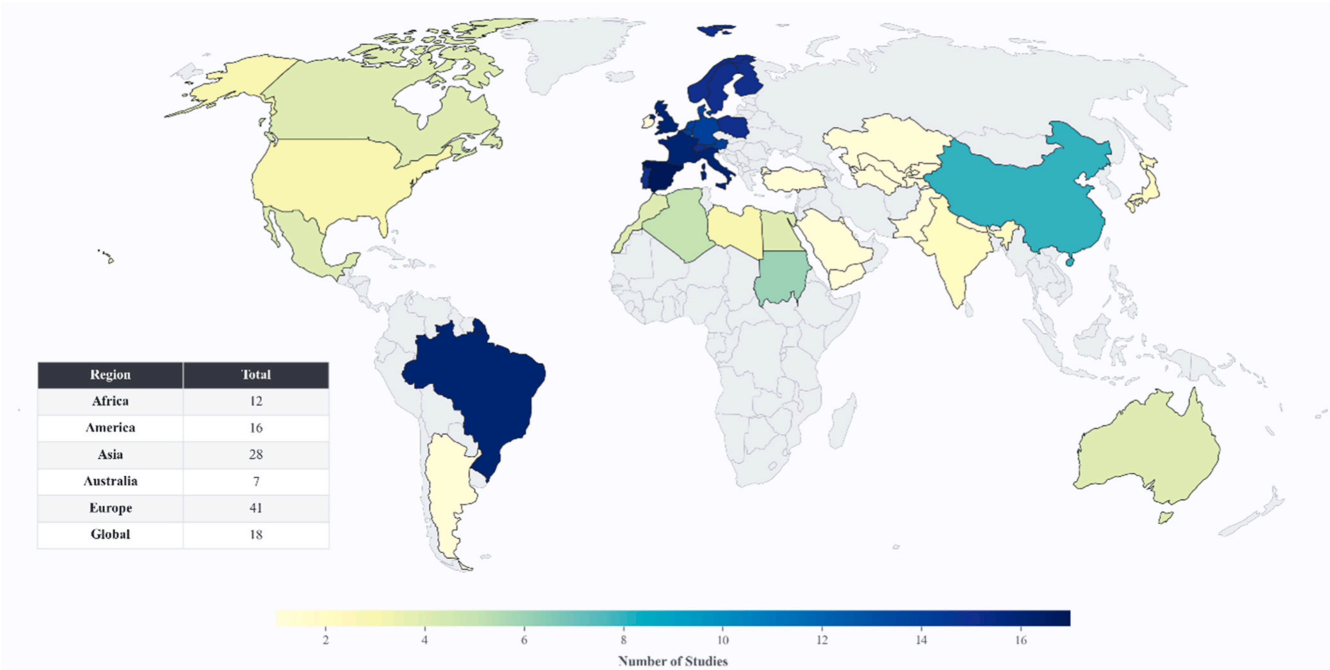


Fig. 1. The global distribution of selected studies included in this critical review paper, highlighting the geographic focus and regional coverage.

America contributed once to the Africa category and once to the North America category. This approach was adopted to accurately represent the geographical coverage of the reviewed literature rather than assigning multi-regional studies to a single geographical category, thereby improving the transparency and reproducibility of the regional synthesis. The geographical distribution of these references is shown in

Review article	Wind energy	Solar energy	Hydropower	Extreme weather / climate variability	Renewable-energy drought	Future climate projections	Indicator / framework comparison	WEF nexus	Emerging technologies / forecasting
Gonçalves et al. (2024)	●	◐	◐	●	◐	◐	○	○	◐
Wasti et al. (2022)	○	○	●	◐	◐	●	○	○	○
Jurasz et al. (2019)	●	●	◐	◐	◐	○	◐	○	◐
Das et al. (2024)	◐	◐	◐	◐	○	○	◐	○	◐
Giedraityte et al. (2025)	●	●	●	◐	○	◐	○	○	●
Masip Macia et al. (2025)	◐	◐	◐	◐	●	○	○	○	◐
Teixeira et al. (2025)	◐	◐	◐	◐	○	◐	○	○	○
Ashraf & Sagheer (2025)	●	●	◐	◐	○	◐	○	○	●
Ferdaus et al. (2026)	●	●	○	◐	○	○	○	○	●
Alam et al. (2020)	●	●	○	◐	○	○	○	○	○
Kleidon (2021)	●	○	○	◐	○	○	○	○	○
Cruz et al. (2025)	●	●	●	●	◐	●	○	◐	◐
Takal et al. (2026)	●	●	●	◐	○	◐	○	○	◐
Present review	●	●	●	●	●	●	●	●	●

● Primary focus (central and in-depth coverage) ◐ Discussed (addressed but not a core focus) ○ Not discussed / minimal (limited or not addressed)

Fig. 2. Conceptual comparison of representative review articles and the incremental contribution of the present review.

Fig. 1. This figure shows that the main focus of the studies was on Europe, China, North Africa, Australia and the United States. Most of these studies addressed topics such as energy drought, the impact of climate variability on energy production, and mitigation solutions such as hybrid systems and energy storage.

2.2. Comparison with previous review articles and incremental contribution of the present review

A comparative evaluation of the related review articles was carried out to place the present review in the body of literature. Table S1 summarizes the thematic coverage, geographical scope, methodological focus and main limitations of representative review papers published in recent years and Fig. 2 offers a visual overview of the comparative thematic coverage of these papers with respect to the present review. These comparisons clearly show the gaps in the literature that were filled by this study and the incremental value of current study over previous reviews.

There have been several recent review articles that have addressed the subject of energy-system resilience, renewable energy, and climate change in important but distinct ways. Some reviews are on the extreme weather impacts on energy systems, some are on vulnerability of hydropower, optimization of hybrid renewable-energy systems, complementarity of renewable resources, forecasting, technology innovation, or regional deployment of renewable energy. For instance, Gonçalves et al. (2024) examined the effects of extreme weather events on energy systems, focusing on infrastructure disruption, mitigation and adaptation measures, particularly for wind-energy systems. Renewable-energy drought definitions, indicator families, and harmonized drought-assessment frameworks, however, were not a primary concern of that review. There have also been significant contributions from technology specific reviews. Wasti et al. (2022) gave a global overview of the impacts of climate change on hydropower, highlighting that the vulnerability of hydropower is context-dependent and depends on reservoir size, water allocation priorities, local hydrology and energy market conditions. The review, however, was only on hydropower and did not consider the droughts of wind, solar and hydropower in a single framework. Likewise, Kleidon (2021) examined the thermodynamic and atmospheric constraints on wind-energy generation but omitted to consider energy droughts, extreme weather effects and multi-resource renewable-energy resilience.

Other reviews have been based on hybrid systems or complementarity or decision-making methods. Jurasz et al. (2020) examined the concept, metrics and applications of renewable-resource complementarity and found that much of the literature is focused on Brazil, Europe, China and the United States. Das et al. (2024) surveyed multi-criteria decision-making methods for sustainable decentralized hybrid energy systems and Giedraityte et al. (2025) surveyed optimization methods for hybrid renewable energy systems, focusing on multi-objective optimization, storage integration and computational tools. While these studies have a high relevance for renewable-energy planning, they are mostly focused on optimization or sustainability assessment or complementarity and do not focus on climate-induced renewable-energy droughts.

There are separate reviews on technology innovation, forecasting and regional deployment. Ashraf and Sagheer (2025) examined the world's renewable-energy capacity and technological innovation, not climate-risk mechanisms, by looking at deployment, policy and technology development. Ferdaus et al. (2026) reviewed the foundation models for clean-energy forecasting which focused on wind and solar forecasting, multi-modal data, and zero-shot learning, but did not include renewable-energy drought assessment or climate-scenario synthesis. Takal et al. (2026) examined the deployment of renewable energy in Africa, noting the trends, opportunities, and ongoing challenges, including grid limitations, financing constraints, and governance challenges.

Adaptation and renewable strategies related to drought are also reviewed, which offers more limited but useful views. In a systematic review of climate adaptation strategies, Teixeira et al. (2025) identified renewable energy as a climate adaptation strategy, but only a few of the reviewed studies considered renewable energy as a primary adaptation response, not primarily as a mitigation pathway. In a bibliometric study, Masip Macía et al. (2025) found that renewable-energy approaches for mitigating the effects of severe droughts on electrical systems have increased in interest over the years, with a particular focus on solar and wind energy in water-stressed areas. It is, however, bibliometric and does not offer a comprehensive technical synthesis of drought indicators for renewable energy, regional mechanisms, or impacts of future climate scenarios.

Previous reviews vary widely in their focus, as listed in Table S1. Many are dedicated to one renewable-energy technology, methodological aspect, or geographic area. Similarly, Fig. 2 shows that while some reviews cover selected topics in detail, none of the reviews brings together renewable-energy drought definitions, indicator harmonization, future climate projections, water–energy–food nexus considerations, emerging renewable technologies, and climate-driven mitigation strategies in a single review framework. Combined, the existing reviews have significantly contributed to the knowledge base of renewable-energy systems, but they are still technology-specific, method-specific, regional or hazard-specific. The majority of reviews are limited to a specific technology (e.g., hydropower or wind) or to energy-system resilience more broadly, but they do not systematically assess renewable-energy drought definitions and indicators. Others look at optimizing the hybrid-system, forecasting, or deployment barriers instead of climate mechanisms causing long periods of renewable-energy deficits.

The integrated scope of the present review is thus the added contribution of the present review. This study is different from previous ones because it simultaneously synthesizes: (i) climate variability and extreme-weather impacts on solar, wind and hydropower; (ii) renewable-energy drought characteristics across regions; (iii) methodological differences among drought indicators and thresholds; (iv) future climate projections under CMIP/RCP/SSP scenarios; (v) mitigation strategies, including hybrid systems, storage, grid interconnection, and complementarity; (vi) implications for the water–energy–food nexus in the context of hydropower droughts; and (vii) emerging technologies, such as floating PV, concentrated solar power with thermal-energy storage, and offshore wind. This holistic evaluation enables the review to go beyond a technology-specific or hazard-specific synthesis and provide a more holistic, system-based approach for planning renewable energy systems that will be resilient to climate change.

3. Results and discussion

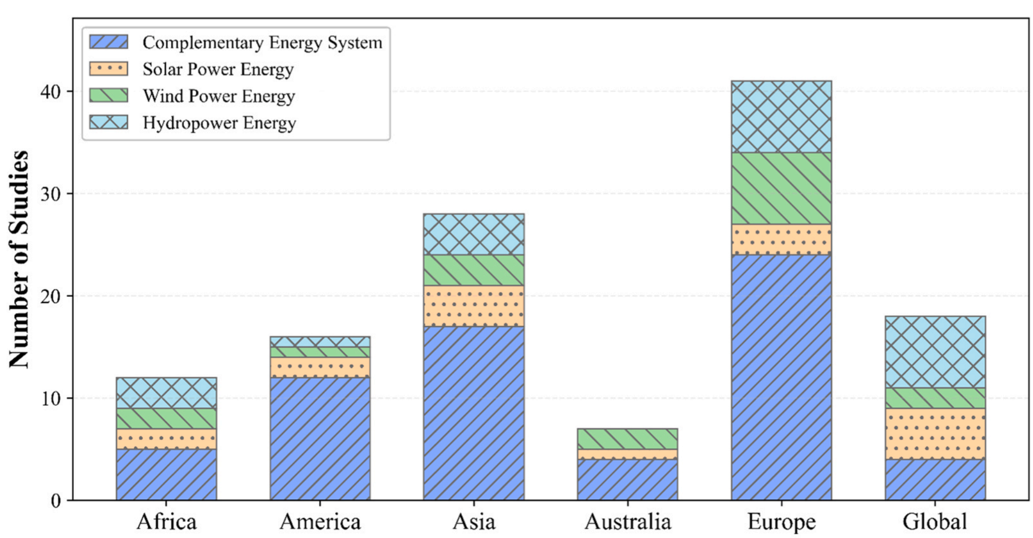
3.1. Climate impact on the resilience of renewable energy sources

In recent years, energy transition has increasingly focused on the expansion of renewable electricity, with solar and wind powers as the two main drivers of this transformation. Hydropower remains an important component of the global electricity system, as it offers flexible and relatively predictable generation capacity. However, this source is not immune to the pressures of climate change. Climate-induced droughts, shifting precipitation patterns, and increasing competition for water resources have challenged the resilience of hydropower in recent years. At the same time, in many regions, renewable technologies have become economically competitive with fossil fuel-based power plants (BNEF, 2017; Staffell and Pfenninger, 2018).

The acceleration of this trend is also clearly visible in the data from the IEA (International Energy Agency) Renewables 2024 report. According to the report, new renewable electricity capacity added worldwide in 2023 reached about 510 GW, a figure that is both a historical record and, with a growth of almost 50%, represents the fastest rate of expansion in more than two decades (IEA, 2024). The bulk of this increase was due to solar energy, which accounted for about 420 GW of new capacity, while wind energy contributed about 116 GW. Although the annual growth of hydropower has been lower compared to these two sources, it is still the largest single source of renewable electricity generation worldwide and plays an important role in providing baseload and compensating for fluctuations in wind and solar generation. The effects of this rapid development are now also evident in the global electricity mix. By 2023, about 30% of the world's electricity will come from renewable sources, with wind and solar PV alone accounting for nearly 15%. If current policy trends continue, the share of renewables is expected to exceed 42% by 2028, with the combined share of wind and solar reaching around 25%, a shift that could fundamentally transform the global electricity generation mix (IEA, 2024). This trend reinforces decarbonization pathways based on renewable energy development and the electrification of end-use sectors. Furthermore, the continued cost competitiveness of solar PV and onshore wind further supports this transition pathway (Williams et al., 2012), whereas some alternative low-carbon technologies still face economic or implementation constraints (Staffell and Pfenninger, 2018). In this context, a global study has also examined the potential of solar and wind resources to meet electricity demand in 42 countries. The assessment considered different hypothetical scales, different renewable generation mixes, and varying levels of energy storage capacity (Tong et al., 2021). Under idealized conditions, solar and wind resources of major countries could cover at least 72% of instantaneous electricity demand without surplus annual generation or the need for energy storage. For example, in the USA, a solar and wind system could fulfill approximately 85% of total electricity demand. These findings demonstrate the substantial global potential of renewable resources, although their performance varies considerably among regions because of differences in land area, geographical setting, and climatic conditions (Tong et al., 2021).

Fig. 3 shows the regional distribution of studies examining the impacts of climate change on renewable energy systems, including solar power, wind power, hydropower, and complementary energy systems. The figure indicates that research focus differs across continents. Europe and Asia contain the largest number of studies overall, with a substantial share devoted to complementary energy systems, reflecting increasing research interest in integrated renewable-energy systems. Wind energy studies are also well represented in the Americas, Asia, and Europe, consistent with the importance of wind resources and the continued expansion of wind energy infrastructure in these regions. Solar energy studies are fewer in number, but they are still regularly represented in Asia, the Americas, and global-scale assessments, reflecting the increasing attention given to solar energy in broader energy planning. Hydropower studies are most visible in Europe and in global assessments, with moderate representation in Africa and Asia. This pattern suggests that hydropower is being examined not only in water-dependent regions, but also in wider assessments of climate-related energy vulnerability and system performance.

Australia has the lowest overall number of studies in this synthesis, with the available literature focusing mainly on complementary systems and wind energy. Overall, the regional contrasts in Fig. 2 show that renewable energy research is unevenly distributed, with differences in emphasis shaped by regional resource conditions, climate pressures, and energy-system priorities. Previous studies have shown that the most reliable renewable-energy configurations vary among regions because of differences in climatic conditions and resource availability. For example, wind-dominated systems generally perform better in some high-latitude regions, whereas greater solar contributions improve system reliability in many temperate and tropical areas (Tong et al., 2021). Nevertheless, wind and solar power are intermittent and dependent on weather, resulting in fluctuations that can last for minutes, hours, or even multiple days (Grams et al., 2017), as well as across years and decades (Duran et al., 2024; Wu et al., 2022). Understanding this variability is essential for planning high-renewable power systems. On seasonal and annual timescales, the operation of power systems is influenced by large-scale climate variability patterns. For instance, in Europe, colder and calmer winters tend to result in higher energy demand and lower wind power generation compared to milder, windier winters (Bloomfield et al., 2022). Weather conditions are therefore



Region	Complementary energy system	Solar power energy	Wind power energy	Hydropower energy	Total
Africa	5	2	2	3	12
America	12	2	1	1	16
Asia	17	4	3	4	28
Australia	4	1	2	0	7
Europe	24	3	7	7	41
Global	4	5	2	7	18

Fig. 3. Regional trends in studies are dedicated to impact of climatic factors on renewable energy: solar, wind, hydropower, and complementary systems.

becoming a dominant factor in power system operation. Consequently, closer integration between atmospheric science and energy-system analysis is increasingly required to better understand renewable-resource variability and improve climate-resilient energy planning.

3.1.1. *Renewable energy drought*

Table S2 provides a comprehensive overview of regional susceptibilities to wind, solar, hydropower, and compound droughts, highlighting the most affected areas, underlying factors, and specific vulnerabilities identified in the selected studies. Fig. 4 shows seasonal patterns of energy droughts in different regions of the world. In this figure, each concentric circle represents a region, and each quadrant represents a season. The colored segments indicate the dominant type of drought, i.e. wind, solar, or mixed drought, as reported in regional studies. A review of studies shows that the seasonal pattern of these droughts is not the same across regions and there are clear regional differences (Fig. 4).

Terminology in literature is not fully standardized. The terms *renewable-energy drought*, *energy drought*, *power drought*, and *energy-production drought* are sometimes used with overlapping meanings. In this review, *renewable-energy drought* is used as the overarching term for prolonged periods of below-normal renewable-energy generation caused by adverse meteorological or hydrological conditions. The term *power drought* is generally used in studies emphasizing electricity-system adequacy or residual-load stress, whereas *energy-production drought* refers more specifically to sustained reductions in renewable-energy output from one or more technologies. Unless explicitly distinguished by the original source, these terms are treated here as related manifestations of renewable-energy drought.

In Europe, Raynaud et al. (2018) showed that wind droughts occur throughout the year, whereas Schindler et al. (2020) demonstrated limited seasonal prevalence of solar droughts because of wind–solar complementarity. More recent work by Kay et al. (2023) further highlighted persistent wind-drought risk under present and future climate conditions. In Liu et al. (2023) characterized seasonal wind droughts, Sun et al. (2024) examined solar and compound droughts, whereas Jiang et al. (2023) evaluated regional renewable-resource complementarity. North American studies frequently report solar-related drought risks, particularly in California, although wind and hydropower droughts have also been documented elsewhere (Bracken et al., 2024; Millstein et al., 2019). Guezgouz et al. (2021) identified predominantly summer solar droughts in North Africa, whereas Jurasz et al. (2024) provided a broader continental assessment confirming these regional patterns. In Australia, drought conditions are concentrated in winter, and mixed events that simultaneously affect both wind and solar are more common in this season (Richardson et al., 2023; Rispler et al., 2022). Overall, the patterns shown in Fig. 3 indicate that energy

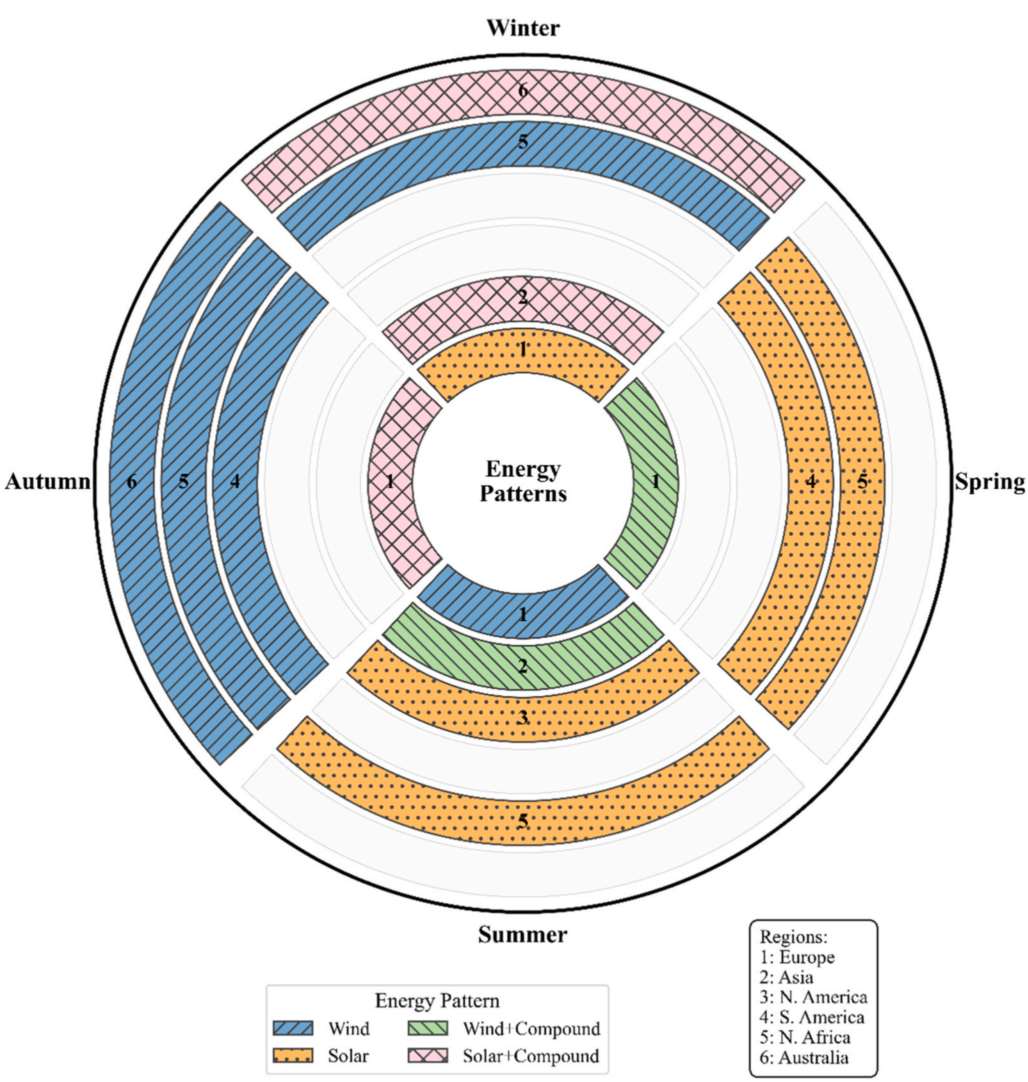


Fig. 4. Seasonal distribution of energy droughts across six global regions.

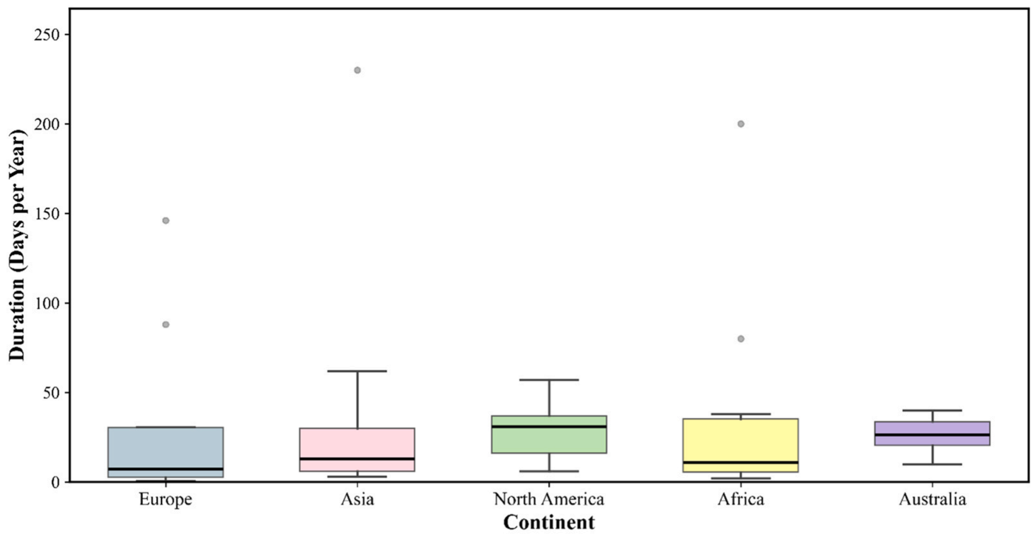
droughts are strongly region- and season-dependent. While some regions, such as Europe, experience recurring wind-related drought conditions throughout the year, others show more seasonally concentrated and resource-specific drought patterns. These differences suggest that the vulnerability of renewable energy systems to climatic drought conditions cannot be generalized across regions and should instead be assessed in relation to the dominant seasonal risk and regional energy structure.

Beyond wind and solar deficiencies, runoff droughts have also caused significant losses to hydropower on a global scale. Based on data from 1975 to 2016, in droughts with a return period of once every 10 years, 67 out of 134 countries experienced annual reductions in hydropower generation of more than 20%, and in 18 countries the reduction exceeded 40%. The largest relative impacts were observed in semi-arid regions, including the western United States and the Mediterranean region (Wan et al., 2021). However, the decline in hydropower generation is not linearly related to the reduction in river flow, as factors such as hydraulic head, installed capacity, plant location, and reservoir operation also play a decisive role (Wan et al., 2021). This suggests that hydropower drought is not simply a water availability issue, but rather a cross-sectoral risk that links water, energy security, and environmental consequences. Using 2003–2020 streamflow records (drought defined as flows below the 30th percentile) across 150 HUC4 (Hydrologic Unit Code (Level 4)) basins, Moghaddasi et al. (2024) estimate that drought conditions reduced hydropower generation by ~300 million MWh, corresponding to ~$28 billion in sectoral losses, while drought-induced substitution with gas-fired generation increased air-pollutant and GHG (Greenhouse Gas) emissions, with the largest vulnerabilities concentrated in Western and Northwestern states (e.g., Washington, California, Oregon). Using plant-level data from 2001 to 2021, Qiu et al. (2023) demonstrate that hydrological drought substantially reduces hydropower generation in the western United States, triggering large-scale substitution by fossil-fuel plants and leading to marked increases in CO_2, NO_x, SO_2 emissions, $PM_{2.5}$ concentrations, and associated health damages. Consistent plant-level evidence from hydro-dominant systems shows that drought impacts are concentrated in hydropower: local droughts can reduce hydropower generation by ~24–28%, while drought effects on wind and solar generation are often statistically indistinguishable from zero after controlling for meteorological conditions (Bagnoli et al., 2025). Taken together, these findings suggest that the consequences of hydropower droughts are not limited to reduced production, but can have broader system-wide effects, including changes in pollutant emissions, increased health burdens, and weakened system reliability.

More recent evidence at the system scale also suggests that the role of hydropower in energy droughts is not solely dependent on the amount of water stored in the reservoir. In practice, operational constraints and regulatory constraints also play a decisive role and can limit the response capacity of this resource. For example, Fälth et al. (2025) show, using a detailed cascade model that also takes into account the effect of hydraulic head, that even in systems with a high dependence on hydropower, sustainable generation during energy droughts of 1–3 weeks typically remains in the range of about 67–96% of installed capacity for Sweden. This result challenges the common perception that hydropower is always assumed to be a resource with unlimited flexibility in energy system models. In parallel, power–water co-management studies emphasize that prolonged drought conditions intensify allocation trade-offs among hydropower generation, agricultural supply, and environmental-flow requirements, while also creating intertemporal trade-offs between storing water for drought resilience and releasing water to manage flood risks (Liu and He, 2023). Borba et al. (2023) further demonstrated that complementarity between hydropower and offshore wind can reduce drought-related generation deficits and reservoir stress in hydro-dominated systems. Adaptive hydropower operation can further improve system resilience during drought conditions (Liu and He, 2023). Drought-induced reductions in hydropower generation can also create significant financial risks for hydropower-dependent countries (Cuppari et al., 2026).

The largest volume of studies has been devoted to Northern Europe, China, Australia, the United States (especially California and Texas), and North Africa (Bracken et al., 2024; Jiang et al., 2023; Liu et al., 2023, 2024; Millstein et al., 2019; Otero et al., 2022; Raynaud et al., 2018; Richardson et al., 2023; Rispler et al., 2022; Sun et al., 2024). Among these regions, Northern Europe stands out due to the detailed studies of both wind and solar droughts, which have primarily examined seasonal variability and renewable-energy drought characteristics (Allen and Otero, 2023; Otero et al., 2022; Raynaud et al., 2018). China is also one of the most studied regions in this field, covering a diverse range of regions from northeast China to the Yangtze River, the Loess Plateau, and the Tibetan Plateau. The main focus of these studies has been on seasonal wind and solar droughts, as well as the risks of combined droughts (Jiang et al., 2023; Liu et al., 2023, 2024; Sun et al., 2024). In Australia, research has focused more on combined droughts, particularly in terms of how simultaneous wind and solar power shortages affect grid stability during critical seasons (Richardson et al., 2023; Rispler et al., 2022). In the United States, most research has focused on California, examining combined droughts and seasonal variability in energy production; While Texas has received more attention due to some specific wind drought events (Bracken et al., 2024; Millstein et al., 2019). In North Africa, northern Algeria and Morocco have been studied more than any other region, and the main focus has been on solar- and wind-drought characteristics (Guezgouz et al., 2021; Jurasz et al., 2024). Among the studies that have focused on hydropower, the most significant policy gaps are seen in systems that rely heavily on hydropower, where droughts simultaneously disrupt generation, impose thermal substitution, and induce long-term shifts in the energy mix, for example toward wind. However, there is limited evidence that investment in hydropower responds systematically to drought exposure in the short term (Bagnoli et al., 2025).

Fig. 5 shows that the duration of energy droughts varies considerably across continents, with some outliers indicating very extreme events. The longest and most severe energy droughts have been observed in Asia and Africa, where the upper outliers reach about 230 days and 200 days, respectively. In Africa, particularly in North Africa, these periods have been reported to last up to 200 days (Jurasz et al., 2024), and in China, particularly in the Yangtze River and Loess Plateau regions, up to 230 days have been reported due to prolonged solar and wind deficiencies (Sun et al., 2024). In North America and Europe, although these droughts are generally shorter, they still show considerable variability, with most values falling below 60 days and several events concentrated in the lower-duration range. Meanwhile, the longest combined droughts recorded in California were 6 days and in Texas 9 days (Bracken et al., 2024), and in northern Europe wind droughts have been reported to occur between 7 and 11.4 events per year (Otero et al., 2022; Millstein et al., 2019). In Australia, energy droughts are typically of moderate to long duration, often ranging from about 10–40 days, with a relatively high median compared with Europe, Asia, and Africa. This is largely due to the simultaneous lack of wind and sun, particularly in Tasmania and Victoria (Richardson et al., 2023). Some of the events recorded in Australia, lasting up to 40 days, are among the longest observed in the region and are notable examples of variability in the dataset (Rispler et al., 2022). In Africa, long-term wind droughts in the Atlas Mountains, lasting up to 80 days (Jurasz et al., 2024), and in northwestern Morocco, lasting up to 200 days (Jurasz et al., 2024), are among the most severe on record, highlighting the severity of renewable-energy droughts in North Africa. In Asia, seasonal variability is particularly pronounced. For example, solar drought in China occurs up to 63% of the year, or about 230 days (Sun et al., 2024), making this region one of the most severely affected by prolonged solar droughts. Overall, the figure shows that North America and Australia have comparatively higher central values than Europe and Africa, whereas Asia and Africa exhibit the most pronounced extreme outliers.



Region	n	Min	Q1	Median	Q3	Max	Mean
Europe	8	0.58	2.58	7.3	30.55	146	33.13
Asia	9	3	6	13	30	230	41.22
North America	9	6	16	31	37	57	28.22
Africa	10	2	5.5	11	35.25	200	38.5
Australia	10	10	20.5	26.5	33.75	40	26.4

Fig. 5. Boxplot visualization of energy drought durations across continents: assessing regional variability and extreme event.

Table 1
Different applied methodologies in defining renewable energy resources drought between 2018 and 2024.

Region	Index Name	Abbreviation	Threshold Definition	Temporal Scale	Drought Type	Reference
Global	Standardized Streamflow Index (3-month)	SSI3	SSI3 < -0.84 (~5-year return period; F=0.2)	Monthly	Streamflow drought	Wan et al. (2021)
Global	Hydropower Deficit Event	—	HP reduction ranked by exceedance probability (10% annual probability)	Monthly	Hydropower deficit	Wan et al. (2021)
Global	Capacity Factor Strike (Insurance Index)	CF VaR80	CF below 20th percentile (80% VaR strike)	Annual	Hydropower financial drought	Cuppari et al. (2026)
Global	Weighted National Drought Index	—	National drought > 0.1 threshold	Annual	Hydrological drought (hydropower-weighted)	Bagnoli et al. (2024)
Europe	Standardized Renewable Energy Production Index	SREPI	SREPI < -1.28 (10% probability level of standard normal distribution)	Monthly	Energy production drought	Allen and Otero (2023)
Europe	Standardized Residual Load Index	SRLI	SRLI $> +1.28$ (90th percentile)	Monthly	Supply-demand drought	Allen and Otero (2023)
Europe	Energy Drought (percentile-based)	ED	Generation below 10th percentile	Daily	Production drought	Otero et al. (2022)
Europe	Energy Production Drought	EPD	Daily production below fixed threshold	Daily	Production drought	Raynaud et al. (2018)
UK	Wind speed percentile threshold	—	Wind speed $<$ 20th percentile	Daily	Wind drought	Kay et al. (2023)
Germany	Low Wind Power	LWP	CF $<$ 2%, 5%, or 10% CBT/MBT (Constantly/Mean Below Threshold)	Hourly	Wind drought	Ohlendorf and Schill (2020)
China	Wind Resource Drought	—	CF $<$ 5%, 7%, or 10%	Daily	Wind drought	Liu et al. (2023)
Argentina	Quantile-based wind/solar drought	Q90	Generation $\leq$ 90% quantile (bottom 10%)	Daily	Wind/Solar drought	Bianchi et al. (2022)
China Basin	Water Scarcity Index	WSI	WSI $=$ WW/RWR $\times$ 100 (classification: low/moderate/high)	Annual	Hydrological stress	Liu et al. (2025)
China	Residual Load Drought	RL drought	Threshold-based net load deficits	Daily	Compound drought	Zuo et al. (2024)
China (Yangtze)	Daily Hydropower Drought	DHP percentile	DHP $<$ 20th percentile	Daily	Hydropower drought	Liu et al. (2023)
India	Energy Drought Intensity	—	5%–50% of climatological daily mean generation	Daily	Solar/Wind/Hybrid drought	Gangopadhyay et al. (2022)
Japan	Dark Doldrum	—	VRE generation $<$ 10% CF	Daily	Compound drought	Ohba et al. (2022)
West Africa	Extreme Low Production Days	—	Bottom 1% of generation	Daily	Solar/Wind drought	Bloomfield et al. (2022)
Ghana	Standardized Precipitation Evapotranspiration Index	SPEI-12 / SPEI-24	SPEI normalized -2 to $+2$; drought at negative extremes	Monthly	Hydrological drought	Adu-Poku et al. (2024)
Australia	Percentile-based solar/wind drought	—	Climate variable $<$ 25th percentile	Daily	Solar/Wind drought	Richardson et al. (2023)

Note: Terminology follows the original studies. Terms such as *power drought*, *energy-production drought*, *energy drought*, and *renewable-energy drought* are treated in this review as related concepts under the broader framework of renewable-energy drought unless the original study defines them differently.

3.1.2. Critical evaluation of energy-drought indicators and toward a harmonized assessment framework

Although there has been an increasing body of literature on renewable-energy droughts, there is no consensus on how to define or quantify them. The studies have used a variety of methods, as summarized in Table 1, such as fixed capacity-factor thresholds, percentile-based measures, standardized indices, hydrological drought indicators, compound-risk measures, and financial-risk measures. This methodological diversity is due to the different study goals, technologies of renewable energy and climatic conditions in the different regions but also poses significant problems for comparison of results between regions and studies. As a result, the frequency, duration, severity and risk of droughts reported based on different indicators can vary considerably.

The literature review shows that there are six main methodological groups: (1) fixed thresholds on the capacity factor, (2) percentile-based thresholds, (3) standardized drought indices, (4) hydrological drought indicators, (5) multivariate or compound-risk approaches, and (6) financial-risk metrics. All these methods have their own advantages and disadvantages and are applicable to specific situations. Table 2 shows a critical synthesis of the main energy-drought indicator families that were identified from the literature reviewed, their methodological properties, limitations, and suggested applications.

There are several common drought assessment methods for wind and solar energy, such as fixed capacity-factor thresholds. These include the 2% threshold proposed by Ohlendorf and Schill (2020) in Germany, the 5% threshold used by Ohba et al. (2022) in Japan, the 7% threshold tested by Gangopadhyay et al. (2022) for India, and the 10% threshold used by Liu et al. (2023) for China. The main benefit of their operation is that they are simple to use and are very helpful in operational reliability assessment and grid management. They also have significant drawbacks, however. The threshold chosen is often arbitrary and results are highly dependent on the methodology used. A 9% capacity factor corresponds to the same meteorological and operational conditions but is considered a drought event on a 10% threshold but not on a 5% threshold. Thus, the frequencies and severities of droughts reported in different studies are not necessarily directly comparable, because they use different drought definitions.

This is somewhat mitigated by using percentile-based approaches, which define droughts based on local climatological conditions. Otero et al. (2022) used percentile thresholds for Europe, Kay et al. (2023) extended this concept for the United Kingdom, and Richardson et al. (2023) applied similar percentile thresholds in Australia. These techniques are especially useful to detect abnormally low production of renewable energy compared to the regional average. Percentiles are more appropriate for regional assessments than fixed thresholds, since they take into account local climate characteristics. However, they also pose difficulties. Absolute energy deficits will vary significantly across regions for the same percentile drought, because a percentile drought in one area may have a different energy deficit than a percentile drought in another area.

The Standardized approaches, such as the standardized renewable energy production index (SREPI) and the standardized residual load index (SRLI), are important methodological development (Allen and Otero, 2023). These indices convert renewable-energy anomalies into long-term climatological normalized statistical deviations that allow comparisons between regions, technologies, and time scales. This is especially useful for climate change research and for conducting large-scale evaluations. But they tend to need a longer time series and more robust statistical assumptions than simpler threshold-based approaches. Also, very standardized metrics can mask operational shortfalls that are significant from a power-system perspective, but not so significant over a short time period.

Unlike wind and solar assessments, hydropower drought assessments require information not only about meteorological conditions but also the hydrological processes, reservoir operations, and water-management decisions. Therefore, various indicators have been used to assess hydropower droughts, such as the standardized streamflow index (SSI), standardized precipitation-evapotranspiration index (SPEI), water scarcity index (WSI), generation-based deficits, and reservoir-storage anomalies (Adu-Poku et al., 2024; Liu et al., 2025; Wan et al., 2021). These indicators offer good information on hydroclimatic stress and water availability but are not necessarily a direct measure of lost electricity generation. Consequently, drought characteristics may vary significantly among studies, even for the same hydroclimatic conditions and using different hydrological indicators.

Several studies have recently used multivariate and compound-risk strategies. Otero et al. (2022) developed the concept of compound renewable-energy drought metrics for multiple renewable energy resources, while Zuo et al. (2024) used RE residual-load drought metrics for future projections based on the CMIP6 model. These methods can be especially useful since they account for interactions between several renewable resources and can help identify compound droughts that impact wind, solar, and hydropower production. These approaches

Table 2
Critical evaluation of major energy-drought indicator families identified in the reviewed literature.

Indicator Family	Examples	Strengths	Limitations	Recommended Application	References
Fixed capacity-factor thresholds	CF $<$ 2%, 5%, 7%, 10%	Simple, operationally intuitive, directly linked to generation deficits	Threshold selection is often arbitrary and region-dependent; results are sensitive to chosen threshold	Grid operation and reliability assessments	Ohlendorf and Schill (2020); Liu et al. (2023); Gangopadhyay et al. (2022); Ohba et al. (2022)
Percentile-based thresholds	10th, 20th, 25th percentile	Accounts for local climatology and resource variability; suitable for identifying anomalous conditions	Difficult to compare across regions because thresholds vary geographically	Regional resource assessment	Otero et al. (2022); Kay et al. (2023); Richardson et al. (2023); Liu et al. (2023)
Standardized indices	SREPI, SRLI	Enables comparison across technologies, regions, and time periods; suitable for climate-change studies	Requires long records and statistical assumptions; may smooth short-duration operational deficits	Climate-change and multi-region studies	Allen and Otero (2023)
Hydrological drought indicators	SSI, SPEI, WSI	Established hydroclimatic interpretation; directly links water availability and drought processes	Often indirect representation of realized electricity-generation impacts; may not capture operational constraints	Hydropower assessments	Wan et al. (2021); Adu-Poku et al. (2024); Liu et al. (2025)
Compound-risk approaches	ED, RL drought, copula methods	Captures simultaneous multi-resource deficits and system-level vulnerabilities	Data-intensive and computationally complex; requires multiple datasets	Multi-source renewable systems	Otero et al. (2022); Zuo et al. (2024)
Financial-risk metrics	CF VaR80	Directly linked to economic losses, insurance design, and revenue risk assessment	Limited representation of physical drought mechanisms	Financial risk and insurance assessments	Cuppari et al. (2026)

more closely simulate what is observed in contemporary power systems, consisting of a variety of renewable resources that operate in complex, interconnected electricity grids. However, they typically need larger data sets, more complex statistical techniques and more computing power than simpler techniques.

3.1.2.1. Influence of indicator selection on drought frequency and severity estimates. Results from the literature reviewed show that there is a strong dependence on the choice of energy-drought indicator. This has been demonstrated by Ohlendorf and Schill (2020) for fixed capacity-factor thresholds, and by Liu et al. (2023) for the Chinese case, and by Otero et al. (2022) and Richardson et al. (2023) for percentile-based approaches. A drought is generally defined by a minimum capacity factor of 10%, resulting in the identification of more drought events than a minimum capacity factor of 5% or 2% (Ohlendorf and Schill, 2020; Liu et al., 2023). On the other hand, lower thresholds will detect fewer events, but only the most significant generation shortages. The same differences exist between percentile-based methods. Otero et al. (2022) employed the 10th percentile while Kay et al. (2023) and Richardson et al. (2023) demonstrated that higher percentile thresholds result in more drought events being classified.

Raynaud et al. (2018), Otero et al. (2022) and Ohlendorf and Schill (2020) all revealed that methodological decisions make a significant difference in the reported drought duration and frequency. Therefore, it is not possible to make a direct comparison of energy-drought statistics reported by different studies without considering the definition and threshold used. This is a major reason for the high inter-regional variability in reported drought characteristics and underscores the need for methodological transparency and standardization (Allen and Otero, 2023; Otero et al., 2022). This is especially challenging for hydropower systems. Wan et al. (2021) quantified hydrological drought, Adu-Poku et al. (2024) emphasized hydropower production, while Moghaddasi et al. (2024) related hydrological drought with electricity generation. While both methods can be informative, they are different points in the climate–water–energy cascade and can thus yield different estimates of drought severity and frequency (Wan et al., 2021; Qiu et al., 2023; Liu et al., 2025). Future research should clearly differentiate between hydroclimatic droughts and actual droughts in electricity production.

3.1.2.2. Toward a harmonized framework for energy-drought assessment. The literature review reveals that none of the indicators is able to cover all dimensions of energy drought for all renewable energy technologies and geographical settings. Allen and Otero (2023) recommended adoption of standardized indicators for cross-regional comparison, Otero et al. (2022) argued for compound approaches, Wan et al. (2021) made the case for hydropower-specific indicators and Cuppari et al. (2026) showed the utility of financial-risk indicators. Based on the strengths and limitations of these approaches, a minimum harmonized decision framework is suggested for indicator selection and methodological consistency and comparability for future energy-drought assessments.

Capacity-factor thresholds are still suitable for operational reliability assessment and grid-management applications as they are directly linked to the performance of the electricity generation. Fixed thresholds have been shown to be useful for defining wind-energy droughts in Europe by Ohlendorf and Schill (2020), and renewable-energy droughts in Japan by Ohba et al. (2022), while Liu et al. (2023) used a 10% capacity-factor threshold to define wind-energy droughts in China. Percentile-based methods can be useful for determining whether a particular resource condition is anomalous for a region relative to a local climatology for a regional climatological assessment. Otero et al. (2022) showed that percentile-based thresholds are appropriate for characterising renewable-energy droughts in Europe, Kay et al. (2023) applied this climatology-based threshold to characterise wind and solar droughts in the United Kingdom, and Richardson et al. (2023) showed that percentile-based metrics are suitable to characterise renewable-energy droughts in the Australian climate. Standardized indicators like SREPI provide more consistency and comparability when making inter-regional comparisons and climate change studies (Allen and Otero, 2023). For systems that rely on multiple renewable resources and contribute significantly to electricity generation, compound-risk and multivariate approaches are recommended, as they more effectively reflect the compounding risks from resource deficiencies and the vulnerabilities of the system (Otero et al., 2022; Zuo et al., 2024; Lei et al., 2024). Lastly, hydroclimatic indicators and realized generation shortfalls should be combined in hydropower assessments to more effectively connect water-resource variability with electricity-system performance (Wan et al., 2021; Adu-Poku et al., 2024; Moghaddasi et al., 2024; Qiu et al., 2023).

Using this comparison, a decision-oriented framework for selecting the most suitable energy-drought indicator is presented in Fig. 6, depending on the main objective of the study, the renewable-energy technology being studied, and the desired level of spatial comparability. The framework suggests that operational reliability studies should use fixed capacity-factor thresholds, regional climatological studies should use percentile-based approaches, cross-regional and climate-change should use standardized indices, and multi-resource or system-level studies should use compound-risk methods. In addition, the framework suggests combining hydroclimatic indicators with generation-based metrics and operational aspects, such as reservoir management, water allocation, and environmental-flow requirements, to better reflect climate–water–energy relationships related to hydropower droughts when hydropower is a significant share of the energy system. The proposed framework establishes a clear and repeatable process for selecting indicators and introduces a connection between study goals and system characteristics to the most suitable indicator family, which enhances methodological consistency in future renewable-energy drought assessments.

The indicator families and harmonized assessment framework presented above provide a foundation for interpreting the diverse evidence reported in the literature. The following sections review energy-drought characteristics across major world regions, emphasizing differences in dominant renewable resources, climatic drivers, drought persistence, and system vulnerabilities, while identifying regions and technologies that remain comparatively underrepresented.

3.1.3. Regional evidence of renewable energy droughts

3.1.3.1. Europe. Three studies have specifically examined solar and wind droughts in Europe, but each with a different methodology and focus on a specific aspect of the problem (Allen and Otero, 2023; Otero et al., 2022; Raynaud et al., 2018). In the study by Raynaud et al. (2018), EPD (Energy Production Droughts) were analyzed and the results showed that solar droughts are more widespread in northern Europe. For example, in Norway, moderate droughts occurred on 40% of days and severe droughts on 24% of days, while in Andalusia these values were only 10% and 1%, respectively. A similar regional pattern was observed for wind power droughts; Moderate droughts lasting 1–7 days were observed with relatively high frequency, around 50–60 events per year, while severe droughts usually lasted less than two days.

Otero et al. (2022) examined energy droughts (ED) using copula analysis and found that they were more frequent in winter than in summer, with 11.4 events per year in winter and 7.6 events per year in summer. However, in some northern European countries with limited solar capacity, such as Latvia, Sweden and Norway, the frequency of energy droughts in summer has been reported to be as high as in winter or even higher. Increasing solar capacity reduced summer droughts, but increased winter droughts. Conversely, expanding wind capacity reduced winter droughts, but had the opposite effect in summer. The return periods of moderate, severe and extreme droughts were estimated

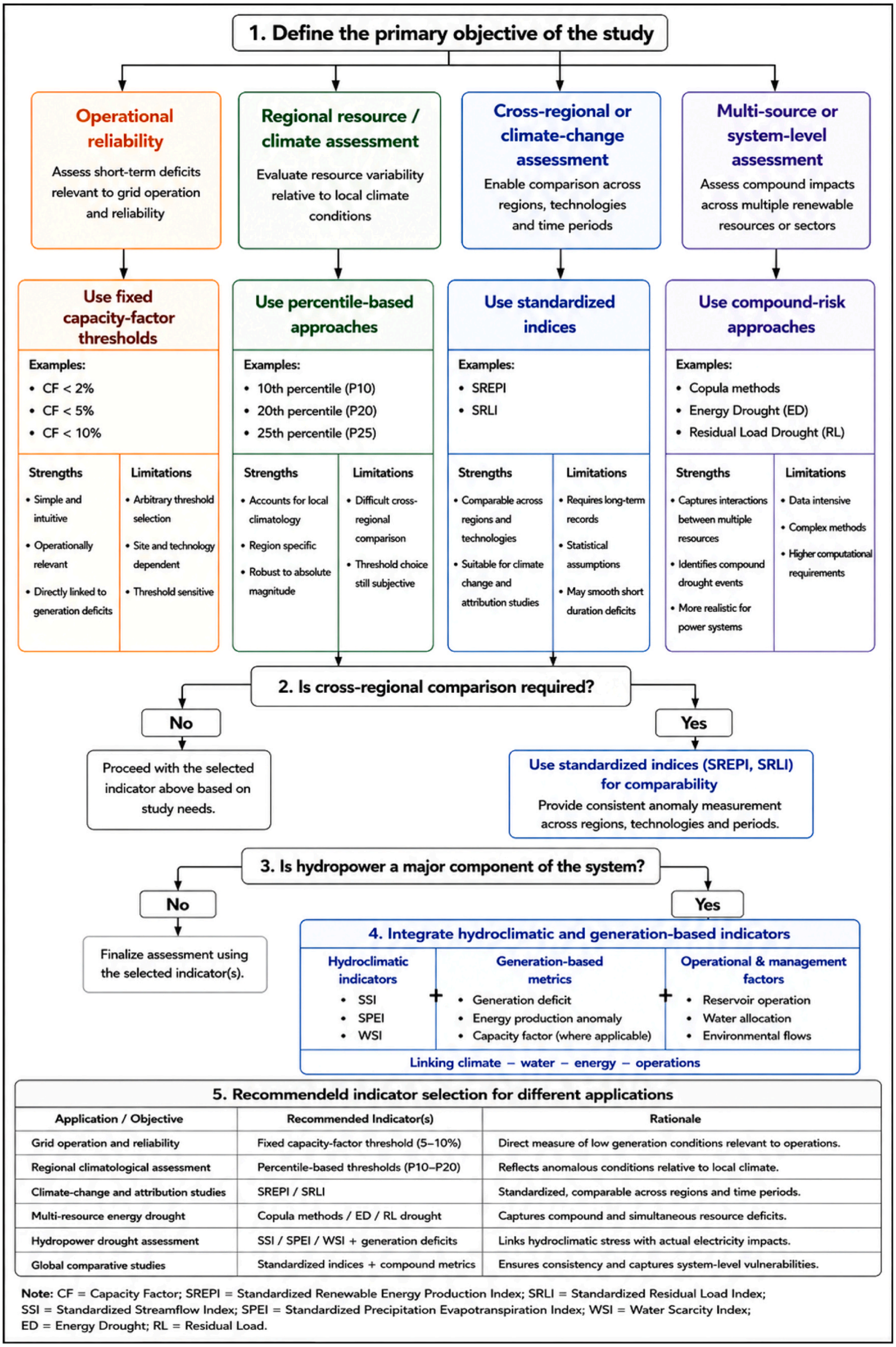


Fig. 6. Proposed harmonized framework for energy-drought assessment. The framework synthesizes the principal methodological approaches identified in the literature and links indicator selection to study objectives.

to be 0.58, 1.6 and 2.9 years, respectively. Extreme droughts were relatively frequent in countries such as the UK and Denmark, occurring approximately every 2–4 years, while they were very rare in Switzerland and Poland, with return periods of more than 30 years.

During the Central European drought of 2003, which lasted from February 2003 to March 2004, hydropower generation across Central Europe fell by 11.4%, and Poland experienced more than eight months of drought. Meanwhile, the models overestimated the magnitude of the production decline in Switzerland and Germany (Wan et al., 2021). These differences are consistent with the known uncertainties in global hydropower simulations under drought conditions, especially in cases where the reservoir operation and turbine release rules are not well constrained and specified. To complement this continental perspective, several country-specific studies have provided more detailed insights. Ohlendorf and Schill (2020) examined prolonged low-wind events in Germany, Schindler et al. (2020) investigated seasonal wind–solar complementarity, whereas Kay et al. (2023) focused on the occurrence of winter wind droughts over the United Kingdom. In Germany, seasonal variations in wind speed and solar radiation show clear patterns: the highest wind speed occurs in winter and the lowest in summer, while solar radiation reaches its seasonal maximum in summer and spring and is at its lowest in winter. Schindler et al. (2020) reported a significant negative mean correlation between seasonal wind speed and solar radiation, ranging from −0.52 to −0.99; This finding suggests a strong seasonal complementarity between the two sources. However, this complementarity is mostly seasonal in nature and is not sufficient to fully compensate for periods of low supply; therefore, Schindler et al. (2020) showed that seasonal complementarity alone is insufficient to eliminate prolonged low-generation periods.

Further analysis of wind power generation in Germany has shown that the longest wind-down event occurred in March. Short-term wind-down events, lasting up to half a day, were more frequent, while very long events were less frequent. The return period estimate shows that Germany experiences a period of about eight days approximately once every decade in which wind power generation falls below 10% of installed capacity. Spatially, the wind capacity factor is also higher in northern Germany, especially near the North Sea and the Baltic Sea, while southern Germany, especially in the Alpine region, shows lower values. It is noteworthy that the spatial distribution of wind capacity in extreme low-wind events does not follow the annual average pattern, suggesting that even areas with strong wind resources on an average scale may be exposed to severe low-wind events (Ohlendorf and Schill, 2020). In the UK, some studies have focused on offshore wind resources. Results show that the probability of experiencing record-low winds in winter is about 3%, i.e. an event that occurs about once every 30 years (Kay et al., 2023). Furthermore, the probability of at least one week of wind drought occurring each winter is estimated to be over 60%. Observational data have recorded up to four non-consecutive weeks of wind drought in winter, while model simulations have reached five weeks. This suggests that winter windless conditions can be of considerable severity, especially during peak demand periods (Bloomfield et al., 2018; Thornton et al., 2017).

3.1.3.2. Asia. Across Asia, energy droughts exhibit pronounced spatial, seasonal, and resource-specific variability, reflecting the continent's diverse climatic regimes, from monsoon-dominated low latitudes to high-elevation continental interiors. Much of this evidence comes from China, with additional insights from Japan and India. In China, wind resource droughts display strong seasonal and regional differentiation. Wind droughts occur predominantly during the warm seasons (summer and autumn), with frequencies 3–13 times higher than in cold seasons (spring and winter) (Liu et al., 2023).

Liu et al. (2023) showed that northern and northwestern China exhibit an autumn–winter dominance of wind droughts, whereas Ren et al. (2009) reported similar seasonal characteristics for long-term wind-resource variability. Northeast China experiences the highest frequency of moderate wind droughts (~30 days/year), compared to ~1 day/year in Northwest China, with persistent events lasting up to 9 days (Lei et al., 2024). Severe droughts remain geographically limited, with 19 days in Northeast China and 24 days in the Tibetan Plateau (Liu et al., 2023). Solar droughts show a contrasting seasonal structure, peaking in winter and accounting for up to 63% of total occurrence time, particularly in the Yangtze River Basin and Loess Plateau (Sun et al., 2024). Wind inefficiency peaks in autumn (~19% of occurrence time), while compound droughts reach ~17%, indicating strong seasonal asymmetry between resources (Sun et al., 2024). Wind energy peaks in April (1.11) and November (1.07), while solar peaks in July (1.25) (Jiang et al., 2023), Low-wind events can persist for up to 13 days in extreme years, while winter solar droughts remain a dominant constraint (Jiang et al., 2023).

In China, the spatial differences in the quality of renewable resources are very significant, and this geographical heterogeneity also shapes the pattern of persistence or persistence of energy droughts. In central provinces, such as Sichuan, Chongqing, and Hubei, wind resources are structurally weak, and wind speeds are usually less than 2.6 m/s; as a result, long-term power outages, sometimes lasting more than 10 days, are more common in these regions. In contrast, northwest China and Tibet have stronger and more stable renewable potential, and the duration of energy droughts is generally less than 3 days (Jiang et al., 2023). For example, in provinces such as Hubei and Henan, continuous periods of renewable generation decline can exceed 10 days, and in Chongqing and Yunnan, solar radiation droughts sometimes last up to 12 days. In contrast, Tibet experiences the shortest periods of wind and solar radiation decline, where these events usually last less than three days (Jiang et al., 2023). In addition to these spatial differences, hydropower also contributes to the risk of energy droughts in many parts of Asia. In the Yangtze River Basin, drought events occur about 10 times per year, last about 7 days on average, and can reduce power generation by nearly 26% (Liu et al., 2023). Extreme events, such as the 2022 drought, have even significantly increased dependence on fossil fuels (Guo et al., 2025). Also, operational studies of combined hydropower–wind–solar systems show that under hydrological constraints, both the flexibility of hydropower and its ability to peak are severely limited, highlighting the sensitivity of cascade hydropower systems to water availability (Jin et al., 2024).

Combined wind-solar droughts also constitute a significant part of this risk, especially in basins such as the Yalong. These events are more common in winter and sometimes last up to 15 days, while moderate-intensity events occur about 35–40 times per year (Lei et al., 2024). Although many of these events are short-lived in isolation, their high frequency increases the total number of drought days and seriously exacerbates the system risk in winter. Moderate shortages in wind and photovoltaics occur about 35–40 times per year and have an average duration of 2–3 days, while severe compound droughts occur less frequently but cause more disruption ((Lei et al., 2024).

At the national scale, Li et al. (2022a) showed that seasonal wind and diurnal solar complementarity can reduce the likelihood of compound low-generation events, although substantial spatial mismatches remain between renewable-resource availability and electricity demand. This highlights the importance of interregional transmission expansion and hybrid wind–solar development for reducing systemic energy-drought risk. Li et al. (2024) further showed that compound wind–solar droughts can exhibit strong spatial correlation across northern Chinese grids, indicating that resource-rich regions may still face systemic reliability risks during synchronized low-generation events.

Similar patterns are observed in other parts of Asia, but with specific regional characteristics. In Japan, wind power generation peaks in winter, as strong northwesterly winds associated with the East Asian winter monsoon are active during this season; in contrast, solar generation is mostly at its peak between May and August, and declines during the rainy season, June to July, and in September, which is affected by typhoons (Ohba et al., 2022). Periods of very low simultaneous wind and solar generation, known as dark doldrums, in which combined output falls below 10% of rated capacity, are less frequent in the cold season and more frequent in the warm season. Although events lasting longer than 5 days are rare, they should still be considered a significant concern if the mix of variable renewable capacity changes in the future (Ohba et al., 2022). In India, studies in Rajasthan and southern India also show a clear seasonal contrast. Solar droughts are relatively rare between November and April, but wind power faces frequent and persistent droughts even during the windy seasons. Wind–solar hybrid systems significantly reduce the frequency and duration of droughts, especially in southern India during the months of May to October. In Rajasthan, this hybridization is also more effective in reducing severe droughts but has limited benefit for moderate droughts (Gangopadhyay et al., 2022).

Recent work in India further suggests that renewable-energy droughts, defined using the lowest 2.5% of combined wind–solar potential, occur predominantly during November–February and can persist for up to 9 days (Dijkstra et al., 2025). Importantly, some drought-driving weather regimes show subseasonal predictability of approximately 10–15 days, indicating potential for early-warning systems and operational energy-security planning. In addition to basin- or plant-based definitions of hydropower droughts, drought index-based approaches, such as SPEI (Standardised Precipitation-Evapot ranspiration Index), have also been used to directly translate hydroclimatic drying into hydropower capacity outcomes. These studies show that the increased frequency of droughts under warmer scenarios could significantly alter the long-term hydropower outlook in large basins, such as the Yangtze (Wang et al., 2020).

4. Southeast Asia and Central Asia: underrepresented Asian regions

In addition to China, Japan and India, there are several subregions in Asia that are relatively underdeveloped for direct energy-drought research. This is especially relevant as Asia has a variety of energy-system structures, from river dependent hydro systems to dryland and continental areas with significant wind and solar power potential.

One area of particular research interest is Southeast Asia. The region has experienced high growth rates in electricity demand, high levels of hydropower reliance in some countries and growing adoption of solar and wind technologies. In Laos, hydropower accounts for over 70% of electricity production and is significant in Cambodia, Myanmar and Vietnam (IEA, 2024a). The impacts of climate change on precipitation, monsoon patterns, and river-flow regimes could lead to greater exposure to extended periods of hydropower shortages (IEA, 2024b). This is particularly true in the Greater Mekong region, where ENSO-induced droughts can cascade from the climate–water–energy nexus, impacting hydropower production, electricity trade, production costs and CO2 emissions (Chowdhury et al., 2021). More recent evaluations suggest that the potential for hydroclimatic change to impact run-of-river hydroelectricity resources throughout mainland Southeast Asia could have implications for energy security and electricity-market stability in the region (Maroufpoor et al., 2025). However, renewable-energy droughts are under-researched in the region of Southeast Asia.

In addition, Central Asia is under-represented in direct energy-drought research, given its significant renewable energy resources and vulnerability to climate change. The majority of the studies available are on changes in the availability of renewable resources rather than explicitly defining and quantifying energy-drought events. However, recent climate-projection studies offer helpful evidence for energy-drought risk screening. Broomandi et al. (2026a) demonstrated that wind-energy potential in Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan may change in the future under different scenarios, both in terms of wind-speed magnitude and seasonal variability, as well as site stability. Likewise, Broomandi et al. (2026b) demonstrated that the surface downwelling shortwave radiation (SWDR) and seasonal variability changes, depending on the scenario, influence solar-resource suitability in Central Asia. The results emphasize the importance of considering renewable-resource drought risk in dryland and continental climate regions.

4.1. North/South America

In the United States, recent research on wind and solar energy droughts has relied on two approaches: using standard infrastructure metrics and high-resolution temporal analyses (Bracken et al., 2024; Millstein et al., 2019). For example, Bracken et al. (2024) showed that, assuming a standard infrastructure configuration in 2020, the characteristics of combined wind–solar droughts are not the same in different regions of the United States and have significant spatial heterogeneity. Among them, California has experienced the longest multi-day events, with the maximum duration of these events reaching 6 days on a one-day scale and 9 days on a three-day scale. In contrast, Texas has shown the greatest persistence of short-term subdaily droughts; Hourly shortages there have lasted up to 37 h, while in California these extreme hourly events have been shorter, about 16 h. The seasonal pattern of these events is also not the same in all regions. In California, energy droughts are clearly concentrated in the summer, but in many other parts of the United States, their seasonal distribution appears to be more uniform. On the other hand, solar variability, which is largely influenced by cloud cover, plays a major role in the formation of short-term droughts, especially on an hourly scale; while wind-only droughts tend to last longer. In general, northern regions experience both shorter-term events and a lower frequency of combined energy droughts than southern and western states, highlighting the crucial role of regional climate controls (Bracken et al., 2024). This indicates that North American energy-drought risks are not only determined by present-day wind–solar variability but also by future infrastructure pathways and climate-driven changes in renewable-resource availability (Bracken et al., 2025).

A complementary analysis of spatial clusters of wind resources also confirms these spatial differences. In Southern California, Millstein et al. (2019) reported capacity factors ranging from 57% in Alta to 31% in San Gorgonio, with significant inter- and seasonal variability among locations. Most sites exhibit peak wind generation during summer, with 33–37% of annual output occurring between July and August, although Alta shows a weaker summer concentration (28%). These findings demonstrate that even within a single state, wind resource variability is highly site-specific and seasonally structured.

In northeastern Brazil, wind–solar hybrid systems have been shown to reduce renewable-energy drought risk by exploiting strong diurnal and seasonal complementarity between wind and solar resources. Wind production generally peaks at night and during drier months, whereas solar output is more stable during summer; this complementarity helps reduce variability and improve grid stability during low-resource periods (Ferraz de Andrade Santos et al., 2020).

In Ecuador, analysis of 14 hydropower plants (total installed capacity 4396 MW) revealed a decline in average fleet power factor from 56.67% to 51.76% between 2010 and 2020 (−9.4%), corresponding to approximately 0.5 %age points per year (Naranjo-Silva et al., 2023). The most pronounced declines occurred in Azuay, Napo, Tungurahua, and Cañar, highlighting the vulnerability of Andean hydropower systems to sustained hydroclimatic stress. Observed empirical evidence from hydro-dominant Latin American systems shows that local drought exposure produces the strongest and statistically robust production losses in hydropower (≈24–28% decline), while drought effects on wind and solar generation can be statistically indistinguishable from zero after controlling for meteorological drivers—highlighting hydropower as the primary drought-sensitive technology in mixed portfolios (Bagnoli et al., 2025). In Chile, the 2010–2020 “megadrought” coincided with a pronounced system response in which declining water availability in hydropower-rich basins was followed by substantial thermal compensation (with thermal generation exceeding hydropower during parts of the period), illustrating how hydropower drought can propagate into portfolio-wide reliability responses (Bagnoli et al., 2025). Further evidence from the Amazon Basin indicates that reduced river discharge may decrease hydropower generation by approximately 19% under RCP4.5 and 27% under RCP8.5 by mid-century, while also increasing operational interruptions and affecting project profitability (Almeida et al., 2021). These findings reinforce that hydropower-related energy droughts in South America are not only production risks but also economic and investment risks.

Hydropower drought impacts in LAC also propagate into environmental and health burdens: droughts affecting hydropower are linked to a shift toward combustion generation and measurable increases in $PM_{2.5}$ concentrations near combustion plants, even for short-duration (≈3-month) drought windows (Eriksson et al., 2025). Taken together, the Americas exhibit two contrasting drought regimes: short-duration atmospheric VRE deficits in the United States and longer hydropower droughts linked to basin-scale hydroclimatic decline in South America. However, compared with Europe and China, the evidence base across the Americas remains comparatively fragmented, with many studies focused on specific countries, basins, technologies, or historical events rather than harmonized multi-technology energy-drought assessments.

4.1.1. *Africa*

Energy drought characteristics across Africa reflect strong climatic gradients between desert, coastal, and monsoon-influenced systems. In North Africa, solar resources over the Sahara Desert exhibit high stability, resulting in relatively rare total energy drought events—approximately one per year (Jurasz et al., 2024). However, prolonged solar droughts lasting 5–7 days occur more frequently in northern Morocco and Algeria. In contrast, aeolian droughts are more prevalent in this region, especially in northwestern Morocco and northern Algeria, where the number of such events can reach at least 10 per year and their total duration can exceed 200 days per year. The spatial pattern of these droughts is not uniform and there are clear regional differences. The longest solar droughts have been observed in northern Algeria, Morocco and southern Egypt, usually lasting between 2 and 4 consecutive days. In contrast, the most persistent aeolian droughts have occurred in the Atlas Mountains, where in some cases this situation has lasted up to 80 consecutive days (Jurasz et al., 2024). The seasonal timing of these events also varies depending on the type of source and geographical location. In southern Mauritania and Libya, solar droughts predominate between May and August, but in Algeria this pattern shifts to December and February. Guezgouz et al. (2021) showed that wind droughts occur mainly between September and December in northern Algeria, whereas Jurasz et al. (2024) demonstrated broader regional patterns across North Africa.

Although the wind and solar capacity factor varies significantly across the region, regions with higher average wind capacity factors do not necessarily have a lower risk of wind droughts; in fact, in many cases, these same regions also experience a higher frequency of wind droughts. This suggests that relative resource abundance on an average scale does not necessarily translate into greater resilience. In such circumstances, the combination of wind and solar systems can significantly reduce drought risk at the system scale, especially in the transition areas between the dominant wind and solar regimes. However, western North Africa, central Algeria and southern Tunisia remain among the most vulnerable regions. In sub-Saharan Africa, the role of monsoon dynamics is very decisive. For example, in Senegal, solar production follows a strong diurnal cycle, but decreases in August, coinciding with the peak of the West African monsoon cloud cover (Bloomfield et al., 2022). Low-production days are mainly concentrated between August and September, a period that also coincides with the activity of the African easterly wave (Cornforth et al., 2017). Wind production is also variable both seasonally and diurnally; It reaches its maximum value in the Northern Hemisphere spring, decreases in the summer, and its minimum is observed in September. In Kenya, the pattern of renewable resources is also strongly dependent on regional climatic conditions. The solar capacity factor reaches its maximum in the Northern Hemisphere in winter and decreases in the Northern Hemisphere in summer; so that its seasonal difference is about 20%. In contrast, the wind capacity factor is seriously affected by the Turkana jet, with the highest wind production occurring in September and the lowest in the period from May to July (Bloomfield et al., 2022). Despite these examples, most African energy-drought studies remain concentrated in North Africa, whereas Sub-Saharan Africa has received considerably less attention despite rapid electricity-demand growth, high hydroclimatic vulnerability, and increasing renewable-energy deployment. This imbalance limits understanding of compound multi-resource drought risks in monsoon-influenced and hydropower-dependent African systems. In addition, multi-year drought indices such as SPEI-24 have shown a high correlation with hydropower generation in the Volta Basin in Ghana; such that a correlation value of 0.67 has been reported (Adu-Poku et al., 2024). This finding confirms the high sensitivity of hydropower systems to prolonged droughts. Future hydropower studies in West Africa further indicate that climate impacts may be highly plant-dependent. For example, projections for Côte d'Ivoire suggest that hydropower generation at Kossou may decline by approximately 6–11%, whereas Buyo and Taabo may experience increases under future climate conditions (Obahoundje et al., 2024). This spatial heterogeneity shows that hydropower drought risk in Africa cannot be generalized at national or regional scales without plant-level or basin-level assessment.

More broadly, the literature on hydropower droughts suggests that the consequences of this phenomenon for hydropower-dependent systems are not limited to production risk but can also lead to financial and revenue vulnerability at the national level. This has made it necessary to design drought risk transfer mechanisms such as index contracts based on remote sensing data and risk pooling structures for hydropower-dependent countries, including a few African countries (Cuppari et al., 2026). This type of financial view of risk is particularly relevant for many African contexts; In these regions, data scarcity and the complexities of transboundary basins limit the accuracy of exploitation forecasts, while remote sensing-based indicators can still provide a basis for scalable and relatively stable drought risk management tools (Cuppari et al., 2026). Recent work also suggests that floating photovoltaics may reduce the risk of hydro-dominated energy development in Africa by providing complementary generation and reducing exclusive dependence on new hydropower expansion (Arnold et al., 2024). This indicates that hybrid hydro–solar strategies may become particularly relevant for African power systems exposed to hydrological variability. Despite these emerging studies, Sub-Saharan Africa remains comparatively underrepresented in the renewable-energy drought literature relative to Europe, China, and North Africa, particularly in relation to compound multi-resource droughts and long-term climate-scenario assessments.

4.1.1.1. Australia. In Australia, energy droughts do not have a uniform spatial and seasonal pattern and are largely influenced by synoptic circulation patterns. There are also clear geographical differences in vulnerability to solar drought: areas north of 35°S are generally less vulnerable than south-eastern Australia (Richardson et al., 2023). Large-scale solar drought events are often accompanied by persistent cloud cover anomalies; in eastern Australia, cloud cover can be up to 55% above normal. In the tropical north, the increase in cloud cover is more closely related to the summer wet season, while at more southerly latitudes, seasonal solar variability is more pronounced and intense. The pattern of wind drought is even more complex. The southern and western regions, particularly South Australia and Victoria, are less vulnerable due to their exposure to mid-latitude storm tracks and the frequent passage of frontal systems (Pepler et al., 2021). In contrast, eastern Australia is more vulnerable to wind-induced drought, particularly when stable high-pressure conditions prevail in winter, spring and autumn. Also, Richardson et al. (2023) showed that offshore areas near Sydney experience lower wind-drought risk than adjacent onshore locations, while Rispler et al. (2022) attributed this to the greater stability of offshore wind regimes.

However, the main risk becomes more pronounced when wind and solar deficiencies occur simultaneously. Combined wind-solar droughts in Australia are more systemic than isolated events and are mainly concentrated in four regions: Three regions in Tasmania and one in Victoria. These events were observed in 28 of the 39 energy-generating regions, on about 20% of days. When multiple regions experience a shortage simultaneously, the possibility of spatial compensation is also greatly reduced. In this respect, winter is the most critical season, with at least five major regions simultaneously affected by this type of event on about 10% of days (Richardson et al., 2023). Recent analysis of Australian solar-resource variability using Himawari-8/9 satellite observations further shows that solar droughts exhibit strong spatiotemporal variability, reinforcing the need for high-resolution monitoring of solar-resource intermittency and drought persistence (Doedens et al., 2026).

4.1.2. Hydropower droughts and water–energy–food nexus implications

Hydropower droughts are different from wind- and solar-energy droughts because they are affected by not only meteorological droughts, but also by water-basin hydrology, reservoir operation, water-allocation policies, environmental regulations, and competing water demands. Therefore, hydropower droughts need to be considered in the context of the water–energy–food (WEF) nexus, because drought-induced water shortages can have a cross-cutting impact on electricity generation, agriculture, ecosystems, and socio-economic development.

The competition between several water users during drought periods is one of the most critical issues of hydropower droughts. Reservoir storage in many river basins needs to meet the demands of power generation, irrigation, municipal water supplies, industry, flood control, environmental-flow needs and more. In times of drought, such competing demands can lead to challenging allocation trade-offs. Release of water for agricultural production may lead to a lower storage capacity in the reservoir for electricity generation, while more water released for electricity generation can lead to a higher stress on irrigation systems and downstream water users. This is a trade-off that has been documented in a number of river basins where hydropower is a key component. These interactions were shown by Chowdhury et al. (2021) in the Mekong Basin, Adu-Poku et al. (2024) in the Volta Basin, and Guo et al. (2025) in the Yangtze River Basin.

There is an extra level of complexity added by environmental-flow needs. To meet the needs of aquatic ecosystems, fisheries, sediment transport, and water quality, many hydropower reservoirs must provide minimum flows at the downstream end. These environmental flows can also be directly diminished during droughts, thereby decreasing the amount of water available for power generation. This challenge is especially relevant to run-of-river and cascade hydro power systems where there is little storage available. Therefore, hydropower drought severity cannot be determined based on hydrological deficits alone, as drought effects on generation can be exacerbated by regulatory and ecological limitations, even if some water is available in the system.

There are also economic and financial risks associated with hydropower droughts. Droughts in countries where hydropower plays a significant role in the national electricity production can have adverse consequences on energy revenues, electricity price, have to be compensated by expensive fossil fuel substitution and put lead on the broader fiscal pressure. Bagnoli et al. (2025) demonstrated that drought-induced hydropower losses raise electricity prices and market volatility in multiple systems in Latin America. Cuppari et al. (2026) also showed how these risks can incentivize drought-index insurance and financial risk-pooling among regions. These risks have sparked a growing interest in drought-risk-transfer mechanisms such as index-based insurance products, index-based drought indices, and regional risk-pooling arrangements that are specifically developed for hydropower-dependent systems (Cuppari et al., 2026).

Hydropower droughts affect more than just the power industry. It has been demonstrated in several studies that the reduction in hydropower generation is often offset by increased thermal power plant operation, which leads to increased amounts of greenhouse-gas emissions and a decline in air quality. For instance, a reduction in the production of hydropower has been linked to an increase in fossil-fuel generation and a measurable rise in PM concentrations at combustion sites during periods of drought in Latin America (Eriksson et al., 2025). The same phenomenon was seen in the 2022 Yangtze River drought when the limited hydropower generation drove up the use of traditional electricity generation methods (Guo et al., 2025). These results show that hydropower droughts can cascade in multi-sectoral energy, environmental and public health systems. Although these issues have been acknowledged, most energy-drought studies still rely on hydrological indicators or generation shortages. Relatively few assessments have integrated water availability, reservoir operation, agricultural needs, environmental-flow needs, electricity generation and economic effects.

4.1.3. Emerging technologies and technology-specific gaps

4.1.3.1. Floating solar as an emerging water–energy nexus strategy. Floating photovoltaic (FPV) systems have become one of the fastest growing renewable energy technologies and are a viable option to improve the resilience of energy systems during drought. The FPV system is installed on reservoirs, lakes and other water bodies, which allows for electricity generation and water-resource management to be carried out simultaneously.

International evaluations indicate that the potential for implementing FPV is significant, with more than a million appropriate water bodies globally offering the potential for significant capacity for renewable energy (Woolway et al., 2024). The theoretical contribution of FPV to the future decarbonization pathways is large, as estimated by Woolway et al. (2024), who computed a theoretical global FPV generation potential of around 14,906 TWh from lakes and reservoirs. One of the key benefits of FPV systems is the ability to minimize water evaporation from reservoirs, further solidifying the connection between energy production and water retention. The deployment of large-scale FPV can simultaneously support the production of renewable energy and mitigate water losses and thus can generate important synergies in regions of water scarcity, as shown by Jin et al. (2023). Previous research has demonstrated that FPV systems can substantially reduce evaporation losses from reservoirs without compromising the conservation of precious freshwater for other purposes such as agriculture, human use and hydroelectric power production (Kassem et al., 2024).

The application of FPV systems to energy-drought mitigation goes beyond water saving. The co-location of FPV systems with hydropower reservoirs opens the door to hybrid renewable-energy systems with solar generation and hydropower flexibility. These setups can enhance the reliability of the system by spreading renewable energy sources and minimize reliance on any one climatic driver. Solar generation can help fill gaps in hydropower generation during times of low streamflow, and reservoir-based hydropower can be used to provide flexibility during periods of low solar irradiance. This complementarity has been emphasized in recent system assessments that are reliant on hydropower. For instance, FPV has the potential to mitigate the risks of hydro-dominated energy development in Africa by offering an alternative or complementary source of electricity to the planned hydropower development (Arnold et al., 2024).

But there are also environmental and operational issues with the use of FPVs. In recent years, there have been indications that a large amount of FPV can change the thermal structure, dissolved oxygen concentration, aquatic ecosystem and local biodiversity of reservoirs (Yang et al., 2024). However, broader reviews have also highlighted that FPV can impact hydrodynamics, shading regimes, benthic habitats, mobile species and water-atmosphere exchange processes, suggesting that energy-system benefits and ecological constraints should be taken into account when deploying FPV (Benjamins et al., 2024). Therefore, the energy benefits and environmental effects of widespread FPV use should be further investigated, especially in water-limited areas where reservoir management already has competing demands.

4.1.3.2. Concentrated solar power with thermal storage: a dispatchable solar-energy solution. The majority of solar-energy drought studies are on PV systems, which are very much reliant on the current solar irradiance. This means that short duration cloud cover, extended periods of low radiation and seasonal variations in the atmospheric environment can directly affect electricity generation. Concentrated solar power (CSP) systems with thermal-energy storage (TES) provide a fundamentally different way of using solar energy, however, and could significantly enhance resilience to some types of solar-energy drought. CSP systems can store the heat energy when the sunlight is available during the day and use it to produce electricity at night, unlike PV technologies. This storage feature enables CSP facilities to separate immediate solar-resource availability from electricity generation, which decreases the impact of generation shortfalls when they occur for a short period. Thermal-energy storage has been identified as a key enabling technology that enables CSP plants to deliver dispatchable solar electricity and to boost the use of solar energy beyond the time of its instantaneous availability of solar irradiance (Palacios et al., 2020; Pascual et al., 2022).

The contribution of CSP in energy-drought mitigation is especially pertinent in the context of future climate change scenarios. Although a prolonged decrease in solar energy input could have an impact on total energy output, the use of thermal-energy storage can mitigate short-term fluctuations in solar energy input and enhance system reliability during cloudy conditions, night-time demand peaks, and transient atmospheric disturbances. Global CSP deployment has been steadily increasing, especially in arid areas with high direct normal irradiance (DNI) and in China (Roca Reina et al., 2025).

However, the deployment of CSPs is still limited geographically due to the requirement of high solar resource availability, significant land needs, and cooling resource availability. Furthermore, many existing energy-drought studies neglect to include CSP systems, leading to a significant gap in knowledge about how well PV and CSP technologies will perform in the future climate scenario. Future energy-drought assessments should therefore include more than just the traditional photovoltaic systems and consider the effects of thermal-energy storage systems on drought frequency, duration, and severity at the facility and power-system level.

4.1.3.3. Offshore wind as an emerging component of energy-drought mitigation. Despite the rapid growth of offshore wind, it is not widely discussed in the literature on energy drought. Existing studies tend to concentrate on onshore wind, solar photovoltaics and hydropower, while offshore wind is often incorporated into a wider renewable energy planning process, but not into an energy drought assessment. This is a significant research gap as offshore wind has resource properties that are significantly different to onshore wind.

Offshore wind generally has higher and more consistent wind speeds, lower surface roughness and less topographic influence, which leads to higher capacity factors and lower short-term wind speed variability in many coastal areas compared to onshore wind resources. Therefore, offshore wind can offer a further diversification for renewables and can help to lessen any vulnerability of the system to periods of low generation from onshore wind and solar. Jurasz et al. (2020) reviewed the complementarity of offshore wind with other renewable resources. Borba et al. (2023) presented a proof of concept of the complementarity of offshore wind and hydropower during droughts in Brazil, while Costoya et al. (2022) showed that the combination of offshore wind and solar energy enhances supply stability in European coastal systems.

Offshore wind is not just about generation diversification. Offshore wind is more than just about generation diversification. The importance of complementarity between resources is now gaining more emphasis in recent risk assessments for renewable energy droughts. Increased emphasis is being placed on the importance of resource complementarity in minimizing the risk of renewable energy droughts in recent risk assessments. Hybrid offshore platforms combining wind, solar and wave energy have been demonstrated to decrease variability and minimize the number of periods with low renewable generation (Vázquez et al., 2024). Moreover, offshore-wind deployment strategies that rely on complementarity have been seen to enhance power-system resilience and decrease storage needs compared to strategies that aim at maximizing energy production (Radu et al., 2022). In addition to resource complementarity, more recent studies have highlighted the need for climate resilience in offshore wind projects. Climate change can affect offshore wind infrastructure through shifts in wind patterns, sea-level rise, storm intensity and frequency, wave patterns, and other climate factors that can affect energy generation, maintenance, and reliability (Kane et al., 2025). The findings indicate that offshore wind should be considered not only as a renewable energy source, but also as a climate-sensitive infrastructure system that, over time, may have an impact on energy-drought risk and power-system reliability.

Even with these benefits, offshore wind poses novel technical and environmental challenges. Significant capital expenditure, marine infrastructure, capacity to connect to the grid and marine spatial planning are needed for deployment. Offshore installations need to also account for interactions with shipping routes, fisheries, marine ecosystems, and extreme weather conditions (Kõrts, 2022; NYSERDA, 2021). Therefore, offshore wind can play an important role in mitigating renewable-energy drought risk, but it will need more comprehensive system-level planning than is currently included in energy-drought studies.

Offshore wind is an important but under-explored and underutilized part of the energy drought mitigation puzzle. Beyond diversification of generations and complementarity of resources, it has the potential to contribute to long-term system resilience in the face of climate change. Future energy drought assessments should explicitly consider offshore wind as part of the onshore wind, solar PV, hydropower, storage, transmission and climate-resilience systems. This integration would give a more realistic picture of future renewable-energy portfolios and their exposure to climate variability, extreme events, and renewable-resource droughts.

4.1.3.4. Implications for future global energy-drought assessments. New research indicates that planning for the future needs to take into account resource adequacy and infrastructure resilience, including offshore renewable energy where climate-related hazards like sea-level rise, changing wind patterns, and more severe storms may be more common (Kane et al., 2025). Future energy-drought evaluations should therefore consider the availability of energy resources as well as the resilience of renewable-energy infrastructure to varying climatic conditions. Therefore, future energy drought evaluations need to be done in a more comprehensive way and should consider the evaluation of several renewable energy sources at the same time. These would better reflect interactions between climate variability, energy generation, energy storage, water resources availability, and transmission limitations.

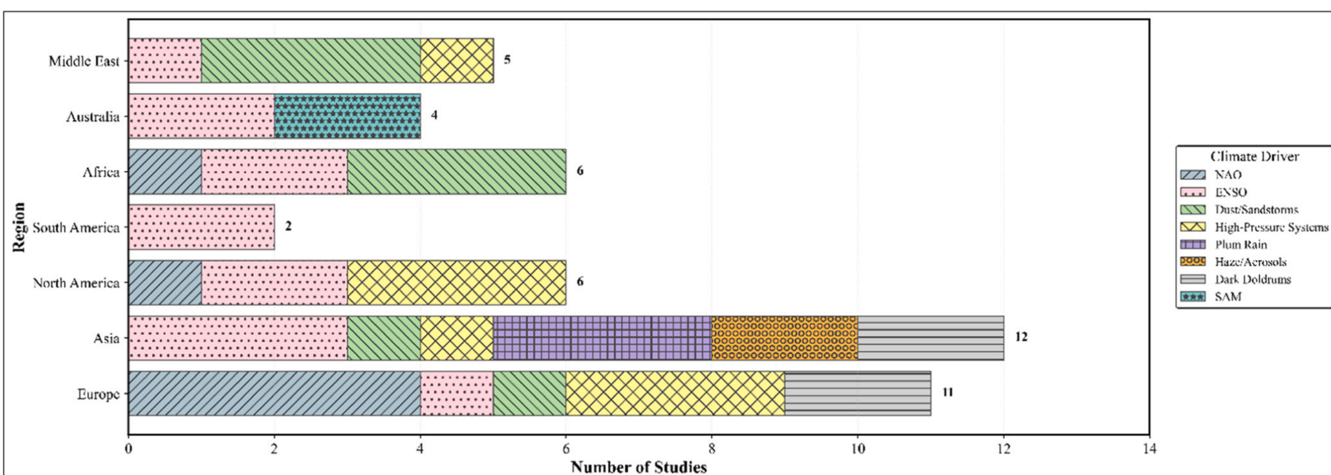
The studies selected offer valuable insights into regional vulnerabilities to energy droughts; however, some limitations suggest areas for further study. The methodologies and thresholds for defining droughts vary greatly across studies, making it difficult to directly compare the results and highlighting the importance of having consistent drought metrics as mentioned in Table 1. This is especially true for drought assessment for hydropower, where there are many different definitions such as streamflow percentiles, reservoir-storage anomalies, or generation-based thresholds, making it difficult to compare meteorological drought indicators with actual impacts to electricity production. Currently, there is limited literature on hydro-energy drought metrics that combine hydrological, operational and power-generation indicators (Wang et al., 2020). Second, a large number of studies are based on historical or near-future climate periods, and few studies investigate long-term projections under the high-end climate scenarios. This gap is significant because the variability of renewable resources can change in the future due to climate change, which could affect both the occurrence and intensity of energy droughts. For instance, Perera et al. (2020) demonstrated that the uncertainty associated with the potential of renewable energy can result in significant performance gaps, up to 34% for grid integration, and up to 16% decrease in power-supply reliability. Moreover, in hydropower-dominated areas, financial and governance risks are becoming more prominent due to the volatility of generation caused by droughts, inspiring the creation of drought-risk transfer instruments, including index insurance based on remotely sensed indicators and pooled financial-protection approaches for hydropower systems vulnerable to climate variability (Cuppari et al., 2026). Future research should combine governance, institutional resilience and policy adaptation with energy-drought assessment frameworks to gain deeper insights into how societies can adapt to the growing variability of renewable energy in the face of climate change.

4.1.4. The impact of climate/weather events on renewable power resources

Renewable energy systems, with their impacts varying across different regions. The stacked bar chart highlights the dominance of major climate and weather drivers affecting renewable energy across continents (Fig. 7). NAO (North Atlantic Oscillation), in both its positive (NAO+) and negative (NAO−) phases, is most strongly represented in Europe (Bloomfield et al., 2020) and appears in North America and Africa (Jurasz et al., 2024), where it mainly affects wind and solar power generation. In Asia, phenomena such as plum rain and haze in China (Sun et al., 2024), together with dark doldrums reported in East Asia (Ohba et al., 2022), disrupt renewable energy generation, largely through monsoon-related circulation and persistent high-pressure conditions. ENSO plays a broad and influential role across multiple regions, with particularly strong representation in Asia, Australia, North America, South America (Gonzalez-Salazar and Poganietz, 2021; Bianchi et al., 2022), and Africa (Bloomfield et al., 2022), affecting wind, solar, and hydropower variability. Dust and sandstorms are especially important in Africa and the Middle East, and they also appear in Europe (Varga et al., 2024b), where they reduce PV efficiency (Micheli et al., 2024) and alter atmospheric conditions relevant to renewable generation (Varga et al., 2024a). In North America, high-pressure systems are among the most prominent drivers and contribute to compound wind and solar droughts (Brown et al., 2021), while in Australia the SAM (Southern Annular Mode) is a key driver of renewable energy variability. In the Middle East, dust and sandstorms (Alanzi et al., 2024; Alhajji et al., 2024), together with high-pressure systems, are the dominant climatic drivers identified in the reviewed studies, with reported impacts on solar output (Alanzi et al., 2024; Feron et al., 2021; Alhajji et al., 2024) and, in some cases, wind energy performance (Alanzi et al., 2024).

4.1.5. Europe

In 2019, the meteorological sensitivity of a heavily renewable-dependent European energy system was investigated (van der Wiel et al., 2019). Severe power outages, which typically occur between October and February, are often associated with the establishment of high-pressure systems over central Europe. This reduces wind speeds, especially around the North Sea, and at the same time limits solar generation capacity due to shorter daylight hours. If these atmospheric blocking patterns persist, low-wind conditions can last for 7–14 days, resulting in extended periods of renewable energy outages (van der Wiel et al., 2019). In winter, the North Atlantic Oscillation (NAO) is a major factor influencing wind and solar power generation patterns in Europe (Bloomfield et al., 2020). When this oscillation is in negative phase, wind speeds in northern Europe, particularly in Great Britain and Scandinavia, decrease, and wind power generation decreases accordingly. In contrast, a positive NAO phase is usually associated with increased wind generation in northern Europe. However, winter solar



Region	NAO	ENSO	Dust/ Sandstorms	High-pressure systems	Plum Rain	Haze/ Aerosols	Dark Doldrums	SAM	Total
Europe	4	1	1	3	0	0	2	0	11
Asia	0	3	1	1	3	2	2	0	12
North America	1	2	0	3	0	0	0	0	6
South America	0	2	0	0	0	0	0	0	2
Africa	1	2	3	0	0	0	0	0	6
Australia	0	2	0	0	0	0	0	2	4
Middle East	0	1	3	1	0	0	0	0	5

Fig. 7. The dominant climate and weather events affect renewable energy generation across continents.

generation is limited by radiation availability rather than being directly affected by the NAO (Bloomfield et al., 2020).

Wind power decline events with a similar pattern have also been reported in the UK. These events are usually associated with persistent high pressures over the North Sea and northern Europe and are consistent with conditions corresponding to a negative NAO phase (Kay et al., 2023). Dynamically, this is characterized by anomalous Easterly flows, weak pressure gradients, and reduced wind speeds. Additionally, long periods of low wind, lasting more than three consecutive weeks, have been associated with El Niño-like sea surface temperature patterns, which increase the likelihood of a negative NAO phase and thereby exacerbate wind generation losses (Kay et al., 2023). In addition to these factors, aerosol-related events can also impose additional constraints on energy generation. For example, in Hungary, dust storms originating from the Sahara in 2022 reduced photovoltaic generation by several gigawatt hours over 72 h, and during large events, the forecast error exceeded 4 gigawatt hours (Varga et al., 2024a). During March 2022 dust outbreaks, Spain's national PV capacity factor fell from a typical March average of $18.9 \pm 5.7\%$ to $9.3 \pm 4.0\%$, with peak daily reductions reaching 80% and multi-day average declines of 46–70% (Micheli et al., 2024). Similar impacts were observed in Portugal, where national PV capacity factors declined by 37.9% compared to climatology, with maximum single-day reductions of 85.5%. In Italy, peak reductions reached 47% during the same event (Micheli et al., 2024).

Multi-hazard assessments further indicate that wind generation exhibits complex responses to hydrometeorological extremes. Wind capacity factors decreased during flood years in Central and Eastern Europe, with reductions of approximately 1.9% per year and 3.7% per year, respectively. During droughts and heatwaves, wind capacity factors increased in Central Europe by around 2% per year but declined in Mediterranean regions by approximately 3% per year. Cold-wave years were associated with reductions in both wind (−1.7%) and solar (−4.5%) capacity factors in Central Europe (Brás et al., 2023). Flood and storm years were associated with strong increases in hydropower capacity factors, with output approximately tripling during floods and quintupling during storm years (Brás et al., 2023). However, long-term shifts in precipitation seasonality can reverse these gains. At the Mont d'Orb reservoir in southern France, hydropower output declined by 25% between 1976–1997 and 2006–2022 due to reduced winter recharge, increased autumn rainfall intensity, and sedimentation rates of 19.3 mm per year (Hazet et al., 2025). Although extreme rainfall events enhanced short-term inflows, altered seasonal recharge timing and storage degradation ultimately reduced generation capacity.

4.1.6. Asia

In East Asia, monsoon dynamics and aerosol loading are among the most important factors regulating renewable energy production. In China, plum rain events in summer and persistent smog in autumn and winter reduce wind and solar production in the Yangtze River basin and northern China (Sun et al., 2024). For example, in Hebei Province, smog periods have been associated with simultaneous low wind and low radiation conditions; these events have sometimes lasted up to 16 days and, in the case of doldrums, even up to 43 days, resulting in prolonged reductions in generation. In Japan, simultaneous low-production events of wind and solar, known as dark doldrums, occur when the combined output of these sources falls below 10% of installed capacity (Ohba et al., 2022). These events are usually associated with monsoon rain fronts and the establishment of the Okhotsk high-pressure system, conditions that lead to persistent cloud cover and weakening surface winds. On the other hand, the interannual variability in the frequency of these events is largely influenced by sea surface temperature anomalies in the tropical Indo-Pacific and ENSO-related circulation changes, as these factors affect moisture transport and atmospheric stability in East Asia (Ohba et al., 2022).

Hydrometeorological extremes also have a significant impact on renewable energy generation in mountainous regions of Asia. In the Himalayas, large floods have disrupted more than 20 hydropower facilities, and after floods caused by sudden discharge of glacial lakes, riverbed instability and sediment transport have persisted for several years (Schwanghart et al., 2021). In the Lancang–Mekong River Basin, adaptive reservoir operation during flood periods has been able to reduce the intensity and frequency of floods, but when flood control was the priority, this decision has been accompanied by a measurable decrease in hydropower generation (Yun et al., 2021). In contrast, in the Bukhangang Basin in South Korea, reservoir operation strategies designed with an emphasis on resilience have increased power generation by nearly 20% within the framework of optimal flood management operations (Kim et al., 2022). Similarly, in the upper Yangtze Basin, optimization of power plant cascades has both increased hydropower generation by about 8.5% and improved floodwater use efficiency (Zhu et al., 2024a).

In arid and semi-arid regions of West Asia, dust and sandstorms are also among the most important limiting factors for solar generation. In Saudi Arabia, the high frequency of these storms along the Persian Gulf and Red Sea coasts limits the performance of photovoltaic systems, and for this reason, solar production in this country experiences significant seasonal variability that depends on the timing of these storms (Alhajji et al., 2024). In Kuwait, two major haboob events in May 2021 reduced photovoltaic and concentrated solar power generation substantially, while simultaneously increasing wind turbine output due to elevated wind speeds. During these storms, wind turbines produced up to 198–238% of typical daily averages, whereas PV generation fell to as low as 49% of normal output (Alanzi et al., 2024).

4.1.7. North/South America

In North America, renewable generation variability is strongly influenced by large-scale atmospheric circulation patterns and hydrometeorological extremes. In the United States, wind low-generation events are typically associated with thermal mid-level ridges and persistent high-pressure systems, while solar low-generation events are linked to mid-level troughs that promote cloudiness and synoptic-scale ascent (Brown et al., 2021). These circulation regimes directly regulate the capacity factor of wind and solar energy by affecting pressure gradients, cloud cover, and atmospheric stability. In addition, winter storm clusters associated with ENSO and the variability of the PNA (Pacific–North American) pattern alter wind resource characteristics in California, although the magnitude and nature of this impact vary depending on the location and type of storm system (Millstein et al., 2019).

In addition to this synoptic variability, seasonal shifts in the hydrological system also play an important role in the complementarity of hydropower and solar power in the western United States. Studies have shown that climate change, through changes in the timing of snowmelt, can disrupt or shift the seasonal synchrony between hydropower availability and peak solar production (Bracken et al., 2025). Extreme precipitation and flooding events also impose direct infrastructure-level constraints on renewable generation. During Hurricane Florence in North Carolina, solar generation losses were strongly dependent on equipment elevation: peak reductions reached 305 MWh at 0 ft elevation, declining to 148 MWh at 2 ft and 33 MWh at 5 ft (Prieto-Miranda and Kern, 2024). In South America, hydrological droughts represent one of the most significant climate-related constraints on renewable generation, particularly in hydropower-dominated systems. Across Brazil's twenty largest basins, drought intensity increased during 1981–2021, with severe droughts between 2014 and 2021 in the Southeast and Midwest basins leading to hydropower generation declines of approximately 8.5 TWh (≈5% of average output) (Cuartas et al., 2022). Similarly, long-term analyses across Latin America show that ENSO-related drought periods substantially reduce hydropower generation, particularly during driest months (Gonzalez-Salazar and Poganietz, 2022).

4.1.8. Africa

In North Africa, the North Atlantic Oscillation (NAO) is an important factor in the interannual variability of renewable energy production (François, 2016; Jurasz et al., 2024; Pozo-Vazquez et al., 2011). A study of the period 1960–2020 shows that there is a moderate positive correlation with the NAO for solar resources in northern Morocco and Algeria, which is also statistically significant (p-values < 0.05). In these regions, the positive winter phase of the NAO is usually associated with relatively cool and dry conditions, which can increase solar potential. Wind resources, however, do not behave uniformly and their response varies from region to region. A negative correlation is observed in northern Egypt and northwestern Libya, while a positive relationship is reported in southern regions. In general, negative values of the NAO index are often associated with a decrease in wind potential in northern coastal areas, but in western coastal areas they may lead to an enhancement of wind production (Jurasz et al., 2024).

In sub-Saharan Africa, it is ENSO that plays a more prominent role in the seasonal control of renewable energy production. In Kenya, wind capacity factor increases by about 20% in JAS during El Niño years, while it decreases by about 10% in La Niña years; however, the pattern is reversed in OND (Bloomfield et al., 2022). Solar generation in parts of East Africa is also sensitive to ENSO, although this sensitivity is less pronounced, but has been reported to be statistically significant. In Senegal, wind capacity factor shows little dependence on ENSO, while solar generation increases by about 1% during El Niño events (Bloomfield et al., 2022). However, it is not only climatic constraints that limit energy production in Africa. In parts of sub-Saharan Africa, hydrological constraints also play a decisive role in hydropower performance. For example, at the Kainji Dam in Nigeria, seasonal fluctuations in yields and high reservoir evaporation severely limit hydropower generation during the dry season (Ogunjo et al., 2023).

4.1.9. Australia

In Australia, widespread solar lows are often associated with large-scale climate anomalies, anomalies that are linked to ENSO and SAM in some seasons. In spring and summer, these events are often associated with a La Niña-like pattern. In autumn, eastern Pacific El Niño-type events are also likely to be associated with solar drought, although the SST (Sea Surface Temperature) anomalies are not as severe. In winter, the SAM appears to play a more dominant role in the solar lows, as evidenced by significant negative MSLP (Mean Sea Level Pressure) anomalies over Antarctica that resemble the positive phase of the SAM (Holgate et al., 2022; Richardson et al., 2023). In contrast, widespread wind lows are associated with El Niño-like SST anomalies in most seasons; The only exception is winter, when ENSO is usually in a neutral state. In winter, a prominent feature of these events is the formation of an area of positive sea surface pressure anomalies over southeastern Australia, sometimes reaching values up to 300 Pascal above average. In spring, a band of high pressure extends across southern Australia. In both seasons, these pressure anomalies can be a sign of increased activity of countercyclical systems or a shift in the track of storms to the south (Richardson et al., 2023). Widespread compound droughts are associated with ENSO and the SAM, showing a La Niña influence in all seasons except autumn, most prominently in spring. Negative MSLP anomalies over Antarctica also highlight the SAM's role, again in all except autumn. These seasons also show positive MSLP anomalies south of New Zealand, common in wind but not solar droughts. This suggests that compound droughts share the La Niña-like SST and positive SAM signatures of solar droughts, while also exhibiting circulation features common to wind droughts (Richardson et al., 2023).

A study conducted in Australia utilized composite spatial fields for different ENSO phases, including El Niño and La Niña, to analyze the relationship between ENSO and wind speed across seasons (Vincent and Dowdy, 2024). During the austral summer, the study found that winds are generally weaker during El Niño and stronger during La Niña around 39°S, especially in some western maritime regions, with opposite anomalies occurring further south around 44°S. In winter, El Niño is associated with weaker winds across much of the western and northern areas, while La Niña results in stronger winds in the northeast and weaker winds in the south. Both El Niño and La Niña led to relatively weak winds along the eastern and southeastern parts of Australia. In spring, weaker winds are observed in various areas during El Niño and La Niña, with generally stronger winds during the ENSO Neutral phase ($-0.8 \leq$ NINO3.4 ≤ 0.8) (Vincent and Dowdy, 2024).

However, it is not only large-scale circulation patterns that affect energy production. Certain meteorological hazards can also cause sudden and sometimes severe drops in production. Among these, dust and sandstorms are among the most direct and measurable factors affecting solar production. Dust storms have been shown to substantially reduce photovoltaic performance across different climatic regions. Varga et al. (2024a) reported severe PV losses during Saharan dust outbreaks in Central Europe, while Micheli et al. (2024) quantified national-scale PV reductions across Spain, Portugal, and Italy. Similar reductions have also been documented in Saudi Arabia (Alhajji et al., 2024) and during haboob events in Kuwait, where photovoltaic output declined while wind generation temporarily increased because of stronger winds (Alanzi et al., 2024). In contrast, during some sandstorm events, increased wind speed can temporarily increase the power output of wind turbines. This shows that the response of different technologies in renewable hybrid systems is not necessarily the same and may even be in the opposite direction to each other in some situations (Alanzi et al., 2024). Hydrometeorological extremes introduce additional complexity. Hydrometeorological extremes also influence renewable-energy production beyond wind and solar. Floods may temporarily increase hydropower generation through enhanced inflows, whereas prolonged droughts, altered precipitation seasonality, and sedimentation can substantially reduce long-term hydropower production (Brás et al., 2023; Hazet et al., 2025; Zhao et al., 2024).

Compound drought, characterized by simultaneous reductions in wind and solar output, are frequently linked to persistent high-pressure systems, atmospheric blocking, or monsoon-driven cloud cover. In Japan, dark doldrums associated with monsoon fronts and the Okhotsk High reduce combined wind and solar output below 10% of installed capacity (Ohba et al., 2022). In the United States and Australia, combined events are also often accompanied by anomalous circulation regimes that simultaneously reduce wind speed and increase cloudiness (Brown et al., 2021; Richardson et al., 2023).

4.2. Future projections of wind, solar, hydro power resources

Understanding the impacts of climate change on renewable energy sources is essential to ensuring their long-term sustainability and availability. Despite the progress made, there are still significant knowledge gaps about how climate-induced risks such as extreme weather events (Feron et al., 2021), seasonal shifts (Kapica et al., 2024; Lira-Loarca et al., 2021; Wu et al., 2022; Martinez and Iglesias, 2022), and long-term climate change (Bloomfield et al., 2021; Bonanno et al., 2022; Costoya et al., 2022, 2023; Duran et al., 2024; Dutta et al., 2022; Weiss et al., 2020) can impact the reliability, efficiency, and availability of these energy systems. Meanwhile, solar, wind, and hydropower systems are particularly sensitive and vulnerable to changes in radiation (Oka et al., 2020; Poddar et al., 2021; Soares et al., 2019; Wu et al., 2022; Yang et al., 2021; Zhao et al., 2020), wind speed (Kapica et al., 2024; Karnauskas et al., 2018; Lira-Loarca et al., 2021; Martinez and Iglesias, 2022; Qian and Zhang, 2021; Zhang and Li, 2021), and hydrological cycles (Cheng et al., 2022; Obahoundje et al., 2024; van Vliet et al., 2016; Yang et al., 2021).

Assessing how different climate scenarios will affect these resources will allow policymakers and energy industry stakeholders to make more informed decisions about infrastructure development, resource management, and investment strategies. However, much of the existing research still presents a fragmented picture, and coherent comparisons

Table 3
The estimated risk levels after Girgibo et al., (2024).

Risk level	Range of estimated risks (Holma et al., 2018)	Definition of range (Holma et al., 2018)
6	> 4.0 = Extremely significant	Extremely high risk
4	2.0–4.0 = Very significant	High risk
2	1.0–2.0 = Significant	Medium risk
1	0.0–0.95 = Somewhat significant	Low risk
0	0.0 = Not significant	No risk

across different types of renewable energy, geographical regions, and emission scenarios are limited. In this regard, a recently published study has identified and estimated the relevant risks using a hybrid approach; an approach that combines expert assessment, quantitative analysis, and literature review, and its structure is presented in Table 3 (Girgibo et al., 2024, 2022).

The risks identified for solar, wind, and hydropower include extreme weather phenomena; wind speed; storms; global warming; temperature increases; ice melting; severe drought; increased precipitation; rising GHG concentrations; water temperature increases; sea level rise; ice thickness; high waves; and sea ice loss (Girgibo et al., 2024, 2022).

- **Onshore wind energy:** The highest risks include extreme weather, wind speed, and storms, with estimated risk levels of 2.7, 2.5, and 2.6, respectively (classified as very significant, risk level 4). Temperature increases show lower risk (0.7) (Girgibo et al., 2024).
- **Offshore wind energy:** Major risks include extreme weather (3.4), wind speed (3.1), and storms (3.3). Additional risks include high waves (1.8) and sea level rise (1.6), while other factors remain below 0.9, and some around 0.5 (Girgibo et al., 2024).
- **Solar energy:** Highest risks (risk level 2) include storms, extreme weather, and wind speed, with values of 1.4, 1.3, and 1.1, respectively, for both panels and collectors (Girgibo et al., 2024).
- **Hydropower:** Primary risks include drought (1.6), extreme weather (1.2), and global warming (1.2), while other factors are ~1.0, and lower risks include heatwaves (0.6) and water temperature (Girgibo et al., 2024).

In addition to hydro-climatic fluctuations, the future feasibility of hydropower may also be affected by infrastructure constraints and competition between sectors for water resources. Global assessments suggest that in some regions, future storage needs may exceed the actual capacity of reservoir expansion, a situation that could limit the reliability of hydropower even under relatively favorable climate conditions (Schmitt and Rosa, 2024).

Based on these risk assessments, the reviewed studies can be broadly classified into two categories: global studies and regional studies. Global assessments commonly employ CMIP6 and RCP/SSP frameworks to evaluate renewable-energy resources across multiple regions (Dutta et al., 2022; Feron et al., 2021). Several studies have also examined renewable-resource changes at the global scale using Earth-system and climate-model ensembles (Karnauskas et al., 2018; van Vliet et al., 2016). In contrast, regional studies rely more on local data and methods to more accurately reflect the specific variability of each region. However, this same feature leads to heterogeneity in scenarios, baseline periods and time scales, making it more difficult to directly compare results across studies.

The review conducted in this study shows that the majority of these studies have focused on renewable energies in Europe; 42% of all studies cover Europe, including research conducted in the Mediterranean basin and the seas surrounding Europe. This is followed by significant research efforts in the United States, China and Africa, each accounting for around 12.5% of the studies. This spatial distribution suggests that the study of the effects of climate change on renewable energy systems is not regionally balanced, and there are clear differences in the level of research attention between different regions of the world.

Furthermore, the results of this review also indicate a methodological shift, in that there is now an increased tendency to use CMIP6 over CMIP5 (Coupled Model Intercomparison Project Phase 5) compared to previous reviews (Jung and Schindler, 2022; Russo et al., 2022; Solaun and Cerdá, 2019). In many older studies, assessments were largely based on a limited number of regional climate models fed from CMIP5 GCMs (General Circulation Models), often focusing on the pessimistic RCP8.5 scenario. However, the present analysis shows that about half of the studies reviewed now use CMIP6 and consider a more diverse range of scenarios, including SSP2–4.5 (Shared Socioeconomic Pathway) and SSP5–8.5. Additionally, the implemented emission scenarios in CMIP6 are based on integrated SSP–RCP frameworks, providing a more detailed description of future society's socioeconomic evolution and a broader range of potential futures compared to CMIP5 (IPCC, 2021). Several studies have demonstrated improved historical climate performance of CMIP6 relative to CMIP5 (Lun et al., 2021; Khadka et al., 2022). Similar conclusions have been reported in multi-model evaluations and probabilistic assessments (Thorarinsdottir et al., 2021; Ma et al., 2024).

Because projected renewable-energy changes are highly region dependent, multi-model ensembles are generally preferred over individual GCMs or RCMs to better represent projection uncertainty. Regional studies often prioritize higher spatial resolution, whereas global studies emphasize larger climate-model ensembles to improve robustness.

4.2.1. Future evolution of renewable-energy droughts under climate change

The preceding sections have highlighted some of the historical features of renewable-energy droughts in various regions, but it is one of the most critical challenges in long-term energy-system planning to understand how these events may change in the future in response to climate change. The Shared Socioeconomic Pathway (SSP) scenarios and CMIP6 climate projections are increasingly used in recent studies to assess future changes in renewable-resource availability, frequency of renewable-energy droughts, and vulnerability of power systems. In the literature, future changes are strongly region-specific, but a common characteristic is that the higher-emissions scenarios tend to lead to larger changes in renewable resources and to increased risk of renewable-energy droughts compared to the lower-emissions scenarios. Typically, studies with SSP1–2.6 have relatively small departures from historical conditions, while studies with SSP2–4.5 have moderate regional changes, and studies with SSP5–8.5 or equivalent high-emission scenarios have the greatest changes in the variability of renewable resources, hydropower availability, and compound low generation events. In addition to climatic changes, future risks are also growing to be more dependent on interactions between growth of electricity demand, increasing renewable energy shares, storage capacity, and transmission capacity. Renewable-energy droughts are becoming more known as a system-level phenomenon in which climate change, energy demand, storage capacity, and transmission infrastructure all play a role in future vulnerability, across all regions (Wilczak et al., 2025; Kittel and Schill, 2026). Historical drought characteristics of renewable energy resources and climate scenarios are summarized in Table 4.

4.2.1.1. Asia. Asia is currently the source of some of the most complete records of future drought evolution of renewable energy. Previous studies suggest that the droughts in renewable energy resources in China are seasonally asymmetric: wind droughts are mainly concentrated in the summer and autumn, while solar droughts are concentrated in the winter (Jiang et al., 2023; Liu et al., 2023; Sun et al., 2024).

Renewable-energy drought risk is projected to grow in all assessments across the range of warming scenarios, based on the use of the CMIP6 models. Based on the use of the CMIP6 models, the assessments consistently show an increase in the risk of renewable-energy droughts with stronger warming scenarios. Residual-load droughts, high-demand energy droughts, and compound low-wind/low-solar events are expected to increase in frequency and severity in China, particularly for SSP3–7.0 and SSP5–8.5. The variability of renewable resources is more relevant to future drought severity than resource changes, as it interacts with the growth of electricity demand (Zhu et al., 2024b; Zuo et al., 2024; Wang et al., 2025). These concerns are further intensified by changes in the renewable-resource base. The country's solar and wind resources are projected to have moderate declines but high regional variations, and hydropower is expected to rise in some basins in the Himalayan region and drop in some drought-stressed basins (Wu et al., 2022; Zhao et al., 2020, 2022; Zhu et al., 2025; Kim et al., 2022). By the end of the century, the generation loss of hydropower plants in China could reach more than 20% in severe drought years, with over 25% of the plants facing such losses (Zhao et al., 2023).

Evidence is scarce outside of China. Direct drought assessments for renewable energy in Central Asia are generally lacking, though recent studies using the climate models from the Coupled Model Intercomparison Project 6 (CMIP6) suggest significant changes in the suitability of wind and solar resources in the near future under scenarios of SSP2–4.5 and SSP5–8.5 (Broomandi et al., 2026a, 2026b). These studies are not quantitative in terms of energy droughts but indicate that climate change may affect the reliability of renewable resources and make them more susceptible to droughts in dryland continental climates in the future. As a whole, based on Asian studies, the drought risk for the future renewable energy sector is likely to be higher than the historical period, and the increase is expected to be more significant in scenarios with high emissions and under conditions of high climatic variability (Wang et al., 2025; Zuo et al., 2024).

4.2.1.2. Europe. The most well-studied area for renewable-energy droughts in Europe is for Dunkelflaute events and compound wind–solar deficits. Winter renewable-energy droughts are always shown in history to pose the greatest risk to the system as periods of low wind and solar generation are often accompanied by high electricity demand (Kittel and Schill, 2024; Van Duinen et al., 2025).

Seasonal shifting of the characteristics of renewable-energy droughts is projected to be significant in the future. The response of solar

Table 4
Comparison of historical renewable-energy drought characteristics and projected changes under future climate scenarios.

Region	Resource	Historical Characteristics	SSP1-2.6 / Low Emissions	SSP2-4.5/ Intermediate Emissions	SSP5-8.5 / High Emissions	References
China	Wind–Solar	Wind droughts mainly occur during summer–autumn; solar droughts peak in winter; compound events already frequent	Compound low-wind/low-solar events increase by ~12.4% relative to historical conditions	Increasing renewable-energy drought risk; regional PV declines and growing residual-load drought risk	Compound events increase by up to ~60.2%; PV declines up to ~6% in some regions; strongest increases in western and high-elevation regions	Wang et al. (2025); Zuo et al. (2024); Zhao et al. (2020); Wu et al. (2022)
Europe	Wind–Solar	Winter Dunkelflaute events dominate renewable-energy drought risk	Smaller departures from historical conditions	Increased winter/ autumn solar scarcity and moderate wind-drought changes	Up to + 20–70 additional winter/ autumn solar scarcity days; larger seasonal redistribution and stronger drought intensification	Kapica et al. (2024); Bloomfield et al. (2021); Dolores-Tesillos et al. (2024)
North America	Wind–Solar	Regional wind and solar droughts with strong spatial variability	Limited direct evidence	Redistribution of wind and solar resources; modest changes in some regions	Wind-resource declines of 30–40% in parts of eastern U.S. and northern Canada; increasing adequacy risks under compound extremes	Martinez and Iglesias (2022); Costoya et al. (2023); Sundar et al. (2024)
Central Asia	Wind–Solar	High renewable-resource potential but no explicit renewable-energy drought assessments	Not assessed	Scenario-dependent shifts in wind and solar suitability; moderate changes in site stability	Greater reductions in stability and stronger resource redistribution under SSP5–8.5	Broomandi et al. (2026a),b)
Global	Solar PV	Strong regional variability in solar resources	Some high-latitude gains; limited changes in many regions	Declines of 5–10% projected for India and China; increases of 2–5% in Europe and the Americas	Increased low-PV days (~16%); over half of global land areas show declining PV potential; tropical regions may lose 10–15% solar output	Dutta et al. (2022); Chen et al. (2024); Adigun et al. (2025)
Global	Onshore Wind	Strong regional contrasts in wind resources	Limited global changes	Declines across several Northern Hemisphere mid-latitude regions	Reductions of 8–18% across parts of the central U.S., Europe, Middle East, and Central Asia; increases in Brazil and Australia	Karnauskas et al. (2018)
Global	Offshore Wind	Historically underrepresented in energy-drought studies but generally characterized by higher capacity factors, lower variability, and stronger complementarity with solar and hydropower than onshore wind.	Small changes with localized gains in several basins.	Mixed regional responses and seasonal redistribution of offshore resources.	Regional declines in parts of the Mediterranean and European seas, but offshore resources generally remain more stable than onshore wind and continue to support energy-system resilience through diversification and complementarity.	Borba et al. (2023); Costoya et al. (2022); Jurasz et al. (2020); Martinez and Iglesias (2023); Weiss et al. (2020); Lee et al. (2025); Zhu et al. (2025)
Global	Hydropower	Strong dependence on streamflow variability	Smaller hydrological impacts	Mixed basin responses	Largest hydropower losses in drying regions despite global generation gains of 2.4–6.3% by the 2080 s	van Vliet et al. (2016)
Europe	Hydropower	Historically strong north–south gradient	Smaller inflow changes	Southern inflows decline (~20%) while northern inflows increase (~14%)	Southern inflows decline by ~31%, northern inflows increase by ~21%; major summer losses and winter shifts in generation	Gøtske and Victoria (2021); Ramião et al. (2023); Wechsler et al. (2023)
Asia	Hydropower	Basin-dependent variability	Moderate increases in some Himalayan basins	Mixed basin responses	National generation increases in some regions (e.g., China), but > 25% of plants may face > 20% generation reductions during severe droughts	Fan et al. (2020); Zhao et al. (2023); Kim et al. (2022)

resources to drought is expected to be negative in summer and positive in autumn and winter, and the response of wind resources is expected to be regionally variable. A number of studies show that the drought risk for renewable energy in winter has been rising over northern and central Europe, especially when emissions are higher (Kapica et al., 2024; Dolores-Tesillos et al., 2024). The projections for hydropower confirm a high north–south gradient. The inflows and generation potential in northern Europe is projected to rise, while southern Europe could see significant decreases in runoff and hydropower production (Gøtske and Victoria, 2021; Ramião et al., 2023). Offshore wind resources seem to be relatively stable in some areas but also have significant climate change sensitivities, especially in Mediterranean basins in SSP5–8.5 (Martinez and Iglesias, 2023; Lira-Loarca et al., 2021). In general, European research shows that the impacts of future climate will gradually increase from RCP4.5 to RCP8.5 and that future system resilience will increasingly rely on storage deployment, transmission expansion and diversified renewable portfolios (Van Duinen et al., 2025; Kittel and Schill, 2024; Kapica et al., 2024).

4.2.1.3. North America. Many of these vulnerabilities are expected to be exacerbated by climate change, according to future assessments. The wind and solar forecasts show significant spatial variation. High emissions scenarios can lead to substantial reductions in wind resources in parts of the eastern United States and northern Canada and increases in parts of Central America and Mexico. Changes in solar resources are typically less extreme, but are also spatially variable (Martinez and Iglesias, 2022; Costoya et al., 2023).

Drought impacts are expected to grow on hydropower systems, especially in the west of the United States. Under the future drought scenarios, the generation capacity will significantly decrease, and the economic loss will increase, particularly when the renewable generation is low, and the temperature is high, and the demand of electricity is also high (Qiu et al., 2023; Shuai et al., 2024; Sundar et al., 2024). Offshore wind resources are also found to be relatively less climate change sensitive than onshore wind resources and can support energy-system resilience in the future (Lee et al., 2025; Adul et al., 2025). The risk of renewable-energy droughts in North America will thus increasingly be shaped by interactions between wind, solar, hydropower, electricity demand, transmission infrastructure, and storage deployment (Sundar et al., 2024).

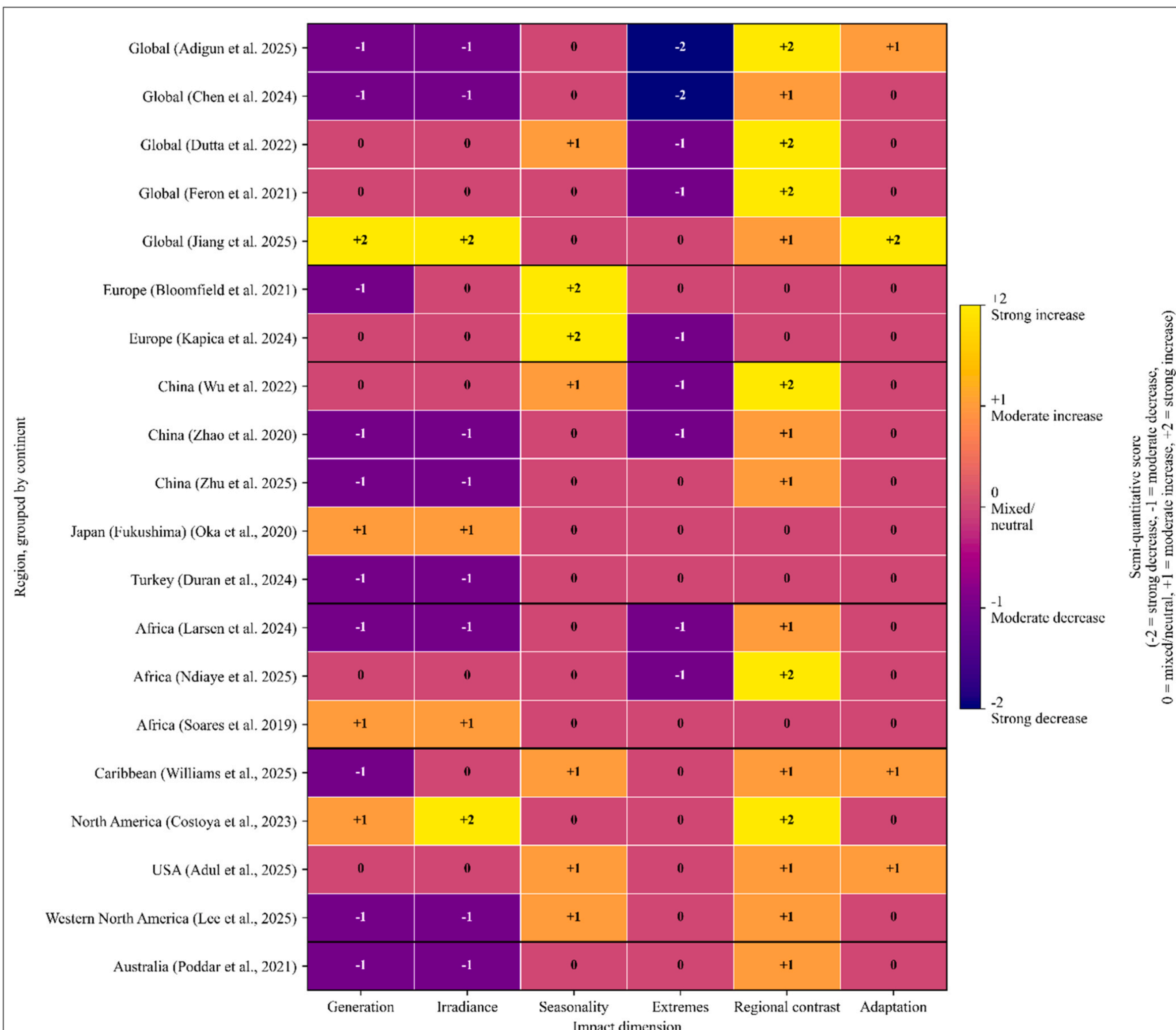


Fig. 8. Evidence matrix summarizing the direction and relative magnitude of climate-change impacts on solar energy generation across regions.

4.2.1.4. Other underrepresented regions. Although renewable energy is becoming increasingly important in Africa, South America, Southeast Asia and Australia, there are relatively few drought assessments available for the future in these areas. Research conducted in Africa indicates hydropower exposure and altered availability of renewable resources (Obahoundje et al., 2024; Larsen et al., 2024). In South America, there are reports of increasing climate sensitivity of renewable energy resources (Almeida et al., 2021; Soares et al., 2019). There are few existing climate future projections in Southeast Asia and Australia (Poddar et al., 2021; de Jong et al., 2021; Fournier et al., 2023). But at present, there is a lack of comprehensive climate-scenario assessments and a lack of consistency in methodologies makes it difficult to make robust interregional comparisons. It is thus still a huge need to extend the study of the drought impacts in these underrepresented areas to further understand the climate risks to renewable-energy systems in the future.

4.2.1.5. Comparison across SSP scenarios and future research needs. While there is significant regional variability, there are common patterns that emerge across future drought assessments for renewable energy. There is a consistent scenario hierarchy that can be seen throughout the regions. The smallest deviations from historical conditions are expected in SSP1–2.6, moderate conditions are expected in SSP2–4.5, and the largest deviations are expected in SSP5–8.5 or other high-emission scenarios, with regard to increases in renewable-energy droughts in frequency, duration, and severity. This is especially noticeable when compound low-wind and low-solar events occur in China, hydropower deficits in drying regions, and the redistribution of renewable resources in Europe and North America.

Second, future drought risk more clearly reflects complex interactions between climatic change and the energy-system's evolution. Greater penetration of renewables leads to greater reliance on weather-dependent generation, which, along with the availability of resources, will depend on how storage is implemented, transmission lines are expanded, demand is accelerated, and renewable resources are

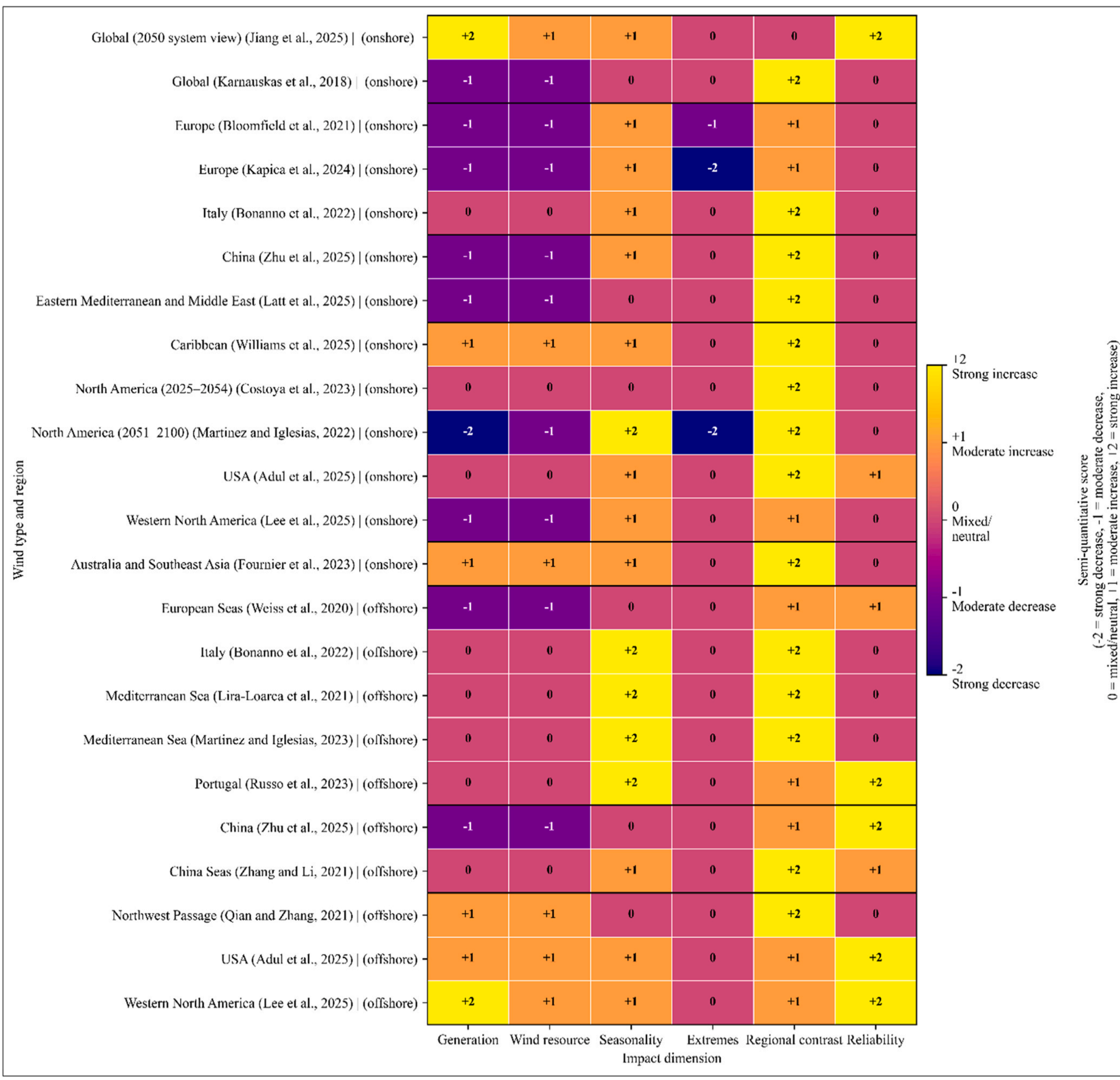


Fig. 9. Evidence matrix summarizing the direction and relative magnitude of climate-change impacts on onshore and offshore wind energy across regions.

diversified in future droughts. Third, future droughts in the renewable energy sector can be likely compound and widespread. Multi-regional shortages can make the use of geographical balancing approaches less effective and force the use of resources with longer time horizons, such as long-duration storage and flexible generation. However, there are key knowledge gaps. Projected future droughts in the renewable energy sector continue to be strongly clustered in Europe and China, and Southeast Asia, Central Asia, Africa, South America and Australia are relatively underrepresented. Furthermore, while the majority of future assessments are based on wind and solar resources, offshore wind, floating solar photovoltaics, concentrated solar power with thermal storage, and integrated multi-resource drought assessments are under-explored. Given the critical need to enhance long-term renewable-energy resilience, the extension of climate-scenario analyses to these regions and technologies is a key research priority. The previous subsection had synthesized the projected changes in renewable-energy droughts from a regional and system-level perspective. The technology-specific sections (Sections 3.4.2–3.4.4) build on this synthesis by considering potential impacts of climate change on specific renewable energy resources, including the physical drivers, regional impacts, and potential vulnerabilities that affect the future climate risk for renewable energy in particular.

4.2.2. Solar power projection

Fig. 8 presents an evidence matrix summarizing the direction and relative magnitude of climate-change impacts on solar energy generation across regions and impact dimensions, including generation, irradiance, seasonality, extremes, regional contrast, and adaptation. The figure shows that climate change does not produce a uniform response in solar energy systems; instead, its effects are expressed mainly through regional redistribution, seasonal shifts, and increasing extremes, while mean generation changes are often more moderate.

A global study examined PV power outputs using the RCP4.5 scenario for the period 2036–2065, compared to the baseline period of 1961–1990 (Feron et al., 2021). Moderate summer changes are projected, including a −4% decrease in parts of the Arabian Peninsula and a + 5% increase in central Europe. Elsewhere, changes remain smaller, including + 3% in the Atacama Desert, −2% in southeastern Australia, northwestern Africa, and the southwestern United States, + 2% in eastern China and southeastern Asia, and −3% in central Asia.

In winter, similar seasonal contrasts are reported, including a −4% decrease in parts of the Arabian Peninsula and a + 5% increase in central Europe. Elsewhere, changes remain smaller, including + 3% in the Atacama Desert, −2% in southeastern Australia, northwestern Africa, and the southwestern United States, + 2% in eastern China and southeastern Asia, and −3% in central Asia (Feron et al., 2021). Another global study assessed PV potential using CMIP6 SSP1–2.6, SSP2–4.5, SSP4–6.0, and SSP5–8.5 relative to the historical (1981–2014) for 2015–2100 (Dutta et al., 2022). In the near-future (2015–2040), the strongest changes occur during boreal autumn and winter. Declines of ∼5% (SSP1–2.6) to ∼10% (SSP5–8.5) are projected in the Indian subcontinent and China during autumn, driven by 1–7% reductions in solar radiation and increased cloud cover. Additional declines of 2–4% occur in the Middle East, parts of Asia, and African regions (e.g., Sudan, Ethiopia, Namibia). In contrast, Europe shows increase during spring, summer, and autumn, especially under SSP5–8.5—due to reduced cloud cover. North America exhibits −4–5% declines in western regions and ∼ + 2% increases in eastern regions, while South America shows + 2–4% increases across most seasons. Australia experiences increase during autumn and summer (Dutta et al., 2022).

In the far-future (2041–2100), similar spatial patterns persist with greater variability. Europe shows strong increases in spring and autumn, but winter declines up to 10% in Nordic regions under SSP5–8.5. North America exhibits widespread decreases, particularly in winter, while South America maintains increases across most seasons. Australia shows declines in most seasons except a slight winter increase. Africa experiences the strongest reductions, exceeding 10% in winter under SSP5–8.5 in regions such as Nigeria, Congo, and Angola (Dutta et al., 2022). These global patterns are consistent with Fig. 6, which indicates that the strongest solar-climate signals are associated less with uniform changes in mean generation and more with enhanced regional contrast, stronger seasonality, and increasingly unfavorable extremes.

Regional analyses further reveal localized responses often masked in global assessments (Table S3). In Europe, solar energy systems exhibit strong seasonal contrasts. Northern and northeastern Europe may experience extended solar scarcity in autumn and winter under RCP8.5, while southern Europe could see reductions exceeding 100 days of scarcity in France during summer (Kapica et al., 2024). Turkey is projected to experience slight reductions in surface radiation (Duran et al., 2024). In Japan, PV generation is projected to increase by up to 4.9% by 2070 due to reduced cloud cover (Oka et al., 2020). In China, however, solar-rich regions such as the Tibetan Plateau and northwest China may experience declines in PV potential, particularly in winter and spring, due to increased cloud cover and seasonal variability (Wu et al., 2022). These regional results also align well with Fig. 7.

The literature also indicates that structural adaptation can reduce the vulnerability of photovoltaic systems to climate-related hazards. Measures such as flood-resilient siting, improved structural design, hail protection, and snow-management technologies have been proposed to enhance system resilience (Jordan et al., 2023; Li et al., 2022b; Prieto-Miranda and Kern, 2024; Stenstadvolden et al., 2023). A more comprehensive discussion of mitigation and adaptation strategies is provided in Section 3.5. Overall, the dominant climate-change influence on solar systems remains the increasing variability in the timing, location, and reliability of energy production rather than a uniform decline in average output (Fig. 8).

4.2.3. Wind power projection

Fig. 9 presents an evidence matrix summarizing the direction and relative magnitude of climate-change impacts on onshore and offshore wind energy across regions and impact dimensions, including generation, wind resource, seasonality, extremes, regional contrast, and reliability. The figure shows that wind-energy responses are highly heterogeneous, with the strongest signals generally associated with regional contrast and seasonality rather than with uniform changes in mean generation. It also highlights a clear distinction between onshore and offshore systems, with offshore wind showing comparatively stronger reliability signals in several regions.

A global study investigated onshore wind power changes using the RCP4.5 and RCP8.5 scenarios from 2020 to 2100, showing a pronounced interhemispheric asymmetry, with decreases in the mid-latitudes of the Northern Hemisphere and increases in the tropics and subtropics of the Southern Hemisphere. Specifically, reductions are anticipated across northern mid-latitude regions, including the US, British Isles, northern Middle East, central and northern Asia, and far eastern Asia (Korean Peninsula and Japan), while increases are projected in Mexico and Central America, eastern Brazil, southeastern Africa (including Madagascar), the southeastern Arabian Peninsula (Yemen and Oman), India, Southeast Asia, and northeastern Australia (Karnauskas et al., 2018). Regionally, in the central US, wind power is expected to decrease by 8% (14%) by 2050 (2100) under RCP4.5 and by 10% (18%) under RCP8.5. In contrast, eastern Brazil shows increases of 21% (42%) under RCP8.5 by 2050 (2100), while northeastern Australia may increase by 41% by 2100 (RCP8.5 only) (Karnauskas et al., 2018). During the near-future (2020–2040), projected changes generally remain within 50–100% of baseline variability, except in eastern Europe and northern Asia where they exceed one standard deviation. By the end of the century, changes surpass internal variability—often several times larger. Seasonal contrasts persist, with reductions in the central US, Japan, and the Horn of Africa mainly in boreal winter, while increases in eastern Brazil, Madagascar, and the southern Arabian Peninsula peak in austral winter, and southern Africa and Southeast Asia show relatively

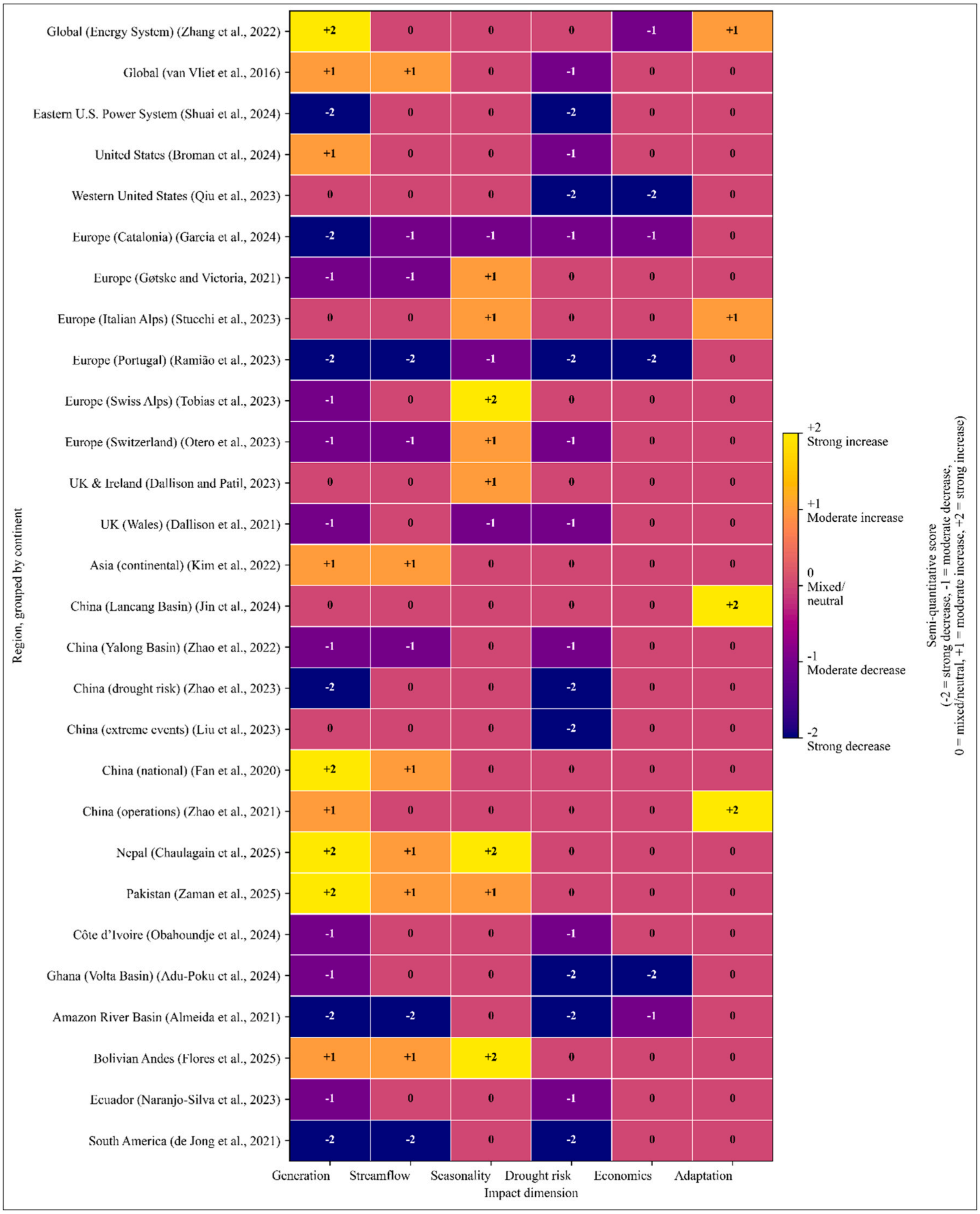


Fig. 10. Evidence matrix summarizing the direction and relative magnitude of climate-change impacts on hydropower across regions.

stable year-round increases (Karnauskas et al., 2018). These large-scale patterns are consistent with Fig. 7, which shows that global onshore wind studies are characterized by mixed to negative signals in generation and wind resource, but stronger positive signals in regional contrast, indicating substantial spatial redistribution of wind potential under climate change.

Regional analyses (Tables S4-**5**) further confirm strong spatial, seasonal, and scenario-dependent heterogeneity. Technology-specific adaptation measures are summarized in Section 3.5. In Europe, projections under RCP4.5 and RCP8.5 (2048–2098 vs. 1970–2020) indicate either stable or increased wind drought duration, particularly in spring. Northern regions may see slight increases, while summer droughts decrease across Spain and much of Turkey, with reductions exceeding 100 days under RCP8.5 (Kapica et al., 2024). In North America (CMIP6 SSP2–4.5 and SSP5–8.5; 2051–2060, 2091–2100 vs. 2005–2014), onshore wind power density declines across the United States and Canada. Under SSP2–4.5, reductions reach 30% in the Eastern United States (Wisconsin, Illinois, Michigan, Indiana, Ohio), while SSP5–8.5 shows overall decreases of 15% and up to 40% in northern regions (Quebec, Nunavut, Alaska). In contrast, increases occur in Central America and southern Mexico (up to 30%), Hudson Bay (up to 25%), and northern Mexico and Texas (up to 15%) (Martinez and Iglesias, 2022).

Under SSP2–4.5, substantial changes in monthly mean wind power density are expected in the mid-term (up to ±40%) and even more in the long-term (±50%), with significant spikes along the Pacific coast of Mexico (exceeding 15%) from February to August and, conversely, a strong decrease (up to 40%) in September. SSP5–8.5 suggests substantial variations in wind power density ranging from −40–60% in the mid-term and from −60–120% in the long-term future (Martinez and Iglesias, 2022). In Australia and Southeast Asia (CMIP6 SSP2–4.5 and SSP5–8.5; 2022–2031, 2056–2065, 2091–2100 vs. 2005–2014), onshore wind power density changes range from −20% to + 20% (SSP2–4.5) and −20% to + 40% (SSP5–8.5) in the near-future, increasing to + 70% and + 150% in long-term projections. However, Australia shows limited net change (−1.5% SSP2–4.5; −3.5% SSP5–8.5), while southern Borneo experiences increases of 60% and 150% (Fournier et al., 2023). Offshore wind projections in the Mediterranean (SSP1–1.9, SSP2–4.5, SSP5–8.5; 2030–2039, 2060–2069, 2090–2099 vs. 2005–2014) show increases up to 30% in the Ligurian and South Tyrrhenian Seas under SSP1–1.9, but decreases up to 20% in the Western Mediterranean, Alboran Sea, and Aegean Sea. Under SSP2–4.5 and SSP5–8.5, declines intensify to ~20–30% in western regions (Martinez and Iglesias, 2023). Seasonally, SSP1–1.9 yields localized increases up to 80% (Italian Peninsula, DJF/JJA), whereas SSP5–8.5 shows decline up to 40% in the Central Mediterranean (MAM, SON), with SSP2–4.5 indicating decreases up to 30% across multiple seasons (Martinez and Iglesias, 2023). EURO–CORDEX (CMIP5 RCP8.5; 2030–2060, 2070–2100 vs. 1979–2020) similarly projects increase of 10–20% in the central and southwestern Mediterranean, declining to 0–10% by century's end. Seasonal increases of 10–30% occur in spring (2030–2060), while winter declines of −5% to −20% affect the eastern Mediterranean (Lira-Loarca et al., 2021). The Gulf of Lion (historical 800–1000 W/m^2) shows minimal change (−5–5%), while the Alboran and Aegean Seas (400–500 W/m^2) increase by 15–20% and 0–10%, and the region north of Algeria (300–500 W/m^2) exhibits robust increases, identifying these as favorable offshore wind zones (Lira-Loarca et al., 2021).

4.2.4. Hydropower projection

Fig. 10 presents an evidence matrix summarizing the direction and relative magnitude of climate-change impacts on hydropower across regions and impact dimensions, including generation, streamflow, seasonality, drought risk, economics, and adaptation. The figure shows that hydropower responses are highly region-specific and are shaped not only by changes in mean generation and streamflow, but also by seasonal redistribution, drought intensification, and economic sensitivity. It also indicates that hydropower has one of the strongest negative drought-risk signals among the renewable technologies considered. Regional analyses (Tables S6) further confirm strong spatial, seasonal, and scenario-dependent heterogeneity.

A global study assessed the effects of changing climate and water resources on hydropower usable capacity from 2010 to 2100, comparing it to the baseline period of 1971–2000 under RCP2.6 and RCP8.5 (van Vliet et al., 2016). The findings projected increases in annual mean streamflow across high-latitude regions (northern North America and northern Asia) and large parts of the tropics (central Africa and southern Asia), with consistent increases over 25% of global land area by the 2050 s. However, decreases in streamflow are anticipated in the United States, southern and central Europe, Southeast Asia, and parts of South America, Africa, and Australia, covering about 8% of the global surface area. Water temperatures are expected to rise, with RCP8.5 predicting a greater average increase (1.0 °C) compared to RCP2.6 (0.6 °C). Significant warming is projected for eastern North America, Europe, Asia, and parts of southern Africa, with moderate increases in South America and central Africa due to enhanced evaporative cooling (van Vliet et al., 2016).

Spatial patterns of hydropower capacity changes align with streamflow impacts, showing increases in Canada, northern Europe, Central Africa, India, and northeastern China. However, 61–74% of hydropower plants are located in regions with projected streamflow declines, resulting in global annual capacity reductions of 1.7–1.9% (2020 s), 1.2–3.6% (2050 s), and 0.4–6.1% (2080 s). Monthly reductions may reach 8.9–17% by the 2050 s, with 5–22% of hydropower plants experiencing > 30% usable-capacity declines. Adaptation strategies, including increasing operational efficiencies, modifying cooling systems, and fuel switching, are therefore essential for maintaining water–energy security (van Vliet et al., 2016). Beyond climate-driven water availability, long-term hydropower deployment is also shaped by economic, technological, and structural dynamics. Using a global integrated multisector framework (GCAM), Zhang et al. (2022) show that hydropower generation may increase by 36–119% by 2050 relative to 2015. Nevertheless, across all scenarios, hydropower's share of total electricity declines relative to historical levels due to spatial constraints, cost competitiveness, and increasing wind and solar penetration. The Amazon basin faced increasing frequency of low-discharge interruptions and decreasing frequency of full-capacity operations (Almeida et al., 2021). Nearly 90% of proposed dams in the basin were expected to generate less power by century's end, with annual losses potentially exceeding $5 billion in Brazil alone. These impacts reflected basin-wide discharge reductions of 13% (RCP4.5) and 16% (RCP8.5). A contiguous U.S.-wide assessment using a CMIP6 multi-model ensemble (SSP5–8.5) indicates median generation increases of ~5% (2020–2039) and ~10% (2040–2059) relative to 1980–2019. However, drought risk intensifies, and ensemble medians may mask substantial drought-year reductions, particularly at interconnection and balancing-authority scales (Broman et al., 2024). CMIP6-based projections further show that drought-induced electricity-sector damages in the western United States may intensify. Under SSP3–7.0, annual damages reach ~USD 293 million, while even lower-emission pathways show persistent impacts (Qiu et al., 2023). At the system level, plant-level derating analysis shows hydropower capacity declines up to 45% during severe droughts, with regional output losses of ~23%. Thermoelectric losses range from 5 to 18%, while wind and solar remain comparatively resilient (<5%). Increasing drought frequency under SSP5–8.5 implies growing adequacy risks (Shuai et al., 2024).

At the continental scale, Asia's technical hydropower potential increases by ~6.1% (RCP4.5) and ~9.0% (RCP8.5) by 2071–2100, with > 10% gains across the Tibetan Plateau and Himalayas (Kim et al., 2022). In China, national projections indicate output increases of 3.2% (RCP2.6), 9.7% (RCP4.5), and 21.9% (RCP8.5) by 2100 (Fan et al., 2020). However, basin-scale analysis shows Ertan Reservoir generation declines of 4–6% due to runoff reductions driven by elevated evapotranspiration (Zhao et al., 2022). National-scale drought projections (SSI3 ≤ −0.84) indicate ≥ 20% reductions in more than a quarter of run-of-river plants by mid-century, intensifying by the late century (Zhao et al., 2023). The 2022 energy drought—historically a ~1-in-52-year event—may recur once per 6–10 years by 2071–2100 (Liu et al., 2023). Operational optimization offers partial mitigation. Reservoir rule adjustments may increase output by ~5% (Zhao et al., 2021).

In the Lancang River Basin, integrated hydro–wind–solar operations enable 13,600 MW of VRE in wet years, ~33.5% more than under dry conditions (Jin et al., 2024). In Switzerland, run-of-river plants face increasing output deficits under RCP8.5, with hot–dry events potentially doubling in frequency (Otero et al., 2023). In Wales, RCP8.5 projections show wetter winters and drier summers, reducing annual abstraction and run-of-river generation potential while increasing unmet water demand (Dallison et al., 2021).

In Côte d'Ivoire, projections under RCP4.5 and RCP8.5 (2040–2100) show plant-specific heterogeneity: Kossou dam exhibits significant annual declines (−6% to −11%), while Buyo and Taabo show increases (Obahoundje et al., 2024). Seasonal underperformance is most pronounced in MAM and JJA. In Ghana's Volta basin, SSP5–8.5 drought intensification reduces Akosombo generation (~6% below baseline) and increases electricity prices by + 1142% (Adu-Poku et al., 2024). These regional findings are well reflected in Fig. 8. Asia shows some of the strongest positive signals in generation and streamflow, particularly at continental and national scales, but these coexist with pronounced negative drought-risk signals in drought-focused and extreme-event studies. Europe is characterized by strong seasonality signals and mixed to negative generation and streamflow responses, indicating that redistribution of flow across seasons is a dominant feature. Africa and South America show generally weaker generation and streamflow signals, but stronger negative drought-risk and economic signals in specific basins, especially where hydropower systems are tightly coupled with declining runoff. Downscaled RCP8.5 projections indicate > 50% streamflow reductions in major basins (São Francisco, Tocantins),

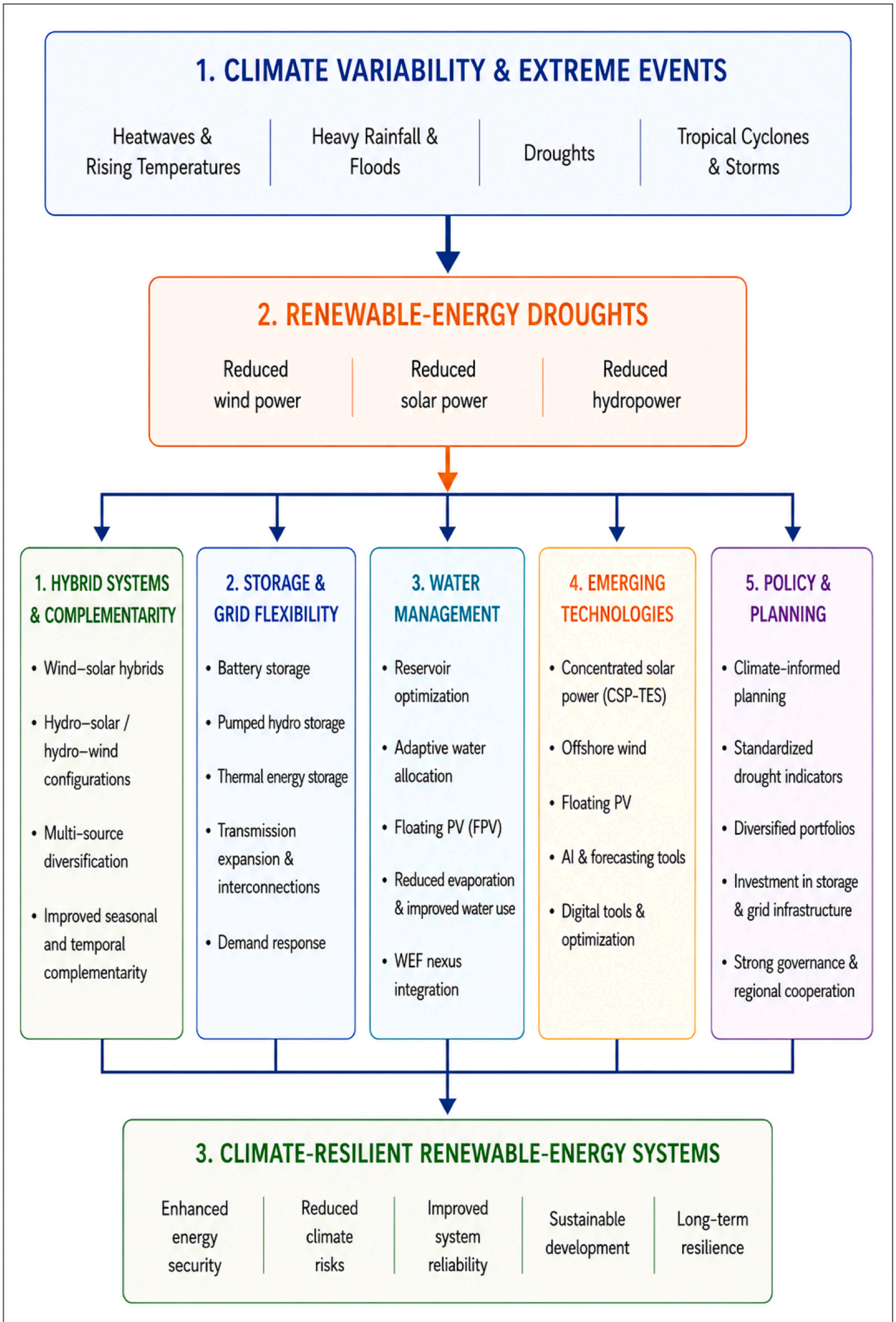


Fig. 11. Conceptual framework summarizing the principal mitigation strategies identified in the reviewed literature for enhancing the climate resilience of renewable-energy systems.

risking severe hydropower losses (de Jong et al., 2021). In Ecuador, fleet-average power factor declined by 9.4% (2010–2020), with additional projected reductions to 2050 under SSP pathways. Given hydropower's 87% grid share, diversification is recommended (Naranjo-Silva et al., 2023).

A comparative examination of the projected changes in solar, wind and hydropower clearly shows that the climate sensitivity and regional exposure of these three technologies are not the same. Among them, hydropower is the most vulnerable resource in terms of hydrology; Because basin-scale variability, increased drought frequency, and reduced evapotranspiration runoff can lead to capacity losses that can exceed 30–45% during periods of severe drought (van Vliet et al., 2016; Shuai et al., 2024; Zhao et al., 2023). In contrast, wind energy shows a hemispheric pattern that is related to large-scale changes in atmospheric circulation, with decreases projected in the mid-latitudes of the Northern Hemisphere, while some subtropical and southern regions will experience increases (Karnauskas et al., 2018; Martinez and Iglesias, 2022). Solar energy also experiences milder changes overall, but these changes are regionally distinct and are more influenced by cloud and radiation dynamics than by hydrological constraints (Feron et al., 2021; Dutta et al., 2022).

4.2.5. Integrated discussion and system-level implications

The collective evidence synthesized in this review indicates that future renewable energy systems will be shaped not only by gradual climatic shifts but increasingly by the intensification, persistence, and co-occurrence of climate extremes. Energy droughts—defined as prolonged periods of low wind and/or solar generation—are projected to increase in duration and spatial extent across multiple regions, particularly Europe, China, and parts of North America (Kapica et al., 2024; Jurasz et al., 2024; Kittel et al., 2024). Such events are usually triggered by large-scale atmospheric circulation anomalies; for example, blocking patterns and the establishment of persistent high-pressure systems are among their most important factors (Kautz et al., 2022). When such conditions occur, reduced wind speeds, enhanced air subsidence, and limited cloud variability can exacerbate the decline in renewable energy production. Moreover, growing evidence of the spread of energy droughts in interconnected hydropower, wind, and solar systems suggests that simultaneous and compound droughts are much more risky than individual disruptions to each source (Lei et al., 2024; Li et al., 2024).

Hydropower vulnerability is of a different nature, but equally complex. Although global estimates suggest an increase in average river flows at higher latitudes and in some tropical regions (van Vliet et al., 2016), studies conducted at the basin scale do not provide a uniform picture. At this scale, significant spatial variations are observed, and in some cases, droughts have led to severe declines in usable capacity and reduced reliability of generation (Shuai et al., 2024). In parts of South America and some regions of Asia, multi-year droughts and reduced runoff can severely limit hydropower generation, even if nominal increases in technical potential are observed (de Jong et al., 2021; Kim et al., 2022). At the same time, hydropower development is not only dependent on the hydrological situation. The future vulnerability of hydropower should therefore be seen not only as a consequence of climate change, but also as a result of water governance and competition between different sectors that use it.

For solar and wind energy, what is likely to happen in the future is more of a spatial realignment of resources than a uniform, general decline. CMIP6-based analyses show that changes in global photovoltaic potential are generally moderate seasonally, but the direction of these changes is not the same in all regions, with increases reported in Europe, while parts of Asia and Africa are experiencing declines, depending on the diffusion pathway (Dutta et al., 2022; Feron et al., 2021). Wind energy also shows a clear asymmetric pattern between the two hemispheres: a decrease is projected in the mid-latitudes of the Northern Hemisphere, but some areas of the Southern Hemisphere may experience an increase under high-emission scenarios (Karnauskas et al., 2018). However, by the end of the century, the magnitude of these changes in many regions will exceed the range of historical interannual fluctuations, suggesting that anthropogenic signals may gradually overcome intrinsic climate variability. Another important point is that ensemble means often mask extreme risks, as in dry years or when compound droughts occur, the production loss can be much larger than expected from the mean estimates (Broman et al., 2024; Shuai et al., 2024).

The transition from CMIP5 to CMIP6 can be considered an important methodological advance in renewable energy prospective studies. CMIP6 provides improved scenario representation and broader socio-economic pathways than CMIP5, although many regional studies still rely on relatively small model ensembles (Riahi et al., 2017; Eyring et al., 2019), a feature that has allowed for a more accurate assessment of scenario-dependent outcomes. However, many regional assessments still rely on a limited number of models, which increases structural uncertainty. Also, the increasing gap between the results of the SSP2 −4.5 and SSP5 −8.5 scenarios, particularly in relation to drought frequency and hydropower reliability, suggests that designing resilient energy systems will not be fully assessed without the simultaneous use of multiple models and scenarios.

Overall, these results provide three main messages for future planning of renewable energy. First, average changes in resource potential are not a sufficient basis for decision-making; what is more important is changes in volatility and extreme events. Therefore, planning frameworks should explicitly consider extreme risks, long periods of scarcity, and hydro-climatic composite events. Second, structural and infrastructural constraints, especially competition for water storage, may limit the adaptive capacity in hydropower-dependent systems (Schmitt and Rosa, 2024). Third, future resilience will depend more than ever on diverse and integrated portfolios; portfolios that combine variable renewables, storage technologies, and grid connectivity across regions. Accordingly, future research should focus on three main axes: (i) standardizing baseline periods to increase comparability across studies; (ii) develop process-based and multi-hazard modeling frameworks capable of resolving the interactions among atmospheric blocking, hydro-climatic drought propagation, and concurrent renewable energy deficits across multiple temporal scales; and (iii) quantify plant- and basin-scale capacity losses across diverse climatic regimes while explicitly incorporating operational rules, storage constraints, and infrastructure sensitivity. In addition, future studies should give greater attention to underrepresented regions, harmonize drought definitions across technologies, and integrate techno-economic and policy dimensions into climate-risk assessments so that resilience pathways can be evaluated more consistently and translated more effectively into planning practice.

4.3. Mitigation strategies for climate-resilient renewable energy systems

The growing number of climate extremes and renewable-energy droughts underscores a need for mitigation measures to make renewable-energy systems more resilient. The literature surveyed confirms that any single mitigation measure is not adequate to deal with the wide-ranging effects of climate variability. Resilience of the system, however, will require a multi-faceted approach of diversified renewable-energy portfolios, energy storage, flexible power systems, adaptive water-resource management, and emerging renewable-energy technologies. Fig. 11 presents an overview of the main mitigation pathways that were found in the studied literature.

4.3.1. Hybrid renewable-energy systems and resource complementarity

Complementary renewable-energy resources are one of the most widely recommended strategies. Hybrid systems include wind, solar, and hydropower, which alleviate the reliance on each type of renewable energy and enhance generation reliability by taking advantage of the temporal and seasonal variability of renewable resources (Jurasz et al., 2020; Gonzalez-Salazar and Poganietz, 2022). There are several studies demonstrating that using several renewables can significantly reduce the impact and duration of renewable-energy droughts. Resource complementarity in Europe has been found to reduce the severity of renewable-energy droughts by a factor of 2–10 (Allen and Otero, 2023; Otero et al., 2022). Likewise, hydro–solar and hydro–offshore wind configurations are more flexible in Brazil during droughts, as they will reduce reservoir depletion and reliance on fossil-fuel backup generation (Borba et al., 2023; Caldeira et al., 2023). The results of these studies show that diversification of resources is one of the most effective strategies to improve long-term renewable energy resilience.

4.3.2. Energy storage, grid flexibility, and system operation

Another key element of a climate-resilient renewable-energy system is energy storage and grid flexibility. Both battery storage and pumped-storage hydropower, thermal-energy storage and increased transmission interconnections mitigate short-term renewable-energy deficits, which are caused by spatial and temporal variability in renewable generation (Palacios et al., 2020; Pascual et al., 2022). Some European studies suggest that further increases in resilience to renewable-energy droughts will be reliant on storage deployment, the expansion of transmission networks and geographically distributed renewable portfolios (Kittel and Schill, 2024; Kapica et al., 2024). Furthermore, adaptive reservoir operation can enhance the hydropower performance during drought and flood periods, by optimizing water allocation to ensure system reliability (Kim et al., 2022; Zhu et al., 2024a).

4.3.3. Water–energy integration and emerging technologies

Mitigation options are not just limited to traditional renewable energy technologies. Floating PV systems not only generate electricity but also help mitigate evaporation losses from reservoirs, offering significant water-saving benefits in water-stressed areas (Jin et al., 2023; Woolway et al., 2024). Likewise, concentrated solar power (CSP) systems with thermal-energy storage can deliver dispatchable solar energy, which is less prone to short-duration cloudiness than traditional photovoltaic (PV) systems (Palacios et al., 2020; Pascual et al., 2022). Additionally, offshore wind can help to enhance system resilience by supplying relatively stable wind resources and complementing hydropower and solar generation, especially in coastal areas (Borba et al., 2023; Costoya et al., 2022). These technologies are not yet widely used in drought assessments for renewable energy, but present tantalizing options for mitigating future renewable energy climate change risks.

4.3.4. Policy implications and future directions

Technological solutions alone are unlikely to eliminate renewable-energy drought risks. All reviewed studies highlight the need for climate-informed planning, standardised renewable-energy drought indicators and integrated assessment frameworks that incorporate multiple renewable resources. Climate change projections in high resolution, resource complementarity, storage expansion, and cross-sectoral strategies like the water–energy–food nexus should therefore be included in future energy planning, to ensure long-term energy resilience (Allen and Otero, 2023; Otero et al., 2022; Cuppari et al., 2026). Additional research in less studied areas, such as Central Asia, Southeast Asia, Sub-Saharan Africa, and South America, will also be key for creating mitigation strategies that can be applied at a global level.

In general, the available literature suggests that the best way to reduce the negative effects of renewable-energy droughts is to combine complementary renewable energy sources, flexible system operation, future storage technologies, adaptive water management, and climate-informed planning under an integrated framework of renewable-energy drought resilience.

5. Conclusion

This study provides a comprehensive synthesis of how climate variability and extreme weather events affect renewable-energy systems, showing that wind, solar, and hydropower resources are vulnerable to production declines across different regions. By bringing together evidence from more than 100 recent studies, the review shows that renewable-energy droughts are increasingly shaped by climate drivers such as the NAO, El Niño–Southern Oscillation (ENSO), atmospheric blocking, hydrological drought, and regional dust storms. Europe is particularly exposed to winter wind droughts, while northern Europe can experience solar-capacity declines affecting up to 24% of days in some cases. North Africa shows persistent solar and wind production shortfalls, whereas hydropower systems are increasingly affected by hydrological drought, changing snowmelt timing, and river-flow redistribution, which influence reservoir operation and long-term generation reliability under warmer climatic conditions.

The reviewed evidence further demonstrates that mitigation strategies, including hybrid renewable-energy systems, energy storage, grid interconnection, and resource complementarity, can substantially reduce renewable-energy drought impacts and improve overall system resilience. Nevertheless, significant challenges remain, including inconsistent energy-drought definitions, limited assessment of extreme climate scenarios, and insufficient integration of socio-economic and governance dimensions into climate-resilient energy planning.

This review should also be interpreted in light of several limitations. First, the synthesis is based on the available published literature, which remains geographically uneven, with Europe and China receiving substantially greater research attention than regions such as Central Asia, Southeast Asia, South America, and Sub-Saharan Africa. Second, considerable methodological heterogeneity exists among the reviewed studies, including differences in drought definitions, indicator selection, climate scenarios, baseline periods, and modelling approaches, which limits direct quantitative comparisons across regions. Finally, although an extensive literature search was conducted, the rapidly expanding nature of renewable-energy and climate research means that newly published studies may further refine current understanding of renewable-energy droughts. These limitations highlight the need for standardized methodologies, broader geographical coverage, and regular updates of evidence syntheses as the field continues to evolve. By synthesizing fragmented evidence across solar, wind, and hydropower systems, this review provides an integrated understanding of how climate variability, extreme weather events, and renewable-energy droughts jointly influence renewable-energy reliability across regions. It also highlights the methodological inconsistencies, geographical research gaps, and emerging technologies that should guide the next generation of climate-resilient renewable-energy assessments.

Based on the findings of this review, future renewable-energy planning should adopt standardized and harmonized energy-drought indicators, multi-model climate projections, particularly CMIP6 and future model generations, and integrated assessments that simultaneously consider solar, wind, hydropower, storage, transmission infrastructure, and socio-economic factors. Policymakers and system planners should prioritize diversified renewable-energy portfolios, hybrid renewable-energy systems, and climate-resilient grid infrastructure to reduce vulnerability to future renewable-energy droughts.

Future research should focus on developing harmonized energy-drought definitions and assessment methodologies, expanding climate-scenario analyses to underrepresented regions such as Central Asia, Southeast Asia, Sub-Saharan Africa, and South America, and evaluating emerging renewable technologies, including offshore wind, floating photovoltaics, and concentrated solar power with thermal-energy storage. Greater emphasis should also be placed on compound renewable-energy droughts, interactions within the water–energy–food nexus, and the integration of socio-economic, governance, and adaptation perspectives to support robust, evidence-based, and climate-resilient renewable-energy planning under future climate change.

Overall, this review moves beyond previous technology-specific and region-specific syntheses by providing an integrated framework that links climate variability, renewable-energy droughts, future climate projections, mitigation strategies, and emerging technologies, thereby offering a comprehensive foundation for future research and climate-resilient renewable-energy planning.

CRediT authorship contribution statement

Ivan Radelyuk: Writing – original draft, Formal analysis, Data curation. **Dorna Gholamzade Ledari:** Writing – original draft, Formal analysis, Data curation. **Parya Broomandi:** Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **David Galán-Madruga:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Michael Leuchner:** Writing – review & editing, Validation. **Ali Mozhdehi Fard:** Visualization, Formal analysis, Data curation. **Mehdi Bagheri:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Conceptualization.

Ethical Approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.egyr.2026.109722.

Data availability

Data will be made available on request.

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