2024 Year in Review:

Climate-driven Global Renewable Energy Resources and Energy Demand

WEATHER CLIMATE WATER

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IRENA
International Renewable Energy Agency

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Foreword

The global energy transition is accelerating, but the window to meet the goals of the Paris Agreement is closing rapidly. As the United Nations Secretary-General reminded us in his address “A Moment of Opportunity”, we are witnessing the dawn of a new energy era, one defined by an unstoppable shift towards clean, secure and affordable energy.

The UAE Consensus resulting from the twenty-eighth session of the Conference of the Parties (COP28) to the United Nations Framework Convention on Climate Change reaffirmed the scale of the challenge: tripling global renewable energy capacity and doubling energy efficiency by 2030 are both aspirational and essential to securing long-term prosperity and well-being.

The work in the present report is a continuation of the ongoing collaboration between the World Meteorological Organization (WMO) and International Renewable Energy Agency (IRENA). Building on previous editions, this *2024 Year in Review* deepens the understanding of how naturally occurring climate variability and long-term changes are shaping renewable energy resources and electricity demand worldwide. They are defining elements in the performance, reliability and planning of renewable energy systems.

Renewable energy, powered by the atmosphere and hydrosphere – sunlight, wind and water – continues to play a key role in the global energy transition. In 2024, installed renewable power capacity grew by a record 582 GW to reach 4 443 GW, with solar photovoltaic (PV) and wind together providing over two thirds of this expansion.

The year 2024 was the warmest on record, with global average temperatures reaching 1.55 °C above pre-industrial levels. The residual effects of a strong El Niño, record ocean heat and shifting atmospheric circulation patterns produced significant regional anomalies in wind, solar and hydropower resources. Southern Africa experienced exceptional gains in solar and wind potential, while hydropower generation in parts of Africa and South America declined under persistent drought conditions. Meanwhile, global energy demand rose sharply – 4% above the long-term average – driven by extreme heat events that amplified cooling needs.

The insights contained in this *2024 Year in Review* provide governments, regulators, utilities, investors and financial institutions with actionable knowledge to accelerate the renewable energy transition, while managing the complex risks of a changing climate. They also highlight the urgent need to close data gaps, strengthen observational networks and develop regional climate services – particularly in regions such as Africa, where renewable potential is vast but remains underutilized.

Through this collaboration, WMO and IRENA reaffirm their shared commitment to advancing climate-informed energy transition pathways. By bridging the fields of meteorology and renewable energy, this report supports countries in building resilient, equitable and sustainable power systems, ensuring that the growth of renewables not only mitigates climate change but also withstands its impacts.

We extend our sincere appreciation to the authors, reviewers and partners from WMO, IRENA and collaborating institutions for their invaluable contributions. Their work reflects the power of partnership in advancing the global renewable energy transformation – one that is informed by science, guided by foresight and grounded in resilience.

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Executive summary

Accelerating action to meet COP28 commitments: Scaling up renewable energy for a net-zero future

The global energy landscape is undergoing a profound transformation. To achieve net-zero emissions by 2050 and keep the 1.5 °C target within reach, the COP28 UAE Consensus calls for tripling global renewable energy capacity and doubling the rate of energy efficiency improvements by 2030. This year's WMO–IRENA *2024 Year in Review* provides compelling evidence that climate variability and change are already influencing the reliability and potential of renewable energy resources. In particular, 2024 offered both new records and critical lessons. It was the warmest year ever recorded, bringing with it intensified heatwaves, evolving atmospheric patterns and shifts in rainfall – all of which affected renewable energy supply and electricity demand across continents.

Now in its third edition, the present report applies a climate-informed framework built around four operational energy indicators: wind capacity factors (CFs), solar CFs, a precipitation-based hydropower proxy, and a temperature-derived energy demand proxy (namely, Energy Degree Days (EDD)). By comparing 2024 conditions to the 1991–2020 climate reference period – both globally and regionally – the report quantifies anomalies and highlights their implications for energy systems. Monthly variability and seasonal forecasts are also analysed to provide insights into intra-annual shifts and to underscore the importance of early warning capabilities.

Climate variability as a strategic risk for clean energy transition: Global climate conditions in 2024

The year 2024 was shaped by the tail end of a strong 2023–2024 El Niño and continued long-term warming. Global average temperatures were 1.55 °C ± 0.13 °C above pre-industrial levels, and the energy demand proxy rose by 4% above the 1991–2020 mean – surpassing 20% in heat-sensitive regions such as Western and Central Africa, South-East Asia and parts of South America.

El Niño played a key role in shaping regional energy outcomes. In Southern Africa and eastern South America, it suppressed rainfall and enhanced solar irradiance due to reduced cloud cover, thereby boosting solar PV generation. Conversely, it strained hydropower systems. In South Asia, El Niño disrupted the monsoons, leading to reduced wind and solar PV generation and elevated cooling demand. Meanwhile, Eastern Africa experienced above-average rainfall and corresponding hydropower gains, likely due to the combined influence of a weakening El Niño and a moderately positive Indian Ocean Dipole (IOD).

Evidence from 2022–2024 key energy indicators: Climate variability shaping the energy mix

Figure A (identical to Figure 10 in the main report) synthesizes percentage deviations from the climatological mean for the four energy indicators for the years 2022 to 2024. The figure reveals important insights:

- **Wind power CF** anomalies showed substantial (several percentage deviation points) year-to-year regional variability. For example, a 5% CF anomaly in East Asia, where wind capacity exceeds 550 GW (mostly in China), could equate to power for approximately 15 million households.

- **Solar power CF** anomalies were more modest in magnitude, reflecting both its lower baseline CF (approximately 0.13 versus approximately 0.26 for wind) and lower inter-annual variability. Still, a 2%–3% variation in Oceania – where solar capacity approaches 40 GW (mostly in Australia) – could offset demand for over 250 000 households, roughly 2%–3% of Australia's population.

- **Hydropower anomalies**, driven by precipitation variability, showed the largest swings. In Central America and Mexico – home to over 20 GW of installed hydropower capacity – year-on-year variation reached 20%, equivalent to the annual electricity consumption of approximately 3.5 million households. This underscores the importance of hydrological early warning systems in hydro-dependent regions.

While three years is a limited sample, these findings underscore the critical role of climate variability in shaping renewable energy performance and energy demand on an annual basis.

Regional disparities: Climate-driven stress on energy systems

- **Southern Africa** experienced strong positive anomalies for both solar (+2%–6%) and wind (+8%–16%) CFs in 2024, driven by high solar irradiance and intensified synoptic pressure gradients. However, hydropower remained below average for the third year running, and energy demand reached record highs in most countries except South Africa.

- **Eastern Africa** saw positive hydropower anomalies from surplus rainfall, while solar and wind CFs were generally near or below average.

- **Central and Western Africa** recorded some of the highest EDD anomalies globally, exceeding +20%, with limited installed solar or hydro capacity to buffer the increase.

- **South Asia**, particularly India, registered high energy demand (+16% in October) alongside notable deficits in wind and solar CF, illustrating the compounded strain of climate variability on power systems.

- **South America** faced suppressed hydropower output and elevated energy demand – especially in Brazil and Paraguay – due to ongoing dry conditions and high temperatures.

Seasonal forecasts as a decision tool for energy security and resilience

This report presents the first evaluation of seasonal forecasts for energy indicators, with the European Centre for Medium-Range Weather Forecasts (ECMWF) model showing skill in predicting regional anomalies related to solar energy output and energy demand. For example, the July 2024 forecast correctly anticipated unusually high energy demand and below-average solar generation performance across Africa. These results illustrate the growing value of seasonal forecasts for operational planning, especially in climate-sensitive power systems.

Early warning of El Niño-Southern Oscillation (ENSO) transitions, rainfall shifts or heatwave risks can support load management, reservoir operations and cross-border electricity trade. Expanding access to reliable climate forecasts will be essential to increase system resilience and reduce volatility in both supply and demand.

Policy and operational implications

As countries are submitting their revised Nationally Determined Contributions (NDCs) under the Paris Agreement, integrating climate information into energy strategies is more urgent than ever. The present report offers four key operational priorities:

- **Data and observational systems –** Critical gaps remain in key variables like wind speed at hub height, solar irradiance and generation statistics. Harmonized data sharing, particularly through regional platforms, is vital to improve planning and management models.

- **Regional climate services –** Climate-informed energy atlases and early warning systems are essential to support the development and reliable operation of renewable energy systems in underserved regions like Africa.

- **Forecast Integration –** Seasonal climate forecasts should be systematically used to inform infrastructure scheduling, flexible generation planning and risk management for utilities.

- **Resilient NDCs –** Countries updating their NDCs should incorporate climate-risk-informed energy targets to ensure alignment with Paris Agreement goals and the COP28 First Global Stocktake (GST-1) outcome and growing exposure to inter-annual climate fluctuations and long-term changes.

From variability to resilience: Climate information for sustainable energy future

The *2024 Year in Review* demonstrates that climate–energy interactions are real, measurable and intensifying. Solar radiation variability, wind anomalies, precipitation shifts and temperature extremes are already reshaping the patterns of renewable energy output and electricity demand. As renewable capacity expands, the urgency to mainstream climate intelligence grows. This report offers governments, utilities and financial institutions a science-based foundation to design more resilient, equitable and climate-ready energy systems.

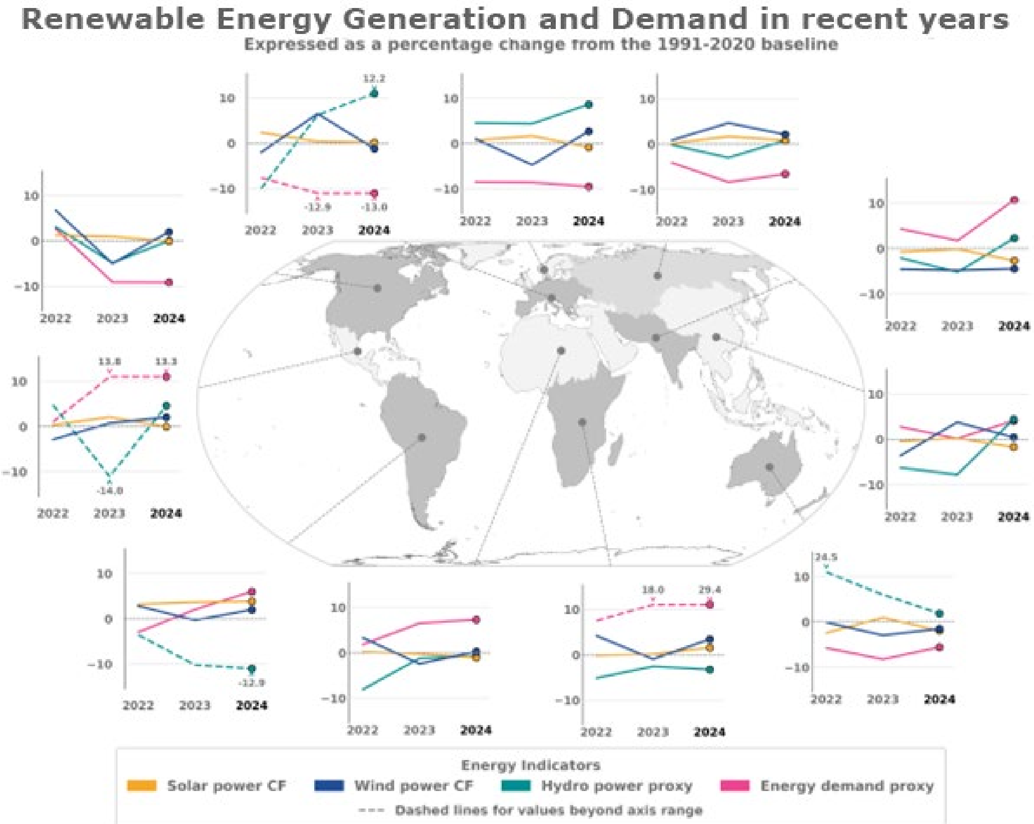

Figure A. Global annual averages of the anomalies for four energy indicators – wind capacity factor, solar capacity factor, a hydropower proxy and an energy demand proxy (EDD) – expressed as percentage deviations for 2022–2024 (namely, covering the present and the previous two *Year in Review* reports) relative to the average of the 1991–2020 reference period, using the same methodology as Figure 10 in the main report. Note: These anomalies reflect the influence of climate variability on the performance potential of different renewable sources and energy demand. They do not reflect changes in installed capacity or generation.

The boundaries and names shown and the designations used do not imply official endorsement or acceptance by WMO or the United Nations.

Key messages

1. **Climate variability should be integrated in national energy planning.** In 2024, measurable effects of climate variability were observed across all continents. Climate anomalies influenced the performance of solar, wind and hydropower systems, as well as energy demand. Notably, Southern Africa experienced large wind and solar energy gains, while parts of South Asia and Southern Europe recorded significant wind energy deficits. These patterns underscore the urgent need for policymakers to integrate climate intelligence into infrastructure investment and energy system planning.

2. **Resilient power systems need to be demand responsive.** Driven by unprecedented heat, the global energy demand proxy rose to +4% above the 1991–2020 baseline. This anomaly far exceeded previous years, with Western and Central Africa, South-East Asia, and much of South America experiencing annual anomalies exceeding +20%. These increases highlight the vulnerability of energy systems to temperature extremes and the need to design demand-responsive, resilient grids and larger power generation capacity in climate-sensitive regions.

3. **Regional climate drives variation in the renewable energy generation mix.** While global anomalies for wind and solar CF were modestly positive, i.e. +1% and +0.2% respectively, strong regional differences emerged. Southern Africa achieved gains of +8% to 16% (wind) and +2% to 6% (solar), whereas places like India and Eastern Africa experienced deficits. These shifts occurred against a backdrop of significant global capacity growth, highlighting the increasing importance of regional climate variations: solar PV capacity rose to 1 860 GW (+32% over 2023) and wind power to 1 130 GW (+11.4%).

4. **Regional hydropower risk management and forecasting need strengthening to address increasing variability.** Globally, the hydropower proxy anomaly rose to +1.6%, well above 2023 and 2022. Eastern Africa, Central Asia and many countries in Europe showed positive anomalies, while Southern Africa and eastern South America faced ongoing drought-induced deficits. The variability of hydropower output in El Niño and warming years highlights the importance of improved precipitation forecasts and water management systems, as well as diversifying energy mixes to reduce overreliance on hydropower and enhance overall system resilience.

5. **Compound climate risks in vulnerable regions must be addressed.** Southern Africa saw exceptional wind and solar CF increases but was hampered by depressed hydropower output and, in most countries, record-breaking energy demand. With rising renewable energy (RE) deployment across the African continent, this example illustrates both the opportunities and risks of climate-driven resource fluctuations in renewable-dependent systems.

6. **There is an imperative to mainstream seasonal forecasting into operational decisions.** Seasonal forecasts demonstrated useful predictive skill, particularly for energy demand and solar CF, as shown by the July 2024 forecast started on 1 June for Africa. Their broader adoption could help energy planners anticipate risk and reduce climate-related system stress. While the present report focuses on seasonal forecast scales, sub-seasonal forecasts also hold strong potential for operational decision-making and warrant further exploration.

7. **Regional atlases and improved climate data are critical to unlocking investment and guiding infrastructure development.** This is especially relevant for Africa, where renewable energy potential remains largely untapped. Despite its vast wind, solar and hydro resources, the continent still accounts for only 1.6% of global RE capacity, with many regions facing limited electricity access and high climate vulnerability.

8. **Closing operational data gaps is essential for strengthening climate–energy resilience.** In many regions, essential data – such as wind speeds at turbine hub height, solar radiation and even installed RE capacity – are either unavailable, inconsistently reported or of insufficient quality due to lack of standardized measurement and quality control practices. Closing these gaps through harmonized, open-access data-sharing platforms is critical to improving forecast skill, system modelling and climate-informed energy investment.

9. **Climate-informed planning is essential to Nationally Determined Contributions (NDC) 3.0 and COP28 targets.** The updated NDCs expected by 2025 must reflect a climate-resilient approach to the energy transition. This includes using climate-informed renewable energy scenarios and strengthening early warning systems to support the COP28 ambition of tripling RE capacity and doubling energy efficiency by 2030.

10. **Improving science–policy integration in resilient energy transition through the WMO–IRENA joint publication**. This joint report delivers a robust, replicable framework for assessing climate impacts on renewable energy systems. It can support policymakers, utilities, independent power producers and grid operators – particularly in the Global South – with actionable, evidence-based insights to guide equitable and resilient energy transitions.

1. Global perspective on renewable energy resources in 2024

1.1 Introduction

The global energy transition is now firmly recognized as one of the most pressing challenges of our time. With the goal of achieving net-zero emissions by 2050 as stipulated in the 2015 Paris Agreement, decisive and accelerated action is required. According to the Intergovernmental Panel on Climate Change (IPCC), achieving this target necessitates a dramatic reduction in fossil fuel use and a large-scale shift toward renewable energy sources. The window for effective action is narrowing, and reaching critical milestones by 2030 is essential. As echoed in the UAE Consensus resulting from the twenty-eighth session of the Conference of the Parties (COP28) to the United Nations Framework Convention on Climate Change, this includes tripling global renewable energy capacity and doubling energy efficiency improvements by the end of this decade.

The WMO *State of the Global Climate 2024* report reinforces the urgency of this transformation. The year 2024 marked the warmest on record, with the global near-surface temperature averaging 1.55 °C ± 0.13 °C above the 1850–1900 baseline. This warming was accompanied by record-setting values for greenhouse gas concentrations, ocean heat content, sea-level rise and widespread marine heatwaves. These shifts are not only indicators of long-term climate change, but also key drivers of annual variability in renewable energy generation and demand.

In this context, 2024 saw the strongest annual growth in renewable power capacity to date. Global installed renewable power reached 4 448 GW, a 15.1% increase (+584 GW) over 2023, and the largest year-to-year increase (IRENA, 2025a). This rapid growth is essential but not sufficient. Achieving the tripling target by 2030 also demands extensive progress in grid infrastructure, market design, operational flexibility and finance. Investment must expand to enable integrated planning that considers climate variability and long-term system resilience. The development of decarbonization pathways consistent with Paris Agreement principles must also centre on a just energy transition, ensuring inclusivity and equity.

To this end, energy security, affordability and resilience are emerging as interdependent priorities. Amid geopolitical instability and volatile fossil fuel markets, many countries are turning to renewables not only for emissions reduction but also as a strategy to strengthen domestic supply and mitigate future price shocks. In 2024, solar photovoltaics (PV) were, on average, 41% cheaper than the lowest-cost fossil fuel alternatives, while onshore wind projects were 53% cheaper. Onshore wind remained the most affordable source of new renewable electricity at 0.034 US dollars (US$)/kWh, followed by solar PV at US$ 0.043/kWh. These trends underscore how renewables are not only cost-competitive but also limit dependence on international fuel markets, improving long-term energy security. The need to anticipate and manage climate-related variability is therefore central to these efforts, and the business case for renewables is now stronger than ever.

WMO and IRENA have responded to this challenge by deepening collaboration. Following their Memorandum of Understanding signed at COP27 in 2022, the agencies committed to jointly advance science-based assessments and capacity development in support of the global energy transition. A core objective of this collaboration is to produce accessible, reliable and climate-informed insights into renewable energy performance and planning.

The present report is the third edition in the joint WMO–IRENA *Climate-driven Global Renewable Energy Resources and Energy Demand* review. As in previous editions (WMO-IRENA, 2023; WMO–IRENA–C3S, 2024), this year's analysis focuses on four core energy indicators – wind power, solar photovoltaic power, hydropower (as inferred from precipitation) and electricity demand (proxied via climate-derived indicators for heating and cooling). These are evaluated with respect to their deviations from the 1991–2020 climate baseline, as well as against the previous two years (2022 and 2023) for contextual comparison.

Installed capacities for these technologies continue to rise (Table 1). Wind power reached 1 130 GW in 2024, reflecting an 11.4% increase over 2023 and a 170% rise over the past decade. Solar PV capacity reached 1 860 GW in 2024 – growing 32% from 2023 and a staggering 730% from 2015. Solar PV is catching up to hydropower generation, and is now at nearly 50% of hydropower generation compared to 40% a year earlier. Hydro installed capacity itself rose modestly to 1 425 GW in 2024 (just over a 1% increase compared to 2023). These expansions form the technical backbone of the net-zero pathway, supported by cost reductions of up to 90% for solar PV and about 70% for wind between 2010 and 2024 in terms of levelized cost of electricity (IRENA, 2024; IRENA, 2025a).

Forecasts suggest that by 2030, wind and solar capacities will reach 3 000 GW and 5 400 GW, respectively, with hydropower projected to grow more slowly to 1 465 GW. For solar this would imply a year-on-year increase of just over 20%, well below the current +30%. By 2050, these figures are expected to climb to 7 800 GW (wind), 18 200 GW (solar) and 2 500 GW (hydropower) (IRENA, 2023). Again, for solar this would imply a modest year-on-year increase of just less than 10%, much smaller than current growth. These projections align with the Paris Agreement and COP28 global targets and reaffirm the centrality of renewable energy in future power systems. They assume major scaling of renewable energy technologies alongside improvements in energy efficiency, electrification and system flexibility.

The link between installed capacity and generation is characterized by capacity factors (CFs), which capture the impact of climatic and operational conditions. According to Ember (2025a), in 2024, hydropower generated 4 420 TWh (+4%), wind 2 500 TWh (+8%) and solar 2 130 TWh (+29%) compared to 2023.

Electricity demand is also rising, particularly in emerging economies. In 2024, global electricity consumption reached 30 850 TWh, a 3.9% increase over 2023 and 30% higher than in 2015 (Ember, 2025a). This demand is increasingly driven by electrification of mobility, cooling, industry and digital infrastructure. In developing economies – which house 85% of the global population – demand has grown by 2.6% annually over the past decade, powered by economic growth, demographic expansion and urbanization. Projections indicate global demand may approach 90 000 TWh by 2050, with renewables supplying about 91% of this demand under the IRENA 1.5 °C pathway (IRENA, 2024).

The role of renewable energy in meeting this demand must also be framed by spatial disparities. For instance, Africa possesses some of the world's highest potential for solar, wind and hydropower – yet remains underdeveloped, accounting for just 1.5% of global renewable energy (RE) capacity (IRENA, 2025a). Unlocking this potential, particularly through distributed systems, could drive industrialization and energy access across the continent. Detailed climate-informed resource assessments are essential to support this ambition.

Moreover, this annual analysis directly responds to calls from WMO Members for regular, authoritative reporting on the intersection of climate and energy. As noted in the 2022 WMO Energy Survey, stakeholders consistently request enhanced tools, data and narratives to integrate climate risk into operational energy decision-making.

Finally, the success of previous editions of this report has laid the foundation for an increasingly robust and influential tool. The 2024 edition aims to broaden outreach, particularly among policymakers, energy regulators and private sector actors, while reinforcing the scientific rigour and operational utility of climate-informed renewable energy planning.

1.2 Indicators and methodological approach

The present report presents the generation potential of RE and the associated energy demand using a set of simple, yet robust, indicators. These indicators are calculated at the national level and cover four key dimensions: onshore wind power (hereafter referred to as simply wind power),[1] solar photovoltaic (SPV) power, hydropower and energy demand.[2]

Table 1. Summary of global installed capacity for wind power (WP), solar power (SP) and hydropower (HP). The corresponding power generation is also shown. The total global electricity consumption is reported in the last row.

Sources: IEA (2024), IRENA (2025a), IRENA (2025b), EMBER (2025a) and https://ourworldindata.org/electricity-mix

	2015		2023		2024		2030	2050
	Power (GW)	Energy (TWh)	Power (GW)	Energy (TWh)	Power (GW)	Energy (TWh)	Power (GW)	Power (GW)
WP	420	830	1 020	2 310	1 130	2 500	3 040	10 300
SP	230	252	1 410	1 660	1 860	2 130	5 457	18 200
HP	1 210	3 980	1 410	4 230	1 425	4 420	1 465	2 500
Electricity consumption		23 660		29 680		30 850		50 000 TWh

Due to substantial differences in national size, cross-country comparisons must be interpreted with caution. In particular, country-level averages may mask important subnational variations, especially in large countries where renewable energy generation potential differs significantly across regions. Moreover, the indicators presented here give equal weight to all grid points within each country, without identifying the most suitable locations for renewable energy deployment. As a result, while national indicators offer a valuable high-level overview, more granular subnational or plant-level analyses are necessary for detailed planning and management decisions.

The primary objective of this publication is to evaluate the influence of climate variability – as distinct from long-term climate change – on renewable energy resources and energy demand. The analysis uses the 30-year period from 1991 to 2020 as the climatological baseline (also referred to as *climatology*), in line with WMO standards. This allows for the calculation of anomalies, or deviations, for the year 2024 relative to a well-defined historical reference, thereby also providing an indication of long-term trends. In addition to this baseline comparison, selected countries are assessed with respect to specific past years (e.g. 2022 and 2023), offering insights into both inter-annual variability and emerging shifts in climate-related energy indicators.

[1] The focus is on onshore wind power, as data are aggregated at the national land level. For most countries – except large ones like China or the United States of America – the signals for onshore and offshore wind power can reasonably be assumed to be similar.

[2] Detailed descriptions of how the indicators are computed can be found in Appendix 1 (Methodology), of the present report.

Given the strong seasonal dynamics that influence energy generation and demand, the report also examines anomalies in two representative months: February and July 2024. These are compared with the corresponding months in the 1991–2020 reference period, offering a deeper view into intra-annual variations and their energy implications.

The anomalies and variations presented in this report are directly relevant to energy resource planning, operational management and maintenance scheduling. Understanding the magnitude and geographic distribution of these climate-driven changes can help energy stakeholders anticipate operational risks, allocate reserve capacity and plan infrastructure upgrades. To support these efforts, the report includes a discussion of seasonal climate forecasts and their retrospective skill in selected regions. These forecasts offer a promising tool for climate-informed energy decision-making, providing stakeholders with early warnings of significant departures from normal seasonal conditions.

The report is structured to first provide global assessments of the four indicators at the country level, followed by a more detailed regional analysis across selected countries in Africa, Asia and Central and South America. The regional lens enables a more nuanced understanding of how multiple energy indicators co-vary and interact in specific geographic contexts.

Terminology note: Throughout the present report, the term *percentage anomaly* is used to describe changes in indicators for a specific year (primarily 2024) relative to the 1991–2020 average. In some contexts, related terms such as *variation*, *signal* or simply *anomaly* may be used interchangeably. This terminology reflects the analytical focus on climate-driven changes rather than absolute values of the energy indicators, which can be influenced by methodological differences in data processing or indicator formulation. The use of percentage anomalies ensures consistency and comparability across regions, time periods and technologies, making the findings more robust and relevant for climate–energy assessments.

1.3 Global overview

Before delving into the indicator- and country-level assessments, it is helpful to examine high-level, global year-to-year variations in the four key energy indicators over the past three years – namely 2022, 2023 and 2024. This short time series does not permit the detection of long-term trends, but it does reveal notable inter-annual variability, especially for hydropower and energy demand indicators, both of which exhibit changes exceeding 5% between 2023 and 2024. Wind and, to a lesser extent, solar power also show meaningful variations from year to year.

To illustrate, the approximately 2% decline in the global wind power capacity factor (CF) from 2022 to 2023, when applied to the current global installed wind capacity of around 1 000 GW, would – hypothetically, if the drop were uniform across the globe – represent a shortfall equivalent to the annual electricity consumption of roughly 10 million households. This example underscores how even seemingly modest percentage shifts in climate-driven CFs can translate into substantial energy supply impacts. As the global build-out of wind and solar continues, such year-to-year fluctuations become increasingly relevant to power system resilience and must be proactively managed.

This three-year comparison captures the transition from La Niña conditions in 2022 to a strong El Niño in 2023, and back to El Niño-Southern Oscillation (ENSO)-neutral conditions during most of 2024. These shifts, explored in more detail in the following sections, highlight the significant influence of large-scale climate drivers on renewable energy potential. The contrast also underscores the importance of incorporating dynamic, climate-informed strategies – including ENSO monitoring, multi-year variability assessments and regional teleconnection patterns – into operational planning and long-term energy development frameworks.

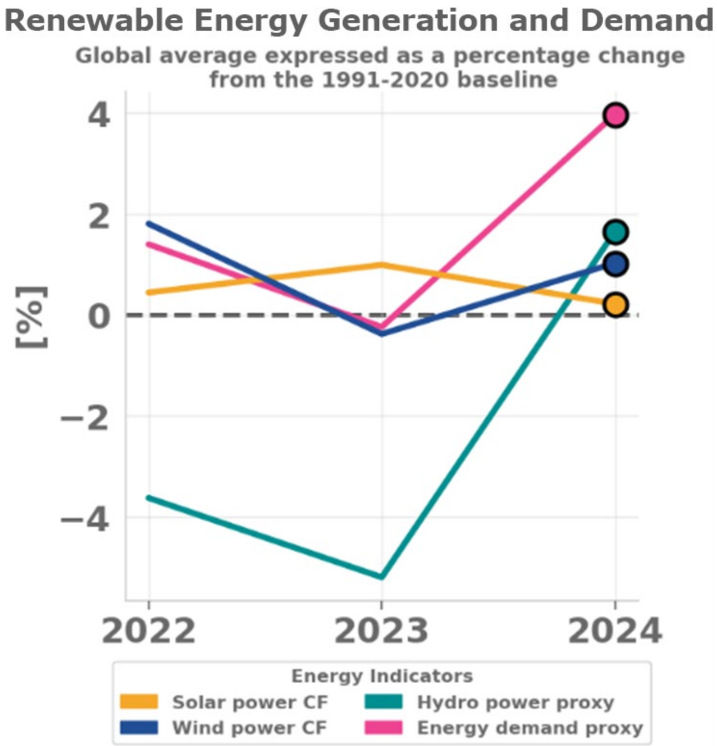

Figure 1. Global annual averages of anomalies for four key energy indicators – wind power, solar PV, hydropower potential and energy demand – expressed as percentage deviations relative to the 1991–2020 climatological reference period. The chart displays data for 2022, 2023 and 2024, providing a comparative view over the three most recent years assessed in this series of reports.

1.4 Key climate observations for 2024

In 2024, the globally averaged near-surface temperature was **1.55 °C ± 0.13 °C** above the 1850–1900 pre-industrial baseline – making it the **warmest year on record**, surpassing the previous record of **1.45 °C ± 0.12 °C** set just a year earlier in 2023 (WMO, 2025). This exceptional warming was sustained by persistently high monthly global temperature anomalies throughout the year, largely driven by a strong El Niño event that developed in mid-2023 and peaked between November 2023 and January 2024. This crest is consistent with the typical lifecycle of El Niño events, which tend to intensify during the boreal winter.

Beyond ENSO, other factors contributed to this warming, including reduced aerosol emissions, variations in the solar cycle and, most notably, the ongoing trend of anthropogenic global warming (WMO, 2025). These combined influences intensified climate-related pressures on energy systems worldwide, exacerbating challenges related to resilience, infrastructure reliability and long-term planning.

Sea-surface temperatures reached record levels across most of the world's oceans. Meanwhile, land-surface temperatures soared across large parts of the tropics, including South America and Western Africa, regions undergoing rapid expansion in solar and wind energy. Persistent marine heatwaves and widespread warming in the Tropical and North Atlantic Oceans had cascading effects on hydropower inflows, wind circulation regimes, cloud formation and solar irradiance, with direct consequences for electricity generation and demand. These events underscore the intrinsic link between climate variability and the operational performance of renewable energy systems, the central theme of this report.

The role of ENSO and other climate drivers

Following a prolonged La Niña phase (2020 to early 2023), a strong El Niño developed by mid-2023, peaking with a sea-surface temperature anomaly in the central Pacific Ocean of +2.0 °C. Although the El Niño began to weaken by mid-2024, returning to ENSO-neutral conditions by June, its earlier strength was sufficient to significantly influence global climate patterns and energy systems well into the first half of the year, and possibly beyond.

El Niño-related anomalies brought widespread dryness to Southern Africa and the eastern Amazon basin, both regions with substantial hydropower generation capacity. In contrast, Eastern Africa experienced above-average rainfall, potentially enhancing hydropower output. Similarly, high-pressure systems and subsidence in key regions enhanced solar radiation in places like Southern Africa and eastern South America, improving solar PV output but also intensifying heatwaves and the associated cooling electricity demand.

A positive Indian Ocean Dipole (IOD) – another key mode of climate variability strongly affecting countries bordering the Indian Ocean – was active in late 2023 and dissipated during early 2024. While short-lived, its delayed effects persisted into the first quarter of 2024, producing, in conjunction with El Niño, below-normal rainfall in Australia and enhanced rainfall in Eastern Africa. These hydrometeorological shifts influenced both hydropower supply and infrastructure stress, with dry spells placing stress on water-dependent systems and wet conditions contributing to flooding risks and maintenance challenges.

Other climatic influences with energy relevance in 2024

Several additional climate indicators reached new extremes in 2024, each with implications for renewable energy infrastructure:

- **Ocean heat content** continued its long-term rise, reaching the highest level ever recorded. Ocean warming can amplify tropical cyclone intensity, disrupt wind and solar energy patterns, and contribute to coastal flooding, thereby threatening coastal energy infrastructure.

- **Global mean sea level** rose to a new observed high. The El Niño event further elevated sea levels by several millimetres early in the year, which may affect tidal energy systems and coastal grid infrastructure.

- **Glacier mass balance** marked a third consecutive record year of decline (2023/2024), affecting seasonal hydropower generation in glacier-fed systems such as those in the Andes and Himalayas. This undermines long-term water availability and electricity reliability in many mountainous regions.

- **Sea-ice extent** in both the Antarctic and Arctic remained below average. The Antarctic minimum was tied for the second lowest on record. Though indirect, these changes alter global heat distribution, influence large-scale atmospheric circulation, and may affect energy supply stability in higher latitudes over the longer term.

In summary, the year 2024 serves as yet another stark reminder of the energy sector's exposure to climate variability and extremes. The confluence of a strong El Niño, rising greenhouse gas concentrations, marine heatwaves and persistent warming amplified risks across hydropower, solar and wind energy sectors, while driving spikes in electricity demand due to prolonged heatwaves.

1.5 Wind power capacity factor

Capacity factor (CF) remains one of the most direct and sensitive indicators for assessing how climate variability influences renewable energy generation. Expressed as percentage anomalies, CF compares performance of a given year against a long-term baseline – here, the 1991–2020 reference period. CF is used for both wind and solar power indicators.

For wind power specifically, CF anomalies reflect how climate-induced changes in wind speed at 100 metres above ground level – the typical hub height of commercial onshore wind turbines – affect potential wind power production.[3]

This analysis uses data from the Copernicus Climate Change Service (C3S) Energy Service, which employs high-resolution (0.25° × 0.25°) reanalysis datasets to compute monthly and annual CF anomalies over land globally[4] (starting from hourly data).

Annual wind CF patterns in 2024

The year 2024 was marked by distinctive shifts in wind resource availability, shaped in large part by the decline of the strong El Niño event, which weakened over the first part of the year, and neutral ENSO conditions, which returned by mid-year. This shift was reflected in regional atmospheric circulation, which adjusted in ways that either enhanced or dampened wind potential across different zones. Some of the signatures of these climatic drivers are shown in Figure 2, where the global annual wind power (WP) CF anomalies for 2024 are presented.

Due to evolving climatic conditions throughout the year, not all observed patterns can be directly attributed to specific climate drivers. However, a widespread increase in wind power CF can be observed: at a glance, there are more blue than brown areas, resulting in an average global CF anomaly of approximately +1% for 2024 (Figure 1).

Specifically, the spatial annual mean pattern reveals strong positive anomalies in several regions, most notably across Western and Southern Africa, and South-East Asia. Countries such as South Africa, Botswana, Zimbabwe and Mozambique recorded increases in CF of 8%–12% above the climatological norm. While ENSO influenced regional climate, the positive anomalies in Southern Africa are better explained by a combination of ENSO and the Southern Annular Mode (SAM).[5] The SAM, representing the north-south movement of the westerly wind belt encircling Antarctica, was in a negative phase during this period, typically associated with a northward shift of the mid-latitude westerlies. This shift increased the frequency of storm systems reaching Southern Africa and enhancing the likelihood of cold fronts reaching the region. Moreover, increased frequency of mid-latitude cyclones contributed to more intense than usual winds, particularly in April, with a marked increase in wind power CF. Specifically, in the case of South Africa, which has an installed wind power capacity of 3.4 GW, an average 10% increase in CF translates into nearly 1 TWh of additional generation over the year,[6] therefore enough to power around 200 000 households.[7]

Even higher positive anomalies, above 16%, were observed in Western and Central Africa (e.g. Côte d'Ivoire) and in South-East Asia (e.g. Malaysia), but these countries typically have low climatological wind speeds, so small absolute increases result in large percentage anomalies.

By contrast, 2024 brought negative annual CF anomalies to much of Mediterranean region, parts of the Middle East, South Asia, Eastern Africa and Central America. Countries such as the United Republic of Tanzania and Uganda in Eastern Africa, and Costa Rica and Nicaragua in Central America recorded reductions larger than 12% – partly due to El Niño in January/February, but also to persistent high-pressure systems in the second half of the year. If we take Costa Rica with its 400 MW of installed capacity, a reduction of more than 16%

[3] The wind power conversion model used is simplified compared to reality, as there exist many different wind turbine types, with a large range of hub heights. The simplified model here is intended to compare the year 2024 with the climatological period 1991–2020, and not to calculate actual values for a specific year (see Appendix 1 (Methodology), for additional details).
[4] Also, offshore wind CFs are computed by the C3S but are not considered here.
[5] Bureau of Meteorology: http://www.bom.gov.au/climate/about/australian-climate-influences.shtml?bookmark=sam
[6] Assuming an annual baseline CF of 0.3 and full operational availability
[7] Assuming an average annual household electricity consumption of 5 MWh: EMBER (2025b) and https://www.un.org/development/desa/pd/data/household-size-and-composition

(approximately 20%) in CF implies a loss of around 200 GWh in electricity generation, necessitating additional supply through imports or other sources to power 40 000 households.

Comparing 2024 with 2023 and 2022

When compared to the WP CF anomalies for 2022 and 2023 (Figure 22, in Appendix 3), the patterns observed in 2024 offer valuable context for interpreting inter-annual variability and potential climatic shifts. The year 2022, dominated by the final stages of a multi-year La Niña, featured widespread positive anomalies across the tropics and parts of the mid-latitudes, including Central and Eastern Africa and the western coasts of South America. These gains were driven by intensified trade winds and shifts in the Walker circulation, which reinforced wind productivity in several key developing regions.

By 2023, as the climate system transitioned toward El Niño, a partial reversal of these anomalies occurred with, for instance, many countries in sub-Saharan Africa experiencing reduced wind CF, while moderate gains appeared in regions such as Central-Eastern Europe, Mexico and parts of Southern Africa. It is also interesting to note that while countries like the USA experienced alternating positive and negative anomalies across the three years, reflecting shifting climate patterns, China maintained consistent positive anomalies.

Monthly variability: February and July 2024

To capture the intra-annual dynamics of wind variability, Figure 3 illustrates the wind power CF anomalies for February and July 2024 – two months representative of contrasting seasonal regimes, with many countries illustrating substantial seasonal differences in wind energy potential.

In February, strong positive anomalies dominated places like large parts of Asia, Southern Africa and Brazil, reflecting the lingering influence of El Niño. Analogously, an increased frequency of cyclonic systems over the North Atlantic brought stronger-than-average westerly flow across Europe, boosting wind generation in many Northern and Central European countries.[8] Meanwhile, areas such as Eastern Africa, the Middle East and northern South Africa experienced notable negative anomalies. These deficits coincided with a period of suppressed convective activity and weak monsoonal influence, leading to atmospheric stagnation.

By July 2024, the spatial anomalies had shifted markedly, reflecting the transition to ENSO-neutral conditions. Localized drivers played a more dominant role in modulating wind patterns. Southern and Eastern Africa recorded strong negative anomalies – up to −40% over a large area. The actual impact from the reduced power generation was small as the installed capacity is currently minimal in these countries (less than 500 MW, and most of it in Kenya), but again, it could be considerably larger over the next few years if a similar climate event occurred again. In this instance however, solar power would have compensated the negative anomaly, given the widespread positive anomaly over most of the same region, especially over Mozambique and Zimbabwe (see next section).

An exception to the negative anomaly in the region was South Africa, which experienced a considerably negative Southern Annular Mode, related to higher-than-usual winds. Other wide areas of negative anomalies were observed in eastern South America, Central Asian countries, Northern Africa and most of Europe. At the same time, moderate to strong positive anomalies emerged across western South America, Western and Central Africa, and Indonesia, noting, however, that wind speeds in equatorial regions (such as much of Central Africa and South-East Asia) are generally low, limiting the operational impact of CF anomalies. Overall, the juxtaposition of annual, February and July patterns offers important insights into the temporal complexity of climate impacts on wind energy. While the annual mean provides a useful baseline, it masks important intra-annual dynamics that can drive operational challenges and investment risks.

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[8] For a discussion about Europeans anomalies in 2024, see also the *European State of the Climate 2024*: https://climate.copernicus.eu/esotc/2024/renewable-energy-resources

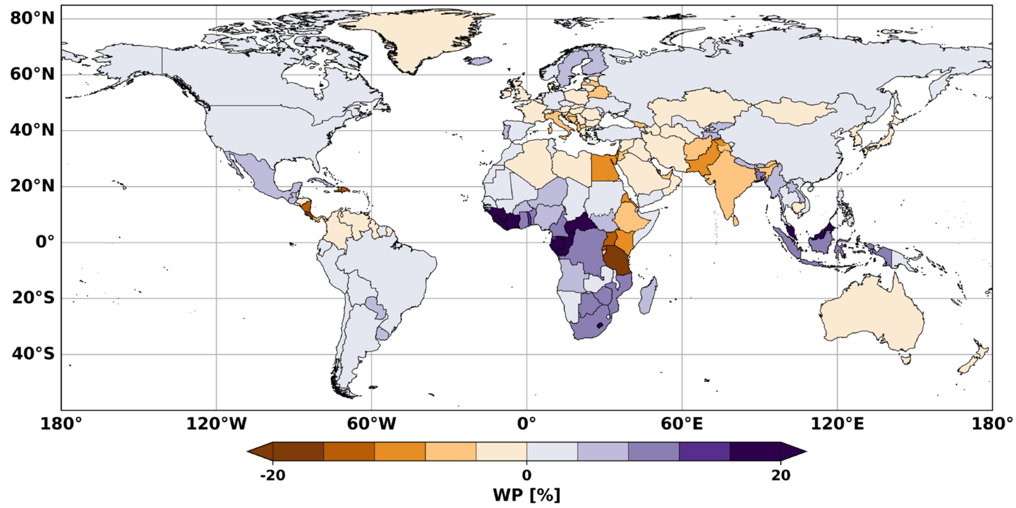

Figure 2. Global annual anomalies for the wind power capacity factor (expressed in %) for 2024 relative to the average of the 1991–2020 reference period. See Appendix 1 (Methodology) for assumptions made in the computation of wind power capacity factors.

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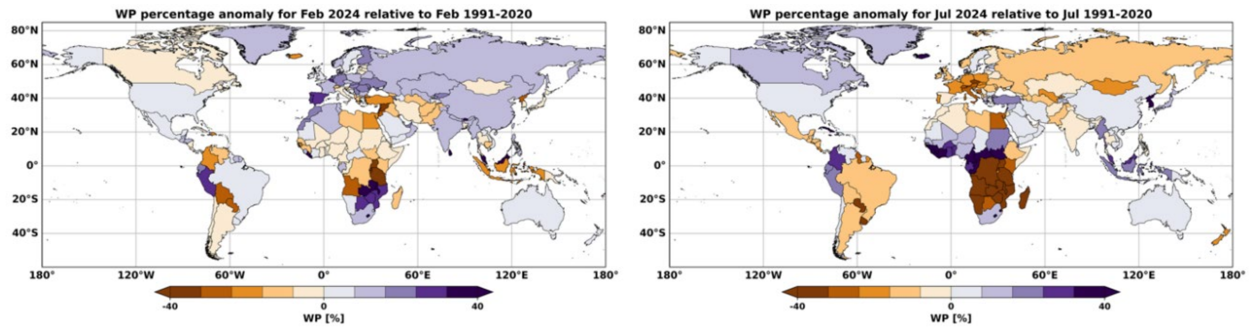

Figure 3. As in Figure 1, but for February (left) and July (right) 2024, relative to their average corresponding month in the period 1991–2020. Note the range of values is twice that of the annual mean.

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1.6 Solar power capacity factor

The solar photovoltaic (SPV) power capacity factor (CF), also referred to as SPV CF, is a key indicator for evaluating the effectiveness of solar resources across different regions and timescales. It is computed using a physical-statistical model that incorporates global solar irradiance, with efficiency adjustments based on air temperature and location-specific panel features (e.g. tilt angle), as adopted by the C3S Energy Service for both the global platform and the European Network of Transmission System Operators for Electricity (ENTSO-E) Pan-European Climate Database (PECD) (see Appendix 1 (Methodology) for additional details).[9] While the specific model formulation is important, the details themselves are however not critical, as the focus of the present report is on relative variations, rather than absolute CF values.

[9] It is worth noting that grid points with CF lower than 0.05 are not considered in country averages (see Appendix 1 (Methodology) for additional details).

Annual overview

In 2024, climate anomalies driven by the strong El Niño, combined with regional circulation changes, produced significant geographic variability in solar CF anomalies relative to the 1991–2020 reference period. These anomalies had a smaller range than wind power CF anomalies (±10% for SPV CF versus ±20% for WP CF). Globally, the annual SPV CF anomaly in 2024 was +0.2% (Figure 1). Although the actual locations of solar installations would determine real generation impacts, this anomaly could hypothetically represent enough additional electricity to supply over one million households, based on the current global installed capacity of 1 865 GW.

Positive annual CF deviations were recorded across large parts of West, Central and Southern Africa, and South America. These are regions that experienced above-average solar irradiance due to reduced cloud cover and persistent atmospheric subsidence, both associated with the mature El Niño phase, but which manifested also later in the year (Figure 4). Most anomalies ranged from +2% to +6%, with local values exceeding +8% in Guyana. In Brazil, where installed capacity reached 53 GW,[10] a 5% increase in CF could have provided enough electricity to supply approximately 800 000 households. Smaller positive anomalies, up to +2%, also occurred in Mexico, the USA, Western Europe and the Russian Federation.

Conversely, significant negative anomalies were observed across South Asia, South-East Asia, China, Australia, Northern and Eastern Africa, and parts of Western Europe. These areas experienced greater-than-normal cloud cover and increased precipitation. Most deviations ranged from –2% to –6%, with countries including the Islamic Republic of Iran, Pakistan and India showing anomalies of –2% to –4%. With 98% of their combined 100 GW installed capacity located in India, this reduction may have translated into a shortfall equivalent to the electricity demand of around 900 000 households.

Comparison with 2022 and 2023

Compared to 2024, the SPV CF pattern in 2023 shows similar regional structures but with shifts in anomaly sign for some key solar markets, such as Australia, China and Western Europe – moving from moderately negative to moderately positive (Figure 23 in Appendix 3). This is also reflected in a higher overall anomaly in 2023, equal to +1%. In contrast, 2022 – marked by persistent La Niña conditions – saw more widespread negative anomalies, particularly across Southern Africa, Australia and Central America. Despite this, the global anomaly for 2022 was +0.4%, slightly higher than in 2024, due to positive values in other high-capacity areas.

Notably, solar-rich countries like India – and high-potential countries such as Pakistan and the United Republic of Tanzania – recorded negative anomalies across all three years. This persistence underlines the importance of diversifying energy sources and considering climate variability in planning. Meanwhile, major markets such as the USA and South America (especially Brazil) consistently showed positive anomalies.

Monthly variability: February and July 2024

As with wind power, seasonal variations in SPV CF are illustrated through anomalies for February and July 2024 (Figure 5). In February, the spatial pattern broadly mirrored the annual trend. Southern Africa exhibited especially high positive anomalies, with Zimbabwe surpassing +16% and Zambia between +12% and +16%, although their current installed capacity remains low.

In contrast, large parts of Europe, Japan and the Republic of Korea experienced strong negative anomalies, with many countries around –16%. However, since solar resources are already low during winter months in these regions, the operational impact was minimal. More

[10] As an aside, Brazil has experienced a nearly exponential growth in solar power installation: only considering the last three years, it went from 25 GW in 2022 to 38 GW in 2023 and then to 53 GW in 2024.

concerning was the −8% to −12% reduction in Madagascar, though its solar capacity is only around 60 MW.

By July 2024, spatial patterns shifted, with some anomalies intensifying (Figure 5, right). Southern South America, especially Argentina and Uruguay, saw transitions from negative to positive anomalies – even though this occurred during their winter season. Positive changes were also noted in the United Republic of Tanzania.

Conversely, Australia, South-East Asia, the USA, Mexico, Central America, the Bolivarian Republic of Venezuela and Western Africa moved from mildly positive to significantly negative anomalies (some less than −12%), notably in Cambodia and Thailand, which have installed capacities of 0.9 GW and 3.4 GW, respectively. Ethiopia, Kenya, Yemen and Oman recorded anomalies between −4% and −8%; their combined capacity is modest (approximately 1.5 GW), with most concentrated in Yemen and Oman.

India, with its nearly 100 GW of SPV capacity, experienced a reinforced negative anomaly of −8% to −12%, resulting in a one-month electricity shortfall equivalent to the monthly consumption of around 3 million households.

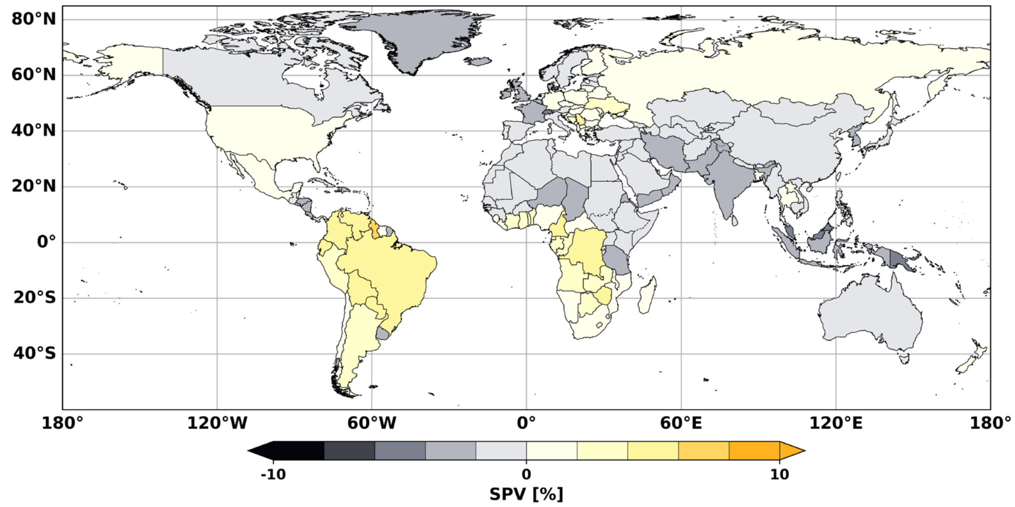

Figure 4. Global annual anomalies of SPV power capacity factor (in %) for 2024 relative to 1991–2020

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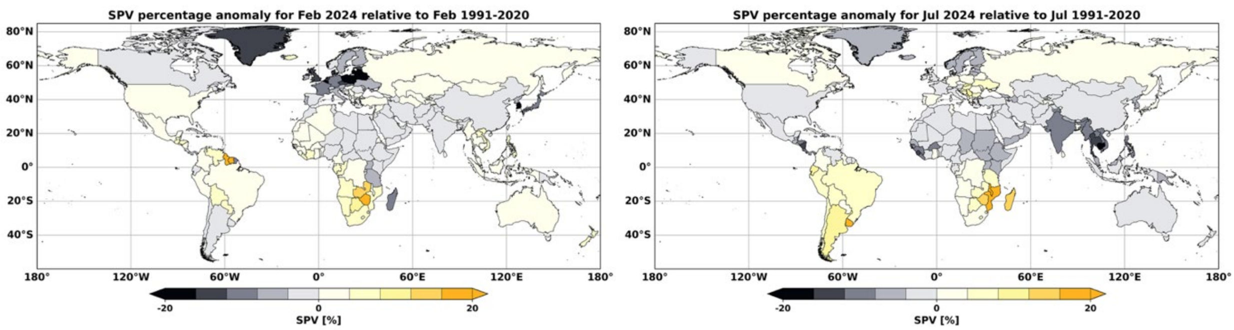

Figure 5. As in Figure 4, but for February (left) and July (right) 2024, relative to their average corresponding month in the period 1991–2020. Note the range of values is twice that of the annual mean.

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1.7 Hydropower proxy

Hydropower continues to play a critical role in many regional and national energy mixes, particularly where reliable rainfall and runoff patterns sustain reservoir-fed generation. In the present report, a hydropower proxy indicator derived from gridded monthly precipitation data is used to assess potential variations in hydropower generation across countries and time periods. It accounts for the installed capacity of hydropower plants at their specific locations, considering only precipitation over sub-country regions where power plants are located, with each plant's installed capacity used to weight the precipitation data accordingly. While not a direct measure of hydropower output, this indicator, referred to as installed capacity weighted precipitation (IWP), offers a valuable proxy for understanding climatic influences on hydropower potential. Figure 6 shows the IWP averaged over 2024, relative to the 1991–2020 period. Countries with no major hydropower plants are excluded from the indicator, as indicated by hatching.

Annual overview

The year 2024 was marked by a notable increase in hydropower proxy anomalies across the globe, with distinct large-scale patterns. Overall, there was a net global shift of nearly +7%, representing a transition from –5.2% in 2023 to +1.6% in 2024 (Figure 1). This improvement reflects the fact that many regions experienced positive anomalies – most notably in Central and South Asia. For instance, Kazakhstan, Uzbekistan and Tajikistan, with a combined installed capacity of approximately 11 GW (2.8 GW, 2.4 GW and 5.7 GW respectively), recorded increases of 20%–30%. Other positive anomalies were observed in the USA, Mexico, Central America, western South America, most of Europe and the United Republic of Tanzania, all of which experienced an increase exceeding 40%. The United Republic of Tanzania's significant rise is particularly notable, given the commissioning of the Julius Nyerere Hydropower Station, which is expected to progressively bring the country's total capacity to over 2 GW (up from the currently reported approximately 1 400 MW). Uruguay also saw a 20%–30% increase, with an installed hydropower capacity of 1 500 MW, which supplies around 40% of the country's electricity, contributing to an overall renewable share of nearly 90%.

Conversely, large negative anomalies were recorded in Southern Africa, particularly in Zambia, which saw a reduction exceeding –40% with 3.2 GW of installed capacity. This deficit could equate to a shortfall in electricity supply for around 1.2 million households.[11] In Zambia, this hydrological deficit was only partially offset by marginal improvements in solar and wind capacity factor anomalies (see Figures 2 and 4), though installed capacities for these technologies remain very low.

Other countries in the region, such as Mozambique (2.2 GW), Zimbabwe (1.1 GW), and Namibia (350 MW), also recorded significant negative anomalies in the –30% to –40% range. These deviations are critical when considering the importance of hydropower in the national energy supply of these countries, which lack diversified energy portfolios.

Comparison with 2022 and 2023

Compared to 2022 and 2023, 2024 shows a widespread intensification of positive hydropower anomalies (Figure 24, in Appendix 3). As mentioned, there was a major shift from a negative global anomaly in 2023 (–5.2%) to a mild positive one in 2024 (+1.6%). In 2022, global anomalies were also negative (approximately –3.6%), influenced by La Niña conditions that resulted in drier-than-average weather across Eastern Africa, South America, the USA, China and parts of Europe. In 2023, some areas improved – such as Central and Southern Africa, and Europe – while others deteriorated, especially in South America, Canada, Mexico and Australia.

The year 2024 marked an important transition for hydropower, with improvements in countries with large installed capacities like China (435 GW) and the USA (105 GW), while Southern

[11] This estimate assumes a globally averaged capacity factor of 0.5 and a decrease of 45% for the hydropower indicator. It is based on an average household consumption of approximately 5 000 kWh/year.

Africa saw a downturn, primarily due to El Niño conditions. Interestingly, India (52 GW) maintained a mild positive anomaly across all three years. Brazil (110 GW), however, recorded consistent negative anomalies throughout the period.

Monthly variability: February and July 2024

The seasonal evolution of the hydropower proxy anomalies offers further insights. In February 2024 (Figure 7, left), potential was markedly depressed across Southern Africa, South Asia, Central America and Brazil. In contrast, Eastern Africa and western South America saw significant positive anomalies, which align with ongoing El Niño teleconnections still active at that time. Moreover, for most of Europe as well as countries like Kazakhstan, anomalies were very high (40%–60%). For Kazakhstan, with 2.8 GW of capacity, this implies a potential electricity boost equivalent to 1.2 million households for the month.

By July 2024 (Figure 7, right), the anomaly pattern shifted toward positive values in North and Central America, northern South America, most of Asia and Europe. In contrast, Africa and South America – particularly Central and Southern Africa – showed strong negative deviations. This is not unexpected, as July falls within the dry season in these regions. As such, even minor deviations from the norm are amplified, given the low climatological baselines.

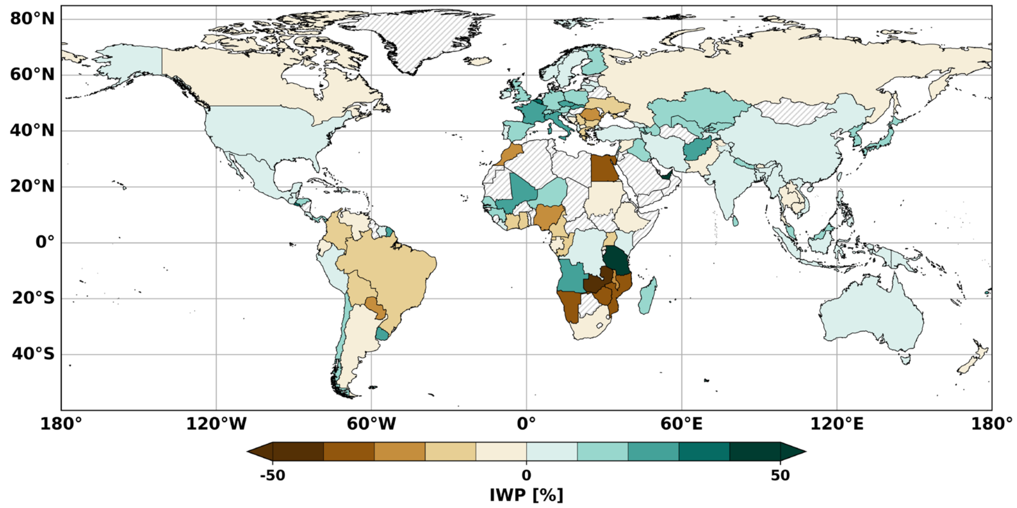

Figure 6. Hydropower proxy (installed capacity weighted precipitation (IWP)) annual mean percentage anomaly for 2024 relative to 1991–2020. Hatching indicates countries for which no data is available, due to assumptions made in the computation of this proxy (see Appendix 1 (Methodology)).

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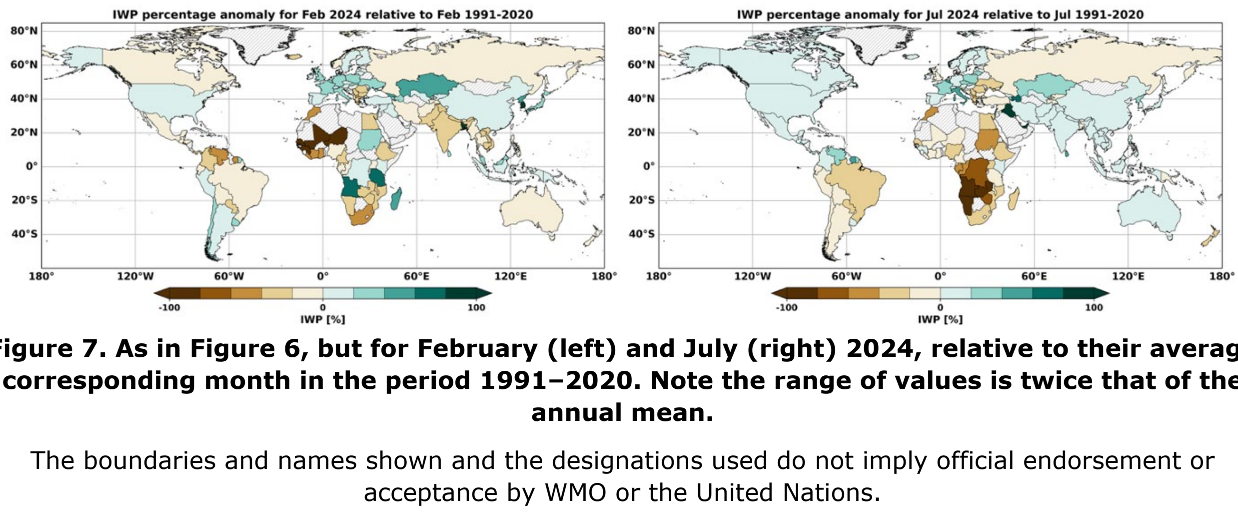

Figure 7. As in Figure 6, but for February (left) and July (right) 2024, relative to their average corresponding month in the period 1991–2020. Note the range of values is twice that of the annual mean.

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1.8 Energy demand proxy

Energy demand is influenced by a complex interplay of socioeconomic factors and climate variability. The Energy Degree Days (EDD) indicator provides a useful proxy for evaluating climate-driven demand for heating and cooling energy. It is defined as the sum of two commonly used indicators: Cooling Degree Days (CDD) and Heating Degree Days (HDD).[12] While these are usually analysed separately – given that they address different needs (cooling and heating, respectively) – EDD is used here to streamline the analysis[13] (IPCC, 2021; IPCC, 2022; Spinoni et al., 2017).

Annual anomalies

In 2024, EDD anomalies showed a marked shift toward increased cooling demand globally, consistent with the record-breaking heat that defined the year. The global EDD anomaly rose to nearly +4% in 2024 – an increase of more than 2.6% from 2023, and significantly higher than in 2022. The warmest year on record was reflected in a well-defined and marked overall pattern with substantial increases in EDD values across tropical and subtropical regions. Deviations exceeded 16% for many countries, including much of West, Central and Southern Africa, Indonesia, the Philippines, Viet Nam, Central America and the Bolivarian Republic of Venezuela (Figure 8).

Unlike the three previous generation-dependent indicators, it is more complex to relate energy demand directly to actual electricity consumption, due to its reliance on behavioural and infrastructural factors. However, the sharp rise in EDD was primarily driven by increases in CDD, elevated temperatures and widespread, prolonged heatwaves – all of which typically translate into greater electricity use for cooling.

Conversely, at higher latitudes, widespread reductions in EDD were observed. These reductions were primarily due to warmer temperatures decreasing HDD, and therefore reducing heating demand. One region with particularly large deviations was Eastern Europe, where countries like Czechia, Poland, Lithuania and Belarus experienced annual anomalies of 2 °C–3 °C. Similarly, Canada and the USA saw EDD reductions between –8% and –12%, reflecting decreased heating requirements.

Comparison with 2022 and 2023

The EDD patterns in 2024 closely mirrored and intensified those of the previous year, 2023 – the second warmest year on record (Figure 25, in Appendix 3). Notably, India shifted from a mild negative anomaly in 2023 to a strongly positive one in 2024 – a jump of over 16% – due to an increase in CDD and therefore greater cooling demand. China also saw a sizeable, although smaller, increase in EDD. This was due to compensating effects: lower HDD (from a milder winter) and higher CDD (from a hotter summer).

In 2022, although the general pattern of reduced EDD in the extra-tropics and increased EDD in the tropics was already emerging, it was less pronounced than in 2023 and 2024. Only a handful of countries in 2022 exceeded +16% deviations (for example, Kenya, Uganda, Angola, Liberia and Tunisia), highlighting the continued rise in temperature in the subsequent two years.

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[12] HDD (CDD) assesses the level of the cold (heat) over a specific time period, typically a month, taking into consideration outdoor temperature and average room temperature, to infer the need for heating (cooling). Similarly to the hydropower indicator, HDD and CDD are used due to the sparsity and disparity of energy demand data at monthly resolution for all (most) countries covering the 1991–2020 baseline period. Several versions of CDD and HDD are available. More details are available in Appendix 1 (Methodology). The individual global gridded CDD and HDD data are based on the ERA5 reanalysis.

[13] The main difficulty with EDD is that it can be difficult to separate the effect of cooling from heating, even if, generally, the former is more pronounced in low-mid latitudes (and in summer), and the latter in mid-high latitudes (and in winter).

Monthly variability: February and July 2024

Examining two contrasting months – February and July (Figure 9) – offers more detailed insight into the separate contributions of heating (HDD) and cooling (CDD) to overall EDD anomalies.

In February (Figure 9, left), tropical and southern hemisphere regions showed already elevated EDD values – especially Central and Southern Africa, Central and South America, South-East Asia and Australia. In many cases, anomalies exceeded +30%. Exceptions included Chile and Lesotho, where reduced HDD drove a decrease in EDD, and Rwanda, which saw reductions in both HDD and CDD – although from relatively low baseline values.

In the northern hemisphere, many countries experienced significantly reduced heating requirements due to milder winter conditions. This led to sharp EDD declines exceeding −32% in countries such as Portugal, Morocco, Tunisia, Libya, Egypt and several Eastern European States. Notable exceptions, with modest increases in EDD, included China, Kazakhstan, Mongolia and Iceland, due to regional cold anomalies centred over Mongolia and central Greenland.

In July (Figure 9, right), widespread heat across the northern hemisphere caused surging CDD values in many countries, especially in Eastern Europe, where countries like Romania and Ukraine experienced record-breaking cooling demand linked to sustained temperature anomalies several degrees above average.

Meanwhile, countries such as Canada, Mongolia, Sweden and Finland experienced reduced EDD values, largely due to reduced HDD, as their summer CDD values remain low. In Southern Africa, EDD also declined – again reflecting reduced HDD. Conversely, southern South America experienced increased EDD anomalies, notably in Argentina (8%–16%), and Uruguay and Paraguay (16%–24%), due to a cold anomaly that drove up heating needs.

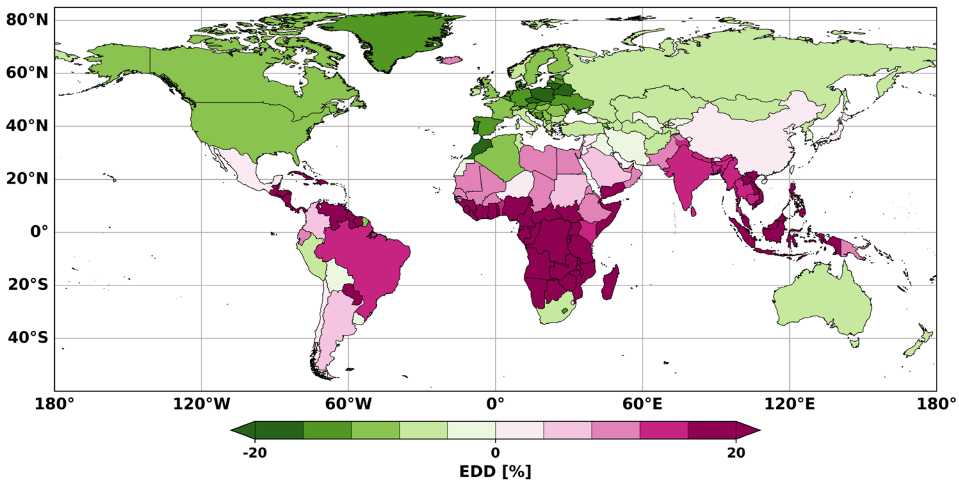

Figure 8. Energy Degree Days (EDD) annual mean percentage anomaly for 2024 relative to 1991–2020

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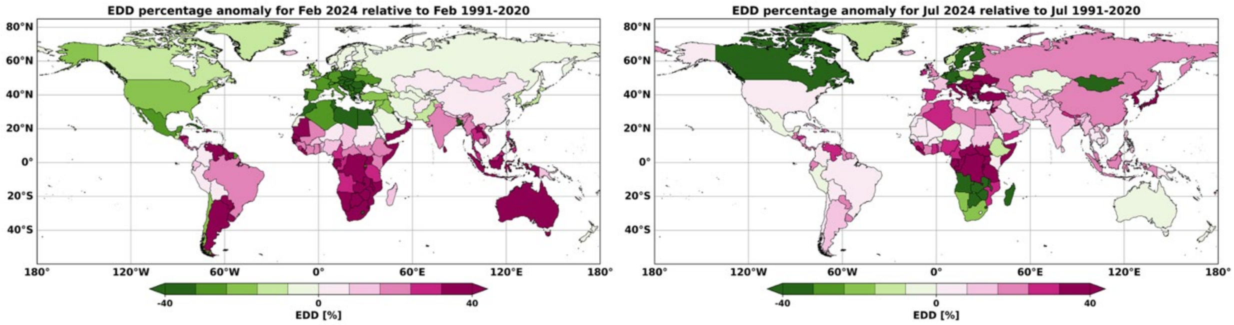

Figure 9. As in Figure 8, but for February (left) and July (right) 2024, relative to their average corresponding month in the period 1991–2020. Note the range of values is twice that of the annual mean.

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2. Regional perspective

To complement the global analysis, Figure 10 presents an aggregate assessment by regions, showing the anomalies for the four energy indicators for 2024 alongside those from the two preceding years. This three-year view helps contextualize the year's climatic and energy performance within recent variability.

As an illustration of regional behaviour, in 2024 Central and Southern Africa experienced the combined influence of a strong El Niño and pronounced northward shifts in the Southern Annular Mode. These large-scale climate drivers contributed to positive anomalies in both wind and solar resources: 3.4% and 1.5%, respectively. Although modest in relative terms, these increases translate to tangible energy gains. With the region's current installed capacities – approximately 8.9 GW of solar PV power and 4.4 GW of wind power – these anomalies are estimated to provide additional power for around 120 000 households.

The most pronounced change in 2024 in Central and Southern Africa, however, was observed in energy demand. As 2024 became the warmest year on record, the energy demand indicator surged nearly 30% above the long-term average. This increase likely reflects a decrease in heating requirements and a sharp rise in cooling demand, consistent with extreme heat events observed during the year.

By contrast, hydropower potential in Central and Southern Africa remained below average, with a –3% anomaly. This marked the third consecutive year of negative hydropower anomalies, attributable to persistent dry conditions and below-average rainfall. The continuing shortfall underscores the vulnerability of hydro-dependent energy systems under changing climate regimes. These findings highlight the growing need to understand and plan for the effects of large-scale climate phenomena – such as El Niño, the Indian Ocean Dipole and long-term warming – on both energy production and demand globally, but especially in regions where renewable capacity is expanding rapidly.

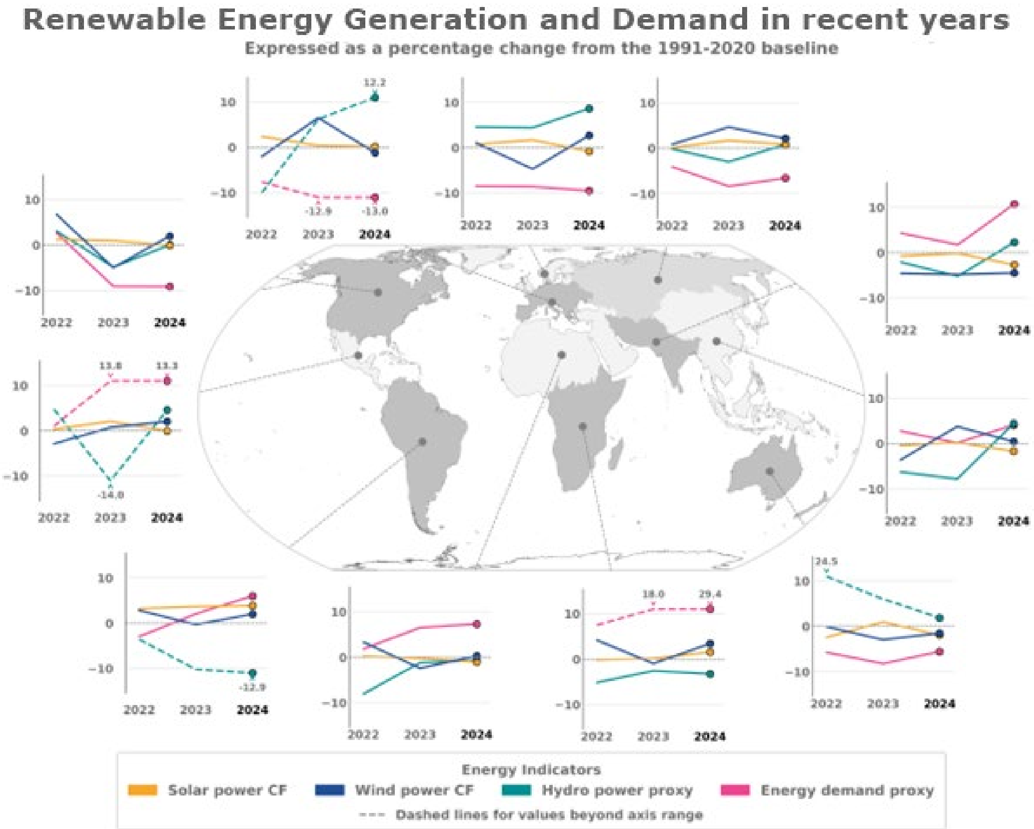

Figure 10. Global annual anomalies (in %) for four energy indicators – wind power, solar power, hydropower and energy demand – for 2022–2024, relative to the 1991–2020 climatological reference period. The indicators represent weighted national averages within each region.

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A more detailed regional analysis was conducted by examining monthly anomalies for the four energy indicators – solar power, wind power, hydropower and energy demand (EDD) – in three climatically and geopolitically significant regions: Africa, East and South Asia, and Central/South America. These regions exhibit a diversity of renewable energy profiles and varying exposure to climate variability. By examining monthly trends relative to the 1991–2020 climatological baseline, the present report highlights how regional and seasonal climate conditions shaped energy outcomes in 2024.

Within each region, four countries that are located near to each other were selected to facilitate comparison and to reflect the possibility of cross-border power transmission, where interconnections exist. This regional selection supports discussion of energy balancing opportunities, particularly for electricity imports and exports, although this report does not attempt to quantify such exchanges.

The analysis provides a three-dimensional framework – indicator, time (month) and country – to examine energy variability and provide insights into potential optimization of energy management. For instance, large monthly variations in wind CF between neighbouring countries might prompt grid operators to explore complementarity and flexible energy sharing strategies.

Violin plots are used to illustrate the monthly distributions of anomalies for each indicator and country, against the 1991–2020 historical range. Each violin shows the distribution of anomalies for each of these 30 values (years) against the 2024 monthly value. Median values are shown within the distributions, and countries are colour-coded for clarity.

It is important to note that the monthly medians shown in the violin plots are not directly comparable to the annual averages discussed earlier. This is because: (i) medians differ methodologically from means; and (ii) the mean annual variations differ from the (visually) computed mean of the individual monthly variations. To aid comparison with earlier sections, the months of February and July – previously highlighted for global analysis – are specifically marked in these plots.

This visualization method enhances understanding of both direction and magnitude of change within and between countries. It also helps to identify extreme monthly anomalies, offering insights into periods of heightened stress or imbalance between supply and demand. Although these plots do not capture operational realities – such as sub-daily load curves, intra-country variability, or actual transmission constraints – they provide a powerful tool for interpreting regional climate–energy interactions and informing future energy planning.

2.1 Africa

In Africa, four countries from the Western Africa region – Ghana (green), Côte d'Ivoire (yellow), Guinea (red) and Nigeria (blue) – were selected for more detailed analysis (Figure 11). These countries are part of the Western African Power Pool (WAPP). A standout feature across most months is the markedly high values of the energy demand indicator (Energy Degree Days (EDD)), particularly from March to July. During this period, the anomalies were among the highest compared to any month in the 1991–2020 reference period, with median deviations often reaching or exceeding 20%. February also showed exceptionally high EDD values for all countries except Nigeria, again with median anomalies above 20%, consistent with patterns seen in the global maps (Figure 10).

Precipitation remained subdued throughout most of the year, except in Guinea, which exhibited positive hydropower indicator anomalies from July to November. The dry season in this region typically runs from November to April, which helps explain the large negative hydropower anomalies earlier in the year, especially in Guinea. This hydrological shortfall posed a serious challenge – particularly given the simultaneous surge in cooling demand, as captured by the anomalously high EDD – since hydropower is the dominant renewable energy source in the region. The combined installed hydropower capacity of these four countries exceeds 6 GW, significantly outweighing the installed capacity of solar and wind power, which together total approximately 390 MW (with wind power being nearly zero). While Guinea recorded higher-than-normal hydropower availability later in the year, its installed capacity of around 800 MW represents only about 13% of the total hydropower capacity of the four countries. As such, it could only partially offset shortfalls in the other countries.

Outside of the July–October rainy season, solar PV performance in 2024 was generally above average, providing partial compensation for the reduced hydropower output, especially in the first half of the year. Wind energy may have contributed from April onward, but its installed capacity remains negligible, partly reflecting the limited wind resource potential in the region.

Overall, 2024 presented a challenging year for balancing renewable energy generation with demand across these four interconnected countries within the WAPP. The combination of suppressed hydropower output during the dry season and heightened electricity demand due to extreme heat underscored the importance of integrated planning and diversification of energy sources.

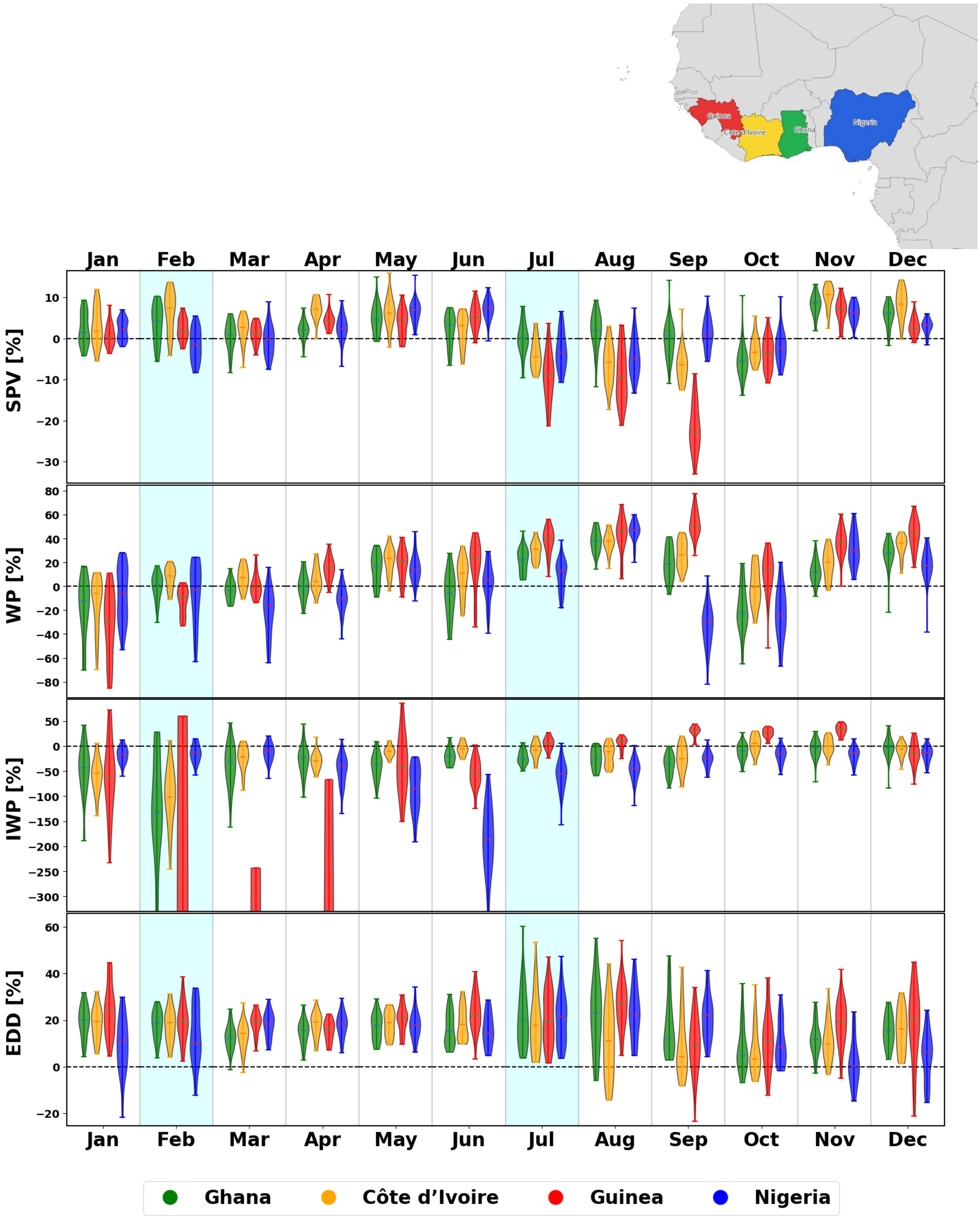

Figure 11. Monthly variations for 2024 in four key energy indicators – solar PV capacity factor, wind power capacity factor, hydropower proxy and energy demand proxy (from top to bottom) – across Ghana (green), Côte d'Ivoire (yellow), Guinea (red) and Nigeria (blue). The violin plots show percentage anomalies for each month in 2024 compared to the corresponding month across the reference period, 1991–2020 (each violin comprises 30 values). The short horizontal line within each violin indicates the monthly median. Some violins have been trimmed to enhance readability – large percentage deviations typically occur due to small denominators. February and July, previously discussed in more detail in the present report, are highlighted.

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2.2 Asia

In Asia, the selected countries – Pakistan (green), Afghanistan (yellow), the Islamic Republic of Iran (red) and Tajikistan (blue) – displayed notable variability in energy demand and supply indicators during 2024 (Figure 12). Although energy demand anomalies were less extreme than those observed in Western Africa, Pakistan experienced persistently high and exceptional positive anomalies in EDD, especially in July and October.

Taking these two months for closer examination, all four countries registered above-average EDD values in July, with median anomalies ranging between 10% and 20% (see also Figure 10). During July, the hydropower proxy was positive across all countries, extending from previous months and possibly allowing for increased water storage. Hydropower remains a key component of the regional energy mix, with more than 30 GW of installed capacity. The Islamic Republic of Iran and Pakistan together account for nearly 80% of this total, with capacities of approximately 13 GW and 11.5 GW, respectively.

This mildly favourable hydropower signal likely helped support the region's elevated electricity demand during the summer months. However, contributions from wind and solar resources were more limited. Capacity factors for both wind and solar power were generally near or below average, with the exception of Tajikistan, where the wind power CF exhibited a positive anomaly of around 10%. Yet, due to the negligible installed capacity of wind and solar power in both Tajikistan and Afghanistan, these favourable conditions could not be translated into significant electricity generation. In contrast, Pakistan and the Islamic Republic of Iran collectively possess over 2 GW each of solar and wind capacity, with the majority of this installed capacity located in Pakistan.

October presented even greater challenges for Pakistan, where the EDD anomaly surpassed +20%, driven by elevated cooling needs. Simultaneously, wind, solar and hydropower indicators were all below average, with wind capacity factor (CF) falling more than 20% below the long-term mean. The Islamic Republic of Iran also faced increased demand in October, though to a lesser extent (+10%). However, hydropower potential remained positive in all countries except Pakistan (near zero), possibly allowing for some regional compensation.

Specifically, Pakistan's 1.4 GW of solar and 1.8 GW of wind capacity would have delivered below-average generation under these resource conditions. The Islamic Republic of Iran, by contrast, had a slight wind surplus (+5%) from its 380 MW of installed wind capacity and a modest solar deficit (a few percent) from its 780 MW of solar PV capacity. Meanwhile, Tajikistan exhibited a strong wind CF anomaly but, due to its lack of wind infrastructure, could not translate this potential into usable power.

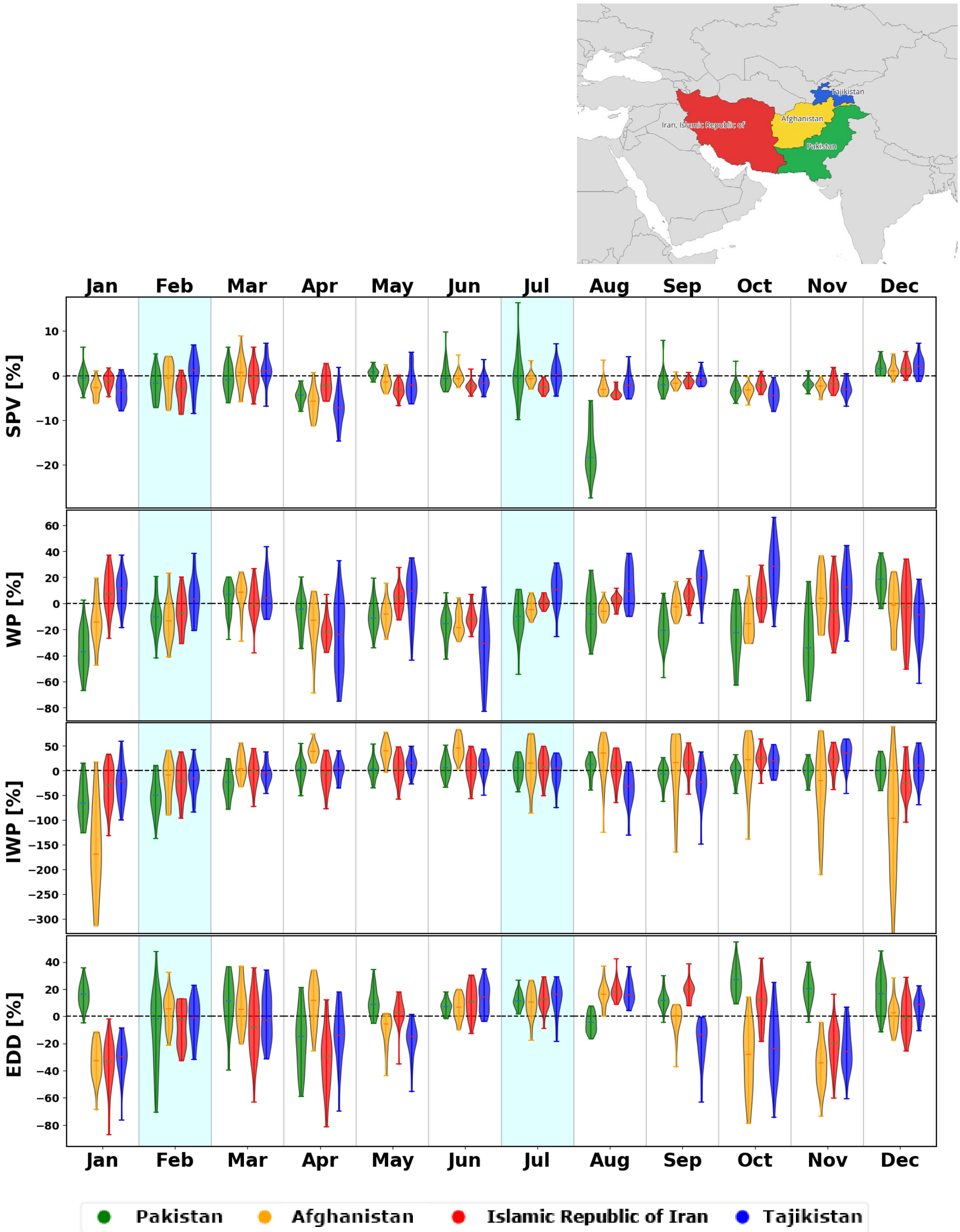

Figure 12. As in Figure 11, but for Pakistan (green), Afghanistan (yellow), Islamic Republic of Iran (red) and Tajikistan (blue)

The boundaries and names shown and the designations used do not imply official endorsement or acceptance by WMO or the United Nations. Dotted line represents approximately the Line of Control in Jammu and Kashmir agreed upon by India and Pakistan. The final status of Jammu and Kashmir has not yet been agreed upon by the parties.

2.3 Central and South America

For Central and South America, the selected countries are Dominican Republic (green), Cuba (yellow), the Bolivarian Republic of Venezuela (red) and Costa Rica (blue) (Figure 13). Unlike the previous regions, considerations of power balancing among these countries are not relevant, as interconnection via a regional grid is challenging.[14] Consequently, the analysis focuses on intra-annual variability within each individual country.

The energy demand indicator (EDD) was generally positive – and in several cases, extremely so – throughout the year. January stands out as a record-breaking month for all countries, with anomalies reaching 50%–60% above the 30-year reference period. However, these large percentage anomalies result from a very low climatological baseline. For all four countries, baseline EDD values are just a few degree-days per month, with peaks at around 10, which are negligible compared to values of several hundred in Mexico or thousands in Canada.

In terms of installed renewable energy capacity, the Dominican Republic has a relatively balanced mix: 635 MW of hydropower, 430 MW of wind power and 1 420 MW of solar power. Despite this, each of these sources contributes only around 5% to national electricity consumption – highlighting a heavy dependence on fossil fuels, which account for about 85% of total generation, with coal alone contributing over 33%.[15] Cuba's total renewable capacity is modest: about 300 MW of solar power and much smaller contributions from wind power and hydropower. Electricity generation remains highly reliant on oil (approximately 85%) and gas (approximately 12.5%).[16] The Bolivarian Republic of Venezuela is dominated by hydropower, with 17 GW of installed capacity accounting for nearly 80% of its electricity production.[17] Wind and solar power are nearly absent. Costa Rica also has strong reliance on hydropower, with about 2.5 GW installed, supplying around 70% of electricity needs. Wind power contributes meaningfully at 400 MW (about 12%), while solar power plays a minimal role at 75 MW (approximately 1%).[18]

During the first few months of 2024, both the Bolivarian Republic of Venezuela and Costa Rica – the countries with the most hydropower capacity among the four – experienced average to below-average precipitation, consistent with the mature phase of El Niño. However, this period coincides with the region's dry season (November to April), during which precipitation levels are typically about one third of the rainy season peak. For instance, the Bolivarian Republic of Venezuela typically receives around 100 mm/month in the dry season and up to 300 mm/month during the wet season; Costa Rica receives approximately 150 mm/month versus 450 mm/month. During the rainy season, the hydropower indicator anomalies in both countries were near or above average, suggesting adequate water availability for power generation. Meanwhile, the Dominican Republic also showed mostly positive hydropower anomalies across the year, though this was less critical, given its comparatively modest installed hydro capacity. This seasonal imbalance is one of the reasons behind the increasing deployment of solar PV in the region, especially in areas with lower precipitation, to enhance energy resilience and reduce dependence on hydropower during the dry season.

Wind power indicators were mostly negative across the region in 2024, with minor exceptions in Cuba and the Bolivarian Republic of Venezuela. However, due to their negligible wind capacity, these anomalies had limited practical implications for electricity generation (see Figure 2).

Solar PV anomalies were predominantly negative in the two countries with the largest installed capacity – namely, the Dominican Republic and Cuba – especially during key transitional

[14] Despite their geographical proximity, no dedicated transmission infrastructure currently connects the electrical grids of Cuba and the Dominican Republic (located on the island of Hispaniola), even though Haiti sits between the two. There is not even a direct electrical link between the Dominican Republic and Haiti, even though both countries share the island of Hispaniola.
[15] https://www.iea.org/countries/dominican-republic
[16] https://www.iea.org/countries/cuba
[17] https://www.iea.org/countries/venezuela
[18] https://www.iea.org/countries/costa-rica

months such as April, June and November. For the Dominican Republic, this was particularly significant given that wind power indicators were also negative during much of the year. However, positive hydropower anomalies may have partially offset these deficits and contributed to balancing supply and demand.

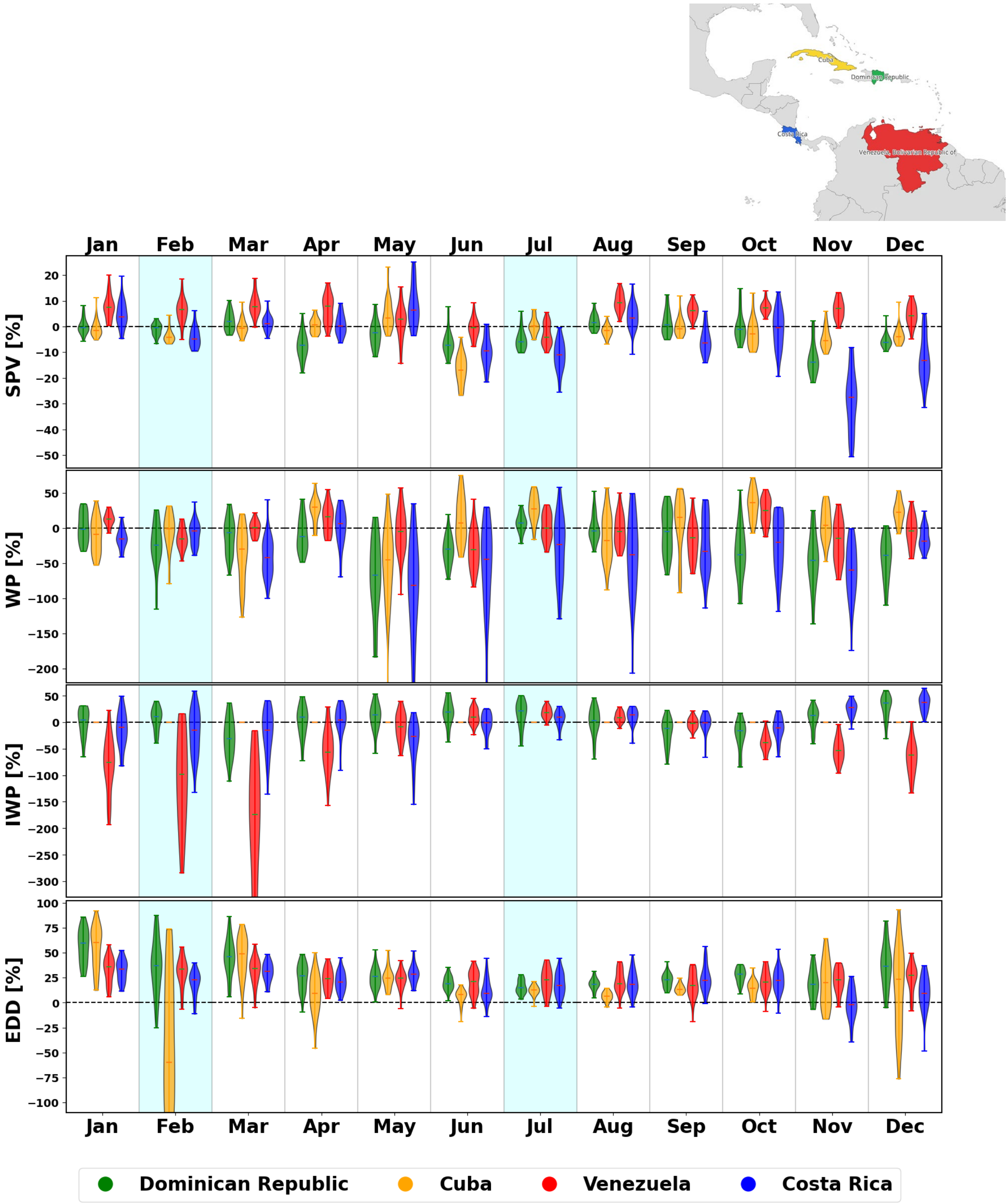

Figure 13. As in Figure 11, but for Dominican Republic (green), Cuba (yellow), the Bolivarian Republic of Venezuela (red) and Costa Rica (blue). Note: The hydropower indicator for Cuba is not shown due to its negligible hydropower capacity.

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3. Adaptation to climate variability with seasonal forecasts

Seasonal forecasts provide insights into climate conditions over monthly to seasonal timescales and are increasingly used to support energy resource management. They enable stakeholders to anticipate and respond to climate variability, helping optimize generation planning, ensure energy security and improve resilience to weather extremes. As the share of renewables in the energy mix grows, so does the importance of reliable seasonal forecasts for operational planning, especially in regions vulnerable to climatic fluctuations (e.g. White et al., 2022).

For example, anticipating precipitation timing and intensity can improve hydropower reservoir management, while temperature forecasts help grid operators prepare for surges in heating or cooling demand. However, the skill of seasonal forecasts varies significantly depending on the region and variable. Temperature forecasts generally perform better than those for precipitation or wind, and skill is typically higher in tropical regions influenced by large-scale drivers like ENSO.

This section of the report illustrates the role of seasonal forecasts as a climate-informed decision-support tool for energy planning and management. It presents selected examples for 2024, focusing on the four energy indicators – solar and wind power capacity factors, hydropower potential proxy and the energy demand indicator – with a regional emphasis on Africa. An evaluation of the seasonal forecast model performance, focusing on the four African countries selected in this report, is provided in Appendix 2.

All seasonal forecasts in this section of the report are presented at the country level. This approach ensures consistency across the indicators: wind and solar data, originally available at a 1° × 1° spatial resolution, have been aggregated to the national level to facilitate comparison with hydropower and energy demand indicators, which are only defined at the country scale due to their specific calculation methods (see Appendix 1 (Methodology)).

Seasonal climate forecasting is a complex domain that incorporates several advanced concepts such as ensemble generation, lead time selection, model bias correction, probabilistic interpretation and forecast verification.[19] To maintain accessibility while conveying robust insights, this report focuses on the following:

- **Forecast model:** ECMWF Seasonal Forecast System 5[20]
- **Skill metric:** Continuous Ranked Probability Skill Score (CRPSS)
- **Region:** Africa
- **Target month:** July 2024

[19] Concepts such as initial conditions, ensemble members and their generation, model bias, probabilistic forecasting and lead times contribute to the complexity of this area. In this section, we will touch upon a few key concepts to aid in understanding the presented material.
[20] The ECMWF System 5 remains one of the most skilful global seasonal forecast models available. However, model performance varies by region, variable and time of year. Research has shown that multi-model ensemble systems (typically combining three or four models) generally outperform individual models. Nevertheless, there is no universal formula for selecting the optimal number or combination of models.

3.1 Seasonal forecast of wind power capacity factor

While much of Africa is influenced by ENSO, the magnitude and type of impact varies by subregion. During strong ENSO phases (El Niño or La Niña), seasonal forecast skill tends to improve due to the dominance of large-scale drivers. By July 2024, El Niño had waned, transitioning toward neutral ENSO conditions.

The right panel of Figure 14 presents the July 2024 seasonal forecast for wind power capacity factor (CF), based on forecasts initiated on 1 June 2024 (lead time 1).[21] The forecast comprises a 51-member ensemble. Rather than collapsing the ensemble into a mean (or median) value, the map displays the *most likely tercile category* – that is, whether wind power CF is more likely to fall within the upper, middle or lower third of its historical distribution.[22] This categorical probabilistic approach retains more information and helps communicate forecast confidence, shown via colour strength for each of the three categories.

For most African countries, the forecast indicates a higher probability of wind power CF being in the upper tercile (green tones), suggesting stronger-than-average wind resource availability. Exceptions include parts of Northern Africa, Uganda and South Africa, where wind CF was forecast to fall in the lower tercile (pink tones), though the confidence was relatively low in these areas, except for Mauritania, Sudan and Madagascar, where signals were stronger. The four countries highlighted in the regional analysis section all showed a higher likelihood of wind CF falling in the upper tercile.

To compare the forecast with the actual event, the left panel of Figure 14 shows the observed wind CF anomaly in July 2024, calculated as the deviation from the 1993–2016 climatology.[23] This map confirms positive anomalies across most of Africa, with notable exceptions in parts of Southern Africa (e.g. Namibia, Malawi, Madagascar) showing below-normal wind CF.

To facilitate comparison between observed and forecast terciles, the centre panel categorizes the observed anomalies into terciles. As shown, most countries experienced upper tercile conditions, particularly across the Saharan and immediate sub-Saharan regions, which is broadly consistent with the forecast. Notably, areas such as Mauritania and Sudan – where the forecast model indicated higher confidence – aligned well with the observed positive anomalies. However, the forecast performed less reliably in parts of Northern Africa, Uganda and South Africa, where it indicated lower tercile wind CF, but where observations instead showed above-normal (upper tercile) conditions. Beyond the inherent limitations of seasonal forecasting – especially for variables like wind – it is important to acknowledge that a single seasonal forecast cannot be definitively assessed in isolation, due to its probabilistic nature.

It should also be noted that the observed anomaly maps shown in the present report do not align exactly with the wind power CF deviation presented in Figure 3 (right). This discrepancy arises from the use of different reference periods: 1991–2020 for the annual wind power CF anomalies, and 1993–2016 for the seasonal forecast evaluation, due to data availability in the Copernicus Climate Change Service (C3S) seasonal forecast archive.

[21] Seasonal forecasts are typically issued at lead times from 1 to 6 months. Lead time 1 refers to forecasts made one month ahead (e.g. issued in June for July conditions).
[22] Seasonal (ensemble) forecasts are commonly interpreted using terciles (upper, middle, lower), balancing ease of interpretation with forecast resolution.
[23] The 1993–2016 reference period reflects the availability of retrospective seasonal climate forecasts from the Copernicus Climate Data Store.

3.2 Seasonal forecast of solar power capacity factor

In July 2024, the seasonal forecast for the solar power capacity factor, issued in June, indicated a strong probability of below-average solar radiation (lower tercile) across most of Africa, while upper tercile conditions were expected in several Southern African countries and in Eritrea (Figure 15, right). Observational data for solar power CF confirmed this general pattern, showing negative anomalies across the northern half of the continent and above-normal values in the southern regions (Figure 15, bottom), consistent with the spatial pattern shown in Figure 5 (right). The central panel, which categorizes observed anomalies into terciles, further highlights the broad alignment between forecast and observations across most of the continent, with notable mismatches in countries such as Mozambique, Malawi, the United Republic of Tanzania and the Democratic Republic of the Congo. Although spatial variations in the solar CF signal were not uniformly captured across the continent, the forecast succeeded in identifying the primary dipole, underscoring the potential value of seasonal forecasts in guiding operational solar energy planning in climatically sensitive regions.

3.3 Seasonal forecast of hydropower proxy

Seasonal forecasts for the hydropower generation proxy, based on precipitation, showed a distinct tendency towards lower tercile conditions across most African countries with hydropower installations in July 2024 (Figure 16, right; countries without hydropower capacity are hatched and excluded from analysis). Only three countries were forecast to fall within the upper tercile: Madagascar, Malawi and Niger. Notably, the forecast indicated particularly high confidence in lower tercile outcomes for several central and south-western countries such as the Democratic Republic of the Congo, Angola and Namibia. However, it is important to note that this strong signal is influenced by the fact that July is part of the dry season in these regions, meaning that the climatological baseline for precipitation – and therefore the hydropower proxy – is already low. Observational data confirmed this broad spatial pattern (Figure 16, left), consistent with the annual anomaly distribution shown in Figure 7 (right). The tercile-categorized observations (Figure 16, centre) closely aligned with the forecast in most areas, including Central and South-Western Africa. Madagascar was the primary exception, with observed conditions falling in the lower tercile despite a forecast for the upper tercile. These findings underscore the importance of reliable precipitation forecasts in anticipating regional hydropower generation and associated energy supply risks.

3.4 Seasonal forecast of energy demand proxy

Seasonal forecasts for the energy demand proxy (EDD) in July 2024 reveal a pronounced dipole pattern, with upper tercile anomalies forecast across much of Africa – particularly strong over Western and Central Africa – and lower tercile values across most of Southern Africa (Figure 17, right). Notably, Ethiopia stands out within this broad spatial structure: while surrounded by countries forecast in the upper tercile, Ethiopia was predicted to experience lower-than-average energy demand (lower tercile), a signal that was borne out in the observations. Rwanda was also forecast in the lower tercile, though its baseline EDD values for July are quite low, making the anomaly less impactful in absolute terms.

Observed anomalies (Figure 17, left) closely mirrored the predicted distribution. Nonetheless, some deviations occurred. For instance, Angola and Madagascar were forecast to be in the upper tercile but observed in the lower tercile, while Rwanda showed the opposite pattern – observed in the upper tercile despite being forecast in the lower (Figure 17, centre). However, both Rwanda and Angola have relatively low baseline EDD values for July (around 5 degree-days), meaning that even small absolute changes can lead to large percentage swings. Observed anomalies were also in line with percentage anomalies shown in Figure 9 (right), although some discrepancies – due to the different reference periods – can be seen in Saharan countries like Sudan and Chad.

The accurate prediction of Ethiopia's distinct lower tercile anomaly is particularly noteworthy, given its divergence from the surrounding regional pattern. This case underscores the added value of spatially resolved seasonal forecasts in identifying sub-regional anomalies, even within broader continental-scale trends. These insights can enhance preparedness for unusual energy demand fluctuations.

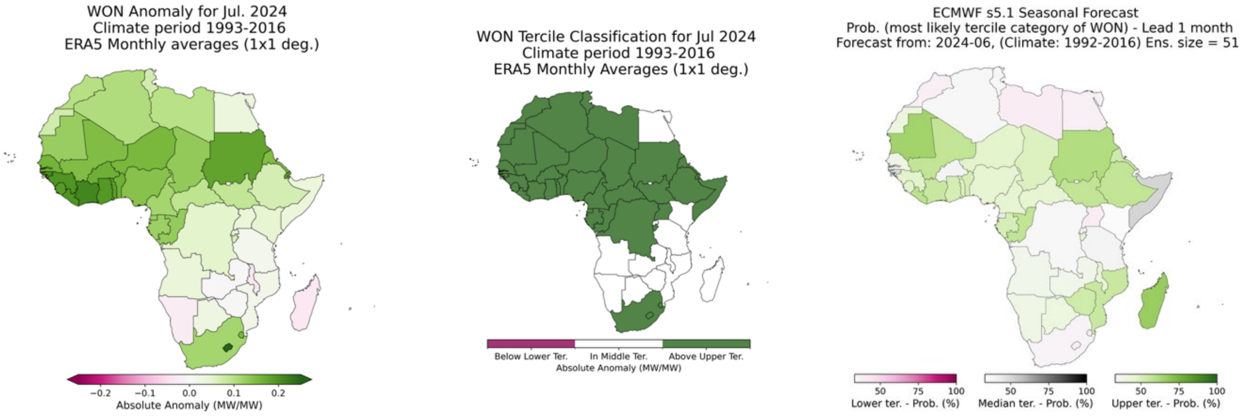

Figure 14. Wind power capacity factor (CF) for July 2024 across Africa (from a global model). Panels show: (left) observed anomalies relative to the 1993–2016 reference period; (centre) observed anomalies categorized into terciles; and (right) the forecasted most likely tercile category from the seasonal forecast issued on 1 June 2024 (lead time 1 month). Green indicates upper tercile (above-normal) and pink indicates lower tercile (below-normal). Colour saturation reflects strength of anomaly (left panel) or forecast confidence (right panel). *Note:* WON = Wind power onshore.

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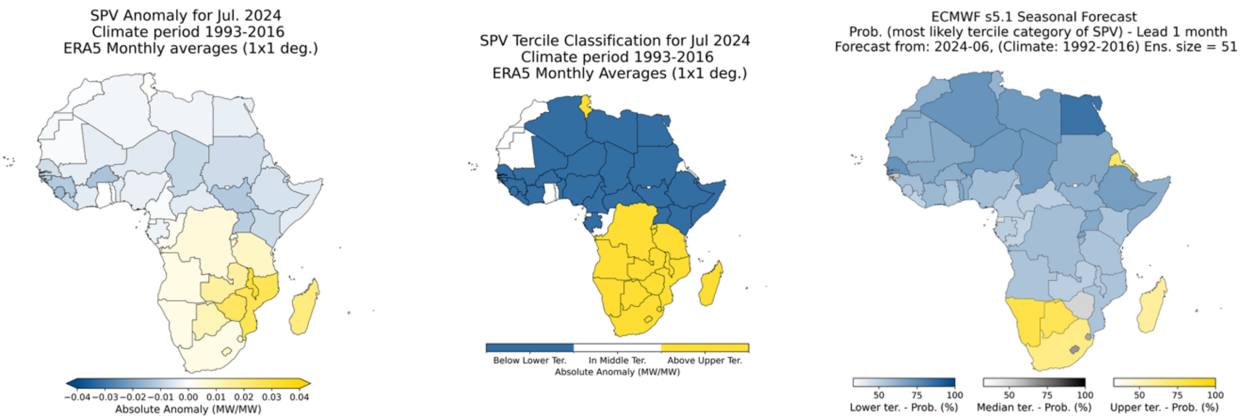

Figure 15. As in Figure 14, but for solar PV power CF

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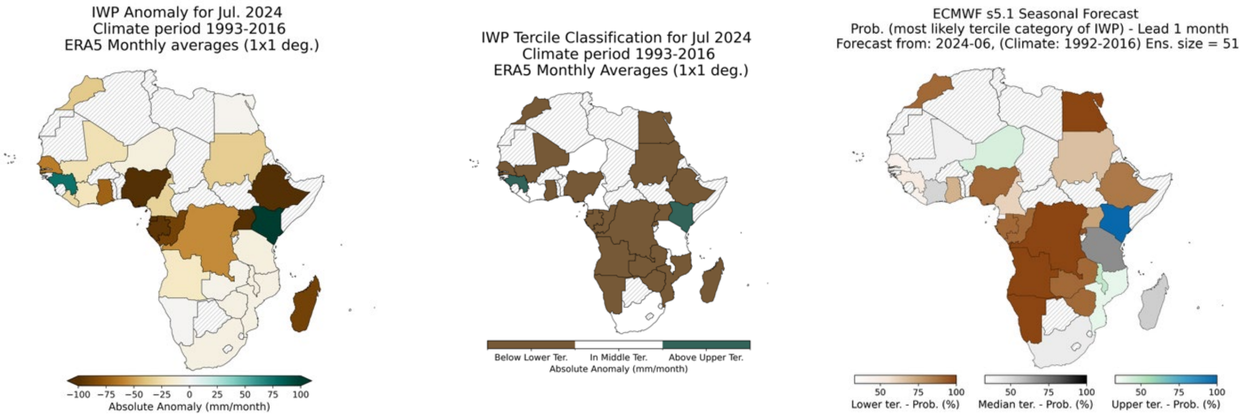

Figure 16. As in Figure 14, but for the hydropower indicator

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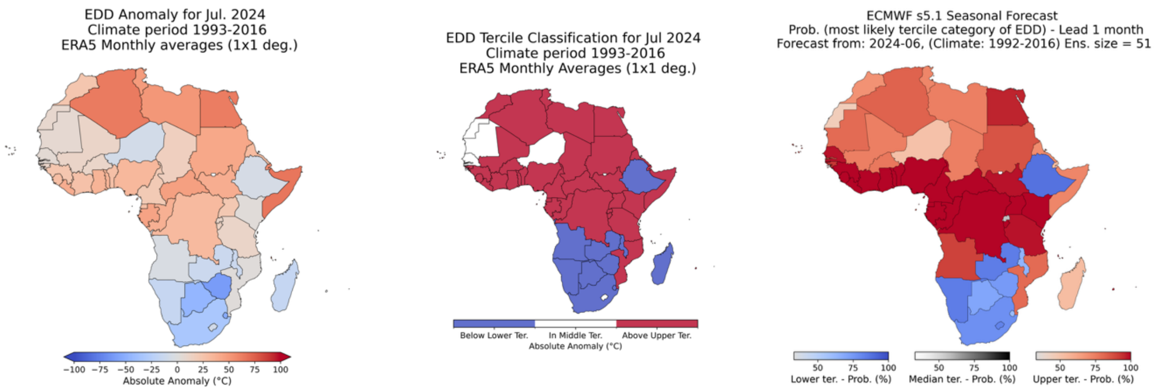

Figure 17. As in Figure 14, but for energy demand indicator

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4. Conclusions and implications

The 2024 edition of the WMO–IRENA *Year in Review* shows that climate variability and change are having measurable effects on renewable energy resources and electricity demand. Building on the momentum of previous years, this report examines climate features of 2024 using a framework based on climate-informed energy indicators – wind and solar capacity factors, a precipitation-based hydropower proxy and a temperature-based energy demand proxy. This framework helps distil complex climate and energy interactions into clear, actionable insights for planners, policymakers and the broader energy community.

Across all continents, 2024 offered compelling evidence of how climate fluctuations influence renewable generation potential and energy demand. Temperature extremes, shifts in wind regimes and hydrological anomalies created multifaceted challenges for energy system operators in many parts of the globe.

This year's report also presents, for the first time, a robust evaluation of seasonal forecasts for energy indicators alongside observed anomalies. The ability of these forecasts to anticipate broad regional signals – especially for temperature-driven energy demand – shows their potential for operational integration into renewable energy planning and risk management.

4.1 Climate drivers of energy variability in 2024

The energy–climate interplay in 2024 was dominated by two major phenomena: the tail end of the strong 2023–2024 El Niño and the pervasive backdrop of long-term global warming, which drove 2024 to become the warmest year on record. The El Niño signal was evident in many regional anomalies. In Southern Africa and South America, it suppressed rainfall and supported high solar radiation, boosting solar PV capacity factors (CF) while simultaneously straining hydropower output. In South and South-East Asia, altered monsoon patterns resulted in complex outcomes, with India experiencing both high cooling demand and deficits in wind and solar power. Eastern Africa, in contrast, saw rainfall surpluses – reflected in positive hydropower anomalies – partly due to residual effects from a fading positive Indian Ocean Dipole.

Globally, anomalies across all four indicators were positive in 2024: wind power CF rose by +1%, solar power CF by +0.2%, the hydropower proxy by +1.6% and Energy Degree Days (EDD) by +4%, with the latter two significantly exceeding values observed in previous years.

Persistent marine heatwaves, especially in the Atlantic, affected wind circulation patterns and contributed to increased cyclonic activity, which in turn led to depressed solar power capacity factors. In Southern Africa, the year saw exceptional wind CF anomalies – reaching up to +10% in some areas on an annual basis – likely linked to strengthened synoptic pressure gradients and atmospheric perturbations south of the continent, driven by northward displacements of the Southern Annular Mode. These patterns, however, were not uniform: Europe, South Asia and Northern Africa recorded widespread negative wind CF anomalies, underlining the variable nature of climate–energy dynamics.

Energy demand followed thermal anomalies closely. Driven by unprecedented global heat, the energy demand proxy rose sharply in 2024 – reaching record highs in many regions, including Western and Central Africa, South and South-East Asia and large parts of South America. These surges in demand were only occasionally matched by equivalent increases in renewable output, underscoring the risks of climate–energy imbalances in heat-prone regions.

4.2 Regional highlights and insights

Regional assessments reveal how localized interactions between climate and energy play out in practice:

- **Africa**: In Western Africa, countries like Ghana, Côte d'Ivoire, Guinea and Nigeria experienced soaring energy demand anomalies during the hot season, with limited capacity to compensate via wind power or hydropower. Solar output was a partial buffer in the dry months, but overall, the renewable supply-demand gap widened.

- **Asia**: In East and South Asia, nations like Pakistan and the Islamic Republic of Iran recorded extreme heat-related demand spikes, particularly in July and October. These coincided with subdued wind and solar power performance, creating potential shortfalls. Some relief came from moderately positive hydropower anomalies, though not uniformly across the region.

- **Central and South America**: The Bolivarian Republic of Venezuela and Costa Rica, highly reliant on hydropower, faced mixed outcomes: El Niño-induced dry spells limited early-year output, while later rains improved reservoir levels. The Dominican Republic saw significant deficits in both wind and solar CF during key transitional months, highlighting vulnerability to climatic fluctuations.

These region-specific findings reinforce the value of integrated, climate-informed energy planning. Understanding how indicators vary not only by geography but also intra-annually is essential for effective infrastructure development, resilience strategies and transboundary coordination.

4.3 Role of seasonal forecasts

A major addition to this year's report is the evaluation of seasonal forecast skill for wind power, solar power, hydropower and energy demand proxies. While challenges remain, the forecasts captured broad regional patterns with reasonable skill:

- For solar PV CF, the July 2024 forecast correctly anticipated negative anomalies across Northern Africa and positive anomalies in the south;

- For hydropower, forecasts broadly matched observed deficits in southern and central regions during the dry season;

- Energy demand forecasts, driven by temperature outlooks, were particularly effective, anticipating both the high anomalies in Western and Central Africa and the milder-than-average signals in Ethiopia and Southern Africa.

The operational relevance of seasonal climate forecasts is thus clear. Their integration into grid operation, capacity planning and energy security strategies could yield substantial resilience dividends – especially when paired with expanding climate services tailored to energy stakeholders.

4.4 From monitoring to action: Operational needs

The collaboration between IRENA and WMO is advancing the tools and knowledge to integrate climate intelligence into energy planning in a routine and operational manner. This integration is essential for improving resilience, system efficiency and investment decisions across the renewable energy landscape. Key focus areas include:

Renewable resource atlases: Updated mapping of renewable resources helps identify high-potential zones for wind power, solar power and hydropower development. This is particularly vital in underdeveloped regions such as Africa, which currently accounts for only about 1.5% of global renewable energy capacity, despite possessing abundant and largely untapped resources. Improved spatial resolution and climate-adjusted resource assessments can support just energy transitions and long-term infrastructure planning.

Sub-seasonal and seasonal forecasts: These forecasts are increasingly being recognized for their utility in energy operations. Sub-seasonal forecasts – covering 2 to 6 weeks ahead – are particularly useful for short-term operational planning such as reservoir optimization, maintenance scheduling and anticipating shifts in weather-driven generation. Seasonal forecasts, on the other hand, provide insights on longer timescales (typically up to 6 months) and are especially relevant for capacity planning and strategic risk management. This report focuses specifically on seasonal forecasts, as they are routinely produced and disseminated by WMO Global Producing Centres, including those available via the C3S Data Store. These forecasts have demonstrated operational value. For instance, forecasts issued in June 2024 successfully anticipated key regional anomalies in July, including positive wind capacity factors in parts of Africa and deficits in solar resource across Central and Eastern Africa. Together, sub-seasonal and seasonal forecasts (S2S) are becoming increasingly important tools for short- to medium-term climate services for energy. Improving the uptake and resolution of these forecasts will allow system operators and planners to make better-informed decisions.

Data and observation infrastructure: A major research and operational bottleneck remains the limited availability and sharing of critical data. For example, wind speed measurements are often only available at 10 m, whereas turbine hub heights typically range from 80–120 m. Accurate vertical wind profiles are crucial for forecasting and model validation. While wind farm operators often collect wind speed data at hub height, such information is rarely made publicly available, limiting its broader use. Similarly, solar radiation measurements, cloud cover and surface temperature datasets are still sparse in many parts of the world, particularly in developing regions. These observations are not only essential for initializing numerical weather models and calibrating climate reanalysis datasets, but also for developing robust nowcasting and post-processing tools. In this context, satellite-based datasets play an increasingly important role, helping to fill observational gaps, especially for solar radiation and cloud cover, where ground-based measurements are lacking. Improving data-sharing practices and adopting international standards for data collection and quality management would significantly enhance the usability and comparability of observational datasets across regions and applications.

Energy system data: Beyond meteorological observations, improved transparency and harmonization in energy system data – electricity generation, installed capacity and electricity consumption – are critical for accurate modelling of capacity factors and system performance. While platforms like the ENTSO-E Transparency Portal provide valuable frameworks, even these contain inconsistencies and reporting lags. In many developing countries, real-time data access remains limited or non-existent. Furthermore, commercial sensitivities often restrict access to granular plant-level information, limiting the capacity to validate and operationalize integrated energy–climate tools.

Operationalizing climate services for energy requires not only advances in forecasting and modelling, but also greater investment in observational networks, improved data-sharing protocols and institutional partnerships to enable timely, transparent and high-quality data flows. Bridging these gaps will be central to enabling climate-informed planning and system operation in the global transition to renewable energy (WMO, 2023; Troccoli et al., 2024).

4.5 Cross-border energy considerations and compensatory strategies

From an electricity production standpoint, the regional declines in capacity factors for both wind and solar observed in 2024 – particularly across South Asia, South-East Asia and parts of Africa – highlight the importance of adopting compensatory strategies. These may include drawing on alternative generation sources or increasing electricity imports from neighbouring regions experiencing more favourable conditions.

For example, in 2024, countries like India, Pakistan and Cambodia saw solar PV CF anomalies ranging from −4% to −12%. Meanwhile, Central Asian countries such as Uzbekistan and Turkmenistan, as well as parts of the Middle East (e.g. Oman), experienced neutral to positive anomalies, suggesting opportunities for power balancing, assuming the necessary infrastructure and agreements are in place.

In Africa, parts of Western and Eastern Africa with negative CFs could, in principle, benefit from increased cross-border cooperation with solar-rich countries such as Zambia or the Democratic Republic of the Congo, which saw stronger solar performance in 2024. Similarly, Southern Africa’s positive wind and solar anomalies might offer export opportunities, though the regional installed capacity remains relatively modest.

It must be stressed, however, that such considerations are illustrative. They do not account for:

(i) Existing generation and storage capacity;

(ii) The availability and condition of transmission infrastructure;

(iii) Absolute CF values and the size of the anomaly relative to baseline capacity;

(iv) Critical meteorological factors affecting balancing at hourly or sub-hourly timescales.

Nonetheless, these insights underscore the value of incorporating climate-driven variability into energy planning. Cross-border energy cooperation, informed by seasonal forecasts and climate intelligence, can support grid resilience, optimize resource use and reduce the risk of supply-demand imbalances under increasingly volatile conditions.

4.6 Recommendations for a resilient energy future through renewables

Growing interest and concern over climate change, energy security and supply chain diversification has helped set a record deployment of renewable electricity generating capacities in 2024. However, despite this progress, the current pace remains far too slow to meet the global commitment to triple capacity by 2030.

Under present dynamics, the expansion of renewable energy remains highly unbalanced across different regions and countries of the world. A small handful of countries feature very prominently. However, for the tripling goal to be a meaningful marker, rapid progress is needed in coming years in a geographically balanced manner.

Achieving energy, climate and sustainability objectives requires a comprehensive and holistic policy package that not only focuses on the deployment of renewable energy systems per se but also encompasses action along the entire value chain, including equipment manufacturing, grid and storage infrastructure, and expansion of mini-grids and other decentralized energy systems.

Geopolitical and geoeconomic dynamics are also increasingly translating into new trade policies with a variety of tariff and non-tariff measures. The desire in many countries to localize part of the value chain is palpable, as it helps to ensure that local communities can derive a greater share of the socioeconomic benefits (such as jobs) that the energy transition offers. However, the emerging zero-sum dynamics are elevating confrontation over cooperation and could produce more losers than winners.

It is also important that policymakers not lose sight of the demands of science. The current report, and its previous editions, have proven the critical role of climate variability in reshaping renewable energy performance and energy demand on an annual basis. In such a context, policymakers must also address both the risks and opportunities posed by climate-driven resource fluctuations in renewable-dependent systems.

Integrating climate-informed planning and management into policy frameworks is therefore essential, not only to safeguard system reliability, but also to ensure that infrastructure investments, market regulations and resilience measures are aligned with long-term sustainability and climate goals.

The risks to address are multiple. From an operational perspective, they include designing energy systems with sufficient flexibility to adapt to fluctuation in resources availability, while also anticipating shifts in consumption patterns driven by temperature extremes and seasonal variability. From a planning perspective, there is also a need for a broader adoption of climate-informed renewable energy scenarios with seasonal forecasts to help energy planners anticipate risk and reduce climate-related stress on energy systems.

Opportunities, on the other hand, lie in embedding improved climate data into policy frameworks, which could attract climate-smart investment, guide infrastructure development and strengthen early warning systems.

Accordingly, rising investment is indispensable – not only in technology development and installations of renewable energy capacities, but also in building in the kind of redundancy that supports greater resilience, and in supporting the human dimension of the transition. Achieving a successful energy transition depends on people – their skills, dedication and ingenuity. Employment in all renewable energy sectors has expanded steadily, to an estimated 16.2 million jobs in 2023, according to IRENA, and will continue to evolve to reflect climate-related skills needs. Greater investment is required in education and training, workforce development and labour market measures, particularly to strengthen system modelling and forecasting capabilities. This will ensure the world can continue building the skilled workforce necessary for a successful and resilient energy transition.[24]

[24] https://www.irena.org/Publications/2024/Oct/Renewable-energy-and-jobs-Annual-review-2024

Appendix 1. Methodology

To assess 2024 patterns of renewable energy resources and demand anomalies we use the 1991–2020 period as a baseline in all cases. This period is officially designated as the new climatological normal.

All calculations for wind power, solar power and hydropower (or their proxies) are based on global monthly data with 0.25° resolution. Wind and solar anomalies are estimated using the power capacity factors. We use precipitation as a proxy for hydropower, but it is weighted according to the number of hydro power plants (HPP) and their installed capacity in a particular area.

Once the power generation (or its proxy) for each of the three renewable energy (RE) sources is calculated, we explore their co-variability and their role in the energy mix in a qualitative way. We also compare the generation indicators with the energy demand proxy.

The following sections describe the methods adopted for the computation of each of the four energy indicators (three for generation and one for demand).

Limitations of climate data

All of the energy indicators are based on climate data from the ERA5 reanalysis (Hersbach et al., 2020). While ERA5 is considered an excellent global reanalysis, the fact that it is, as with all reanalyses, a combination of observations and numerical weather model processes, it is in general not as accurate as direct observations. Reanalyses are used as they provide complete datasets, both temporally (over the required period, 1991–2023) and spatially (at 0.25° x 0.25° over the whole globe), which is normally not the case with observations. Alternative observational datasets, such as the Global Precipitation Climatology Centre (GPCC) for precipitation and CLARA-A3 for solar radiation, are in principle available and valuable; however, ERA5 was chosen for its harmonized, self-consistent structure and broad variable coverage, which facilitates integration into the Copernicus Climate Change Service (C3S) Energy Service and its derived energy indicators as used in this publication.

Masks

For each energy source, an appropriate mask is used in addition to a general land-sea mask. The details for each mask are given below in the appropriate section, but in general, areas not suitable or which have restrictions for power plant construction (such as natural reserves, steep slopes, etc.) are excluded.

Display

Maps at a global level are presented as country averaged data. Further aggregation at a wider resolution (regions such as Northern Europe, Southern Europe, Northern Asia, etc.) is also conducted by computing a weighted average of the country anomalies, taking into consideration area extent or population (for EDD), mean country climatological values or the countries' installed capacities (in the case of the hydropower proxy) (further details are available in the indicators' specific sections). Also, for selected countries, time series of percent anomalies for each month of 2024 with respect to the corresponding month of each of the 30 baseline years (1991–2020) are calculated and displayed as violin plots.

1. Wind power capacity factor calculation

We use the wind power capacity factor data produced by the C3S Energy Service[25] for 1991–2020 and 2024. It represents the percentage of power output over nominal power expected from a wind turbine on a specific point of the grid for a specific time.

Base data

Wind speed at 100 m from C3S Energy Service:

- Spatial resolution: 0.25° x 0.25° latitude/longitude
- Coverage: Global
- Temporal resolution: Monthly
- Temporal period: 1991–2020 and 2024

Wind mask

- This product, produced by the C3S Energy Service, is considered as time-invariant
- Spatial resolution: 0.25° x 0.25° latitude/longitude
- Coverage: Global
- Binary layers accounting for:
  - Protected areas
  - Topographic conditions with high elevations and high slopes
  - Areas of urban coverage
  - Polar areas

Land-sea mask

A simple mask that identifies land and oceans at 0.25° (from ERA5); the same mask is used for solar power.

Formula used by C3S Energy Service

$$CF_{t,i,j} = \frac{1}{n} \sum_{t \in T} \frac{P_{output}^{t,i,j}\left(W_{100}^{t,i,j}\right)}{P_{nominal}}$$

where:

$W100^{t,i,j}$: wind speed at 100 m above surface at time *t*, latitude *i* and longitude *j* (m/s)

$Poutput^{t,i,j}$: net electrical power output at time *t*, latitude *i* and longitude *j* (MW)

$Pnominal$: nominal output of the wind turbine (MW)

[25] To be made available on the C3S Climate Data Store (CDS) in 2026 Q1: see https://cds.climate.copernicus.eu/

T: time considered, e.g. day

t: hours in the interval *T*

n: number of hours in *T*

i,j: latitude *i* and longitude *j* of the grid point

$Poutput^{t,i,j} = f(wind\ speed\ 100m^{t,i,j})$ is the power curve of the selected wind turbine, in this case the GE Energy 2.5-103 model turbine.[26]

Workflow

The wind power capacity factor (CF) data behind the figures is calculated, starting from the C3S Energy Service gridded data, as follows:

1. Mask the monthly gridded wind capacity factor data using the land-sea mask (that masks out all oceans);
2. Spatially aggregate data at country level (ADM0):
   a. Consider grid points for each country and retain only the points for which the climatological CF is above threshold of 0.05, to avoid including areas where wind power is unlikely to be developed;
   b. Retain a country only if the number of grid points above the threshold is greater than 20% of all grid points for that country, otherwise the country is not considered (i.e. set to NA);
3. Calculate anomalies for 2024 using 1991–2020 as baseline (monthly means):

   Anomaly= Monthly mean of 2024 – monthly mean of the period 1991 to 2020;
4. Calculate region anomalies as follows:

$$PA_{reg} = \frac{\sum_{i=1}^{n} A_i \cdot CF_i^{(H)} \cdot PA_i}{\sum_{i=1}^{n} A_i \cdot CF_i^{(H)}}$$

   where i indicates one of the n countries contained in region reg, PA stands for percent anomaly value (e.g. 2024 versus baseline), A_i indicates the country area extent (km²), and $CF_i^{(H)}$ the mean historical capacity factor for the country (mean over climatological baseline period).

2. Solar photovoltaic power capacity factor calculation

The solar photovoltaic (SPV) power model developed for C3S Energy Service estimates electricity generation from utility-scale, fixed-tilt, ground-mounted PV systems using hourly climate data. The model builds on the methodology of Saint-Drenan et al. (2018), incorporating optical, thermal and electrical losses, and assumes a standardized plane-of-array (POA) orientation – south-facing in the northern hemisphere – with tilt angles set to 75% of the site-specific optimal, derived from ERA5 reanalysis data (2015–2020). This tilt adjustment balances irradiation capture with reduced inter-row shading to enhance land-use efficiency. The model adopts a simplified configuration by applying a single orientation and tilt per

[26] The GE Energy 2.5-103 is a three-bladed, upwind onshore wind turbine with a rated capacity of 2.5 MW and a cut-in wind speed of 3.5 m/s. It features a 103 m rotor mounted on a tubular steel tower – typically 100 m tall – and pairs this with a high-capacity generator to deliver strong energy output in moderate wind conditions, offering both reliability and adaptability across varied terrain (https://www.thewindpower.net/turbine_en_1112.php).

location, enabling computational scalability for global applications. It further accounts for the improved cooling conditions typical of open-field installations, thereby reducing thermal losses relative to rooftop systems.

Base data

Downward solar irradiance (radiation within a wavelength interval 0.2–4.0 μm) from ERA5:[27]

- Spatial resolution: 0.25° x 0.25° latitude/longitude
- Coverage: Global
- Temporal resolution: Monthly
- Temporal period: 1991–2020 and 2024

Air temperature at 2 m from ERA5 reanalysis data:

- Spatial resolution: 0.25° x 0.25° latitude/longitude
- Coverage: Global
- Temporal resolution: Monthly
- Temporal period: 1991–2020 and 2024

Workflow

The SPV capacity factor (CF) data behind the figures is calculated, starting from C3S Energy Service gridded data, as follows:

1. Mask gridded solar capacity factor data using the land-sea mask;
2. Spatially aggregate data at the country level (ADM0):
    a. Consider grid points for each country and retain only the points for which the climatological CF is above the threshold of 0.05, to avoid including areas where PV solar power is unlikely to be developed;
    b. Retain a country only if the number of grid points above the threshold is greater than 20% of all grid points for that country, otherwise the country is not considered (i.e. set to NA);
3. Calculate anomalies for 2024 using the same baseline and formulas as for wind power;
4. Calculate region anomalies using same approach and formula as for wind power.

3. Hydropower proxy

The installed capacity weighted precipitation (IWP) is a simplified proxy produced by the C3S Energy Service for estimating hydropower potential based on precipitation patterns and the spatial distribution of hydropower (HP) infrastructure. It combines monthly total precipitation from the ERA5 dataset with georeferenced hydropower plant data, including installed capacity (IC). While alternative observation-based gridded precipitation datasets, such as from GPCC, exist and are also used in other WMO reports, ERA5 was selected to ensure consistency across the C3S Energy Service. Notably, the spatial patterns observed in our results are broadly

[27] Note that for detailed national assessments, high-quality satellite-based datasets are also available.

consistent with GPCC, suggesting that the use of anomalies helps mitigate bias-related concerns. The use of GPCC or other observational datasets could be explored in future analyses.

Both operational and "in-construction" HP plants are considered, to account for important near-future hydropower installations, and are assigned, based on their locations, to administrative regions (NUTS2 for Europe; ADM1 elsewhere), and precipitation is cumulated (to mimic accumulation of water for HP) over a country-specific number of months (n), chosen to best reflect observed HP generation patterns where available.[28] Each region's precipitation is weighted by its share of national hydropower capacity, and the national IWP value is computed as the weighted average.

Base data

Precipitation from ERA5:

- Spatial resolution: 0.25° x 0.25° latitude/longitude
- Coverage: Global
- Temporal resolution: Monthly averages
- Temporal period: 1991–2020 and 2024

Plant locations and installed capacity

We use the HP plants information coming from the Global Energy Monitor (GEM)[29] hydropower database, which is a comprehensive and up-to-date database:

- Spatial resolution: Latitude/longitude datapoints
- Coverage: Global

Workflow

The IWP hydropower proxy data is already available at the country level (ADM0), therefore the data behind the figures is simply obtained as follows:

1. Calculate anomalies for 2024 using the same baseline and formulas as for other energy indicators;
2. Calculate region anomalies as follows:

$$\mathrm{PA}_{\mathrm{reg}} = \frac{\sum_{i=1}^{n} \mathrm{IC}_i \cdot \mathrm{PA}_i}{\sum_{i=1}^{n} \mathrm{IC}_i}$$

where i indicates one of the n countries contained in region reg, PA stands for percent anomaly value (e.g. 2024 versus baseline) and IC_i indicates the country's total hydropower installed capacity.

[28] Monthly power generation data for available countries were taken from EMBER (https://ember-climate.org/data-catalogue/monthly-electricity-data).
[29] The Global Energy Monitor includes a Global Hydropower Tracker, which is a worldwide dataset of hydropower facilities with location, status and installed capacity, among other information (https://globalenergymonitor.org/projects/global-hydropower-tracker/).

4. Energy demand proxy

To provide an assessment of the (im)balance between demand and renewable energy, in the context of energy mix, we consider an energy demand proxy.

Given the sparsity and disparity of energy demand data at monthly resolution for all (or most) countries covering the 1991–2020 baseline period, the use of proxy data had to be considered instead. To this end, the Energy Degree Days (EDD) indicator – the sum of Cooling Degree Days (CDD) and Heating Degree Days (HDD)[30] – as a proxy for energy (electricity) demand is selected. The definition of EDD has been used for Europe (Spinoni et al., 2017) and globally (Spinoni et al., 2021). Having only one single demand indicator, EDD, rather than two, CDD and HDD, allows us to simplify the presentation and discussion.

Global EDD data are made available by the C3S Energy Service as a sum of CDD and HDD, calculated as described in Table 2, starting from ERA5 2-m air temperature data. CDD is a climate indicator used to estimate energy needs and demand for cooling purposes. It is defined as the monthly sum of the daily differences between a reference temperature (perceived as comfortable) and the daily average of the outside air temperature (at 2-m height, T2M), but only when T2M exceeds a threshold temperature. This condition defines the "cooling days" throughout the year, according to the following formula (all temperatures in °C):

If $T2M \geq T_{threshold}$: $CDD = T2M - T_{ref}$

If $T2M < T_{threshold}$: $CDD = 0$

This is referred to as CDDThold21 (IEA/CMCC, 2023; Scoccimarro et al., 2023), with reference temperature 21 °C and threshold temperature 24 °C. As an example, this means that if the daily mean air temperature is 26 °C, for that day the value of the CDD is 5 (26 °C – 21 °C). If the daily mean air temperature is 22 °C, for that day the CDD is 0.

Similar to CDD, HDD is a climate indicator used to estimate energy needs and demand for heating purposes. There are several operational definitions of HDD. For the present report, HDD is defined as the monthly sum of the daily differences between a reference temperature (perceived as comfortable) and the daily average of the outside air temperature (at 2-m height, T2M), but only when T2M falls below a threshold temperature. This condition defines the "heating days" throughout the year, according to the following formula (all temperatures in °C):

If $T2M \geq T_{threshold}$: $HDD = 0$

If $T2M < T_{threshold}$: $HDD = T_{ref} - T2M$

The HDD definition of HDDThold18 (IEA/CMCC, 2023; Scoccimarro et al., 2023) has been used, with reference temperature 18 °C and threshold temperature 15 °C. As an example, this means that if the daily mean air temperature is 12 °C, for that day the value of the HDD is 6 (18 °C – 12 °C), whereas if the daily mean air temperature is 16 °C, for that day the HDD is 0.

Since the spatial distribution of population highly influences the energy demand of a country, EDD gridded data are weighted by population prior to calculating country averages.

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[30] HDD (CDD) assesses the level of the cold (heat) over a specific time period, typically a month, taking into consideration outdoor temperature and average room temperature, to infer the need for heating (cooling), and then counting how many days the temperature is above or below a predefined threshold.

Table 2. Selected indices for CDD and HDD (see also the Weather for Energy Tracker)

Variable	Short name	Short explanation
CDD (21 °C, 24 °C threshold)	CDDThold21	Cooling degree days (reference temperature 21 °C and threshold temperature 24 °C. Examples: if the daily mean air temperature is 26 °C, for that day the value of the CDD is 5 (26 °C – 21 °C). If the daily mean air temperature is 22 °C, for that day the CDD is 0).
HDD (18 °C, 15 °C threshold)	HDDThold18	Heating degree days (reference temperature 18 °C and threshold temperature 15 °C. Examples: if the daily mean air temperature is 12 °C, for that day the value of the HDD is 6 (18 °C – 12 °C). If the daily mean air temperature is 16 °C, for that day the HDD is 0.)
EDD	**EDD**	**Sum of CDDThold21 and HDDThol18**

Base data

Air temperature at 2 m from ERA5 reanalysis data:

- Spatial resolution: 0.25° x 0.25° latitude/longitude
- Coverage: Global
- Temporal resolution: Monthly
- Temporal period: 1991–2020 and 2024

Population data

Provided by the Euro-Mediterranean Center on Climate Change (CMCC)[31](year 2020 used as reference):

- Spatial resolution: 0.25° x 0.25° latitude/longitude
- Coverage: Global

[31] CMCC data are derived from: (i) the Center for International Earth Science Information Network (CIESIN, Columbia University) Gridded Population of the World Version 4 dataset, 2018; and (ii) the European Commission Joint Research Centre GHS population grid (IEA/CMCC, 2023). Data for a reference year (2020) are used both for baseline years (1991–2020) and the year 2024, to focus on the effect of climate on energy demand.

Workflow

EDD proxy data are already available (C3S Energy Service) at country level (ADM0), therefore the data behind the figures is simply obtained as follows:

1. Calculate anomalies for 2024 using the same baseline and formulas as for other energy indicators;

2. Calculate region anomalies as follows:

$$\mathrm{PA}_{\mathrm{reg}} = \frac{\sum_{i=1}^{n} \mathrm{Pop}_i \cdot \mathrm{EDD}_i^{(H)} \cdot \mathrm{PA}_i}{\sum_{i=1}^{n} \mathrm{Pop}_i \cdot \mathrm{EDD}_i^{(H)}}$$

   where i indicates one of the n countries contained in region reg, PA stands for percent anomaly value (e.g. 2024 versus baseline), Pop_i indicates the country population count, and $\mathrm{EDD}_i^{(H)}$ the mean historical EDD value for the country (mean over climatological baseline period).

Appendix 2. Seasonal forecast assessment

Seasonal forecasts bridge the gap between short-term weather forecasts and long-term climate projections. They provide probabilistic forecasts of key climate variables, such as temperature, precipitation, solar radiation and wind patterns, that directly affect renewable energy resources. Wind and solar power production, for example, are highly sensitive to atmospheric conditions, while hydropower generation depends on streamflow levels influenced by rainfall. Incorporating these forecasts into operational and management planning can help minimize risks, reduce costs and maximize energy efficiency.

Recent advances in climate modelling and the increasing availability of tailored forecast products, such as those provided by the Copernicus Climate Change Service (C3S, 2023), make this approach more accessible than ever. The integration of seasonal forecasts could save millions of dollars annually by reducing unexpected disruptions and optimizing resource allocation (IRENA, 2023; Troccoli, 2010; Troccoli, 2018).

At the same time, the ability to produce skilful predictions a few months in advance is somewhat limited, depending on both the region and the variable. For instance, regions affected by strong climate drivers such as ENSO generally allow for more accurate predictions, whereas skill is often lower for mid-latitude regions like Europe. Similarly, forecasts tend to be more accurate for relatively homogenous variables such as temperature compared to precipitation or wind speed.

Given that seasonal forecasts are probabilistic in nature, it is not possible to determine whether a forecast is accurate or not based on a single event – in this case, the forecast for July 2024, as considered in the present report (Section 3). This is why it is essential to assess model performance using historical data. To achieve this, forecast skill metrics are applied to retrospective forecasts, which, in this case, cover the period 1993–2016.

Seasonal forecast skill measure

There is a wide variety of metrics available for assessing seasonal forecasts, ranging from deterministic metrics (which rely on ensemble means) to probabilistic ones that consider the full ensemble distribution. For the present assessment, we selected the Continuous Ranked Probability Skill Score (CRPSS), a probabilistic metric that is particularly well suited to evaluating the performance of multi-category seasonal forecasts (see Table 3).

The CRPSS compares the Ranked Probability Score (RPS) of the actual forecast against the RPS of a reference (typically climatology-based) forecast. The RPS evaluates how well forecasts distinguish among possible outcomes and penalizes both displacement errors and incorrect confidence levels. A positive CRPSS indicates that the forecast outperforms the climatological reference, with 1 being a perfect score and 0 indicating no improvement over the reference. The CRPSS is particularly practical as it condenses the information from the entire ensemble into a single value, unlike measures such as the Brier Skill Score, which focus only on specific parts of the distribution (such as the upper tercile).

Table 3. Summary of the main features of the Continuous Ranked Probability Skill Score (CRPSS)

Metric	Purpose	Range	Characteristics
Continuous Ranked Probability Skill Score (CRPSS)	Measures relative improvement of a probabilistic forecast over climatology in predicting the observed outcome's category.	The range is from negative infinity to 1. A score of 0 indicates no skill when compared to the reference forecast. A score of 1 is a perfect score.	Evaluates full forecast distribution. Strictly proper scoring rule. Accounts for climatological frequency. Sensitive to sample size. CRPSS is a generalization of RPSS, whereby the thresholds are continuous rather than discrete.[a]

[a] https://confluence.ecmwf.int/display/FUG/Section+12.B+Statistical+Concepts+-+Probabilistic+Data#Section12.BStatisticalConceptsProbabilisticData-RankProbabilityScores(RPS)

The forecast skill scores presented below are calculated for the four countries in Western Africa highlighted in the Regional Perspectives section of the current report: Ghana, Côte d'Ivoire, Guinea and Nigeria. Figures 18–21 display the CRPSS values for July predictions, calculated from forecast start dates ranging from (1st of) June (1-month lead) back to (1st of) February (5-month lead). Each figure corresponds to one of the four energy indicators.

It is important to note that the metric, in our case the CRPSS, measured over this period, only gives an indication of the quality of the forecast; in practice, years with strong climate signals from, for example, ENSO or IOD, as was the case in 2024, might provide a higher quality forecast. Additionally, forecast skill tends to be higher in the tropics compared to the extra-tropics, even if coastal and complex terrains like those found in Western Africa are more challenging than others, as ocean–atmosphere interactions in this region are not fully resolved in most global models, limiting forecast reliability (Vellinga et al., 2013; Pirret et al., 2020).

Since the skill shown in Figures 18–21 reflects the quality of retrospective forecasts over the period 1993–2016, it is not possible to draw definitive conclusions about the accuracy of the specific forecast for July 2024 shown in Figures 14–17 (right).

Wind power CF

Wind power generally shows low seasonal forecast skill. CRPSS values are close to zero or negative. This is expected given the chaotic nature of wind at regional scales, which is less directly influenced by dominant climate modes such as ENSO. However, three observations are worth noting: (i) unlike the other countries, Guinea's skill scores are generally closer to zero, with positive values at the 2- and 4-month leads; (ii) rather than a clear decrease in skill with increasing lead time, a seasonality appears, with the 4-month lead (forecast issued 1 March) displaying the most favourable results; (iii) these findings are somewhat in contrast with the relatively good agreement between the 2024 forecast and observed anomalies (Figure 14, right and centre), suggesting that skill may vary substantially year to year, depending on climate drivers and regional dynamics.

Solar power CF

Solar radiation is influenced by large-scale cloud cover and aerosol distributions, often linked to ENSO and monsoonal variability. The CRPSS for solar PV forecasts in July shows generally low or negative skill, particularly at longer lead times, highlighting the challenges in forecasting solar capacity factors at seasonal scale. Among the four countries analysed, Côte d'Ivoire shows the highest skill, albeit still modest (Figure 19). Nonetheless, as for wind power, the July 2024 forecast showed good alignment with observed anomalies (Figure 15, right and centre), suggesting that skill may be enhanced in years with strong, predictable climate signals.

Hydropower proxy

The hydropower generation proxy, represented by accumulated precipitation, shows moderate forecast skill. For July, the CRPSS indicates positive forecast skill at 1- and 2-month lead times, though scores vary across the four countries analysed (Figure 20). Forecast skill tends to decline beyond 2-month leads, but notable exceptions are observed in Ghana and Guinea, where positive CRPSS values persist at 4- and 5-month leads. However, forecast performance remains sensitive to basin-scale precipitation variability and is typically lower during transitional seasons. For smaller countries, or those with complex topography and limited data, the use of generalized proxies presents significant challenges, highlighting the need for locally calibrated, country-specific models where possible. Overall, while the skill may be insufficient for fine-scale hydropower operations, it is suitable for anticipating broader regional hydropower trends and planning at seasonal timescales.

Energy demand proxy

Forecasts of temperature-driven energy demand exhibit the highest CRPSS among all four energy indicators. July predictions show consistently strong positive skill across all lead times, particularly at 1- to 3-month leads (Figure 21). One clear exception is Guinea, where the CRPSS is negative and warrants further investigation. The overall strong skill reflects the relatively high predictability of seasonal temperature patterns – especially in regions influenced by ENSO. Since energy demand is closely tied to temperature changes, this result supports the operational use of seasonal EDD forecasts to help anticipate cooling-related electricity needs and improve energy system resilience in Western Africa.

While seasonal forecasts are not deterministic, they offer valuable guidance when understood and used appropriately. The evaluation presented in the present appendix highlights the varying levels of skill across energy indicators and emphasizes the importance of adopting forecast-informed strategies in energy system planning. Over time, familiarity with forecast products and improvements in climate models will enhance their practical application and impact.

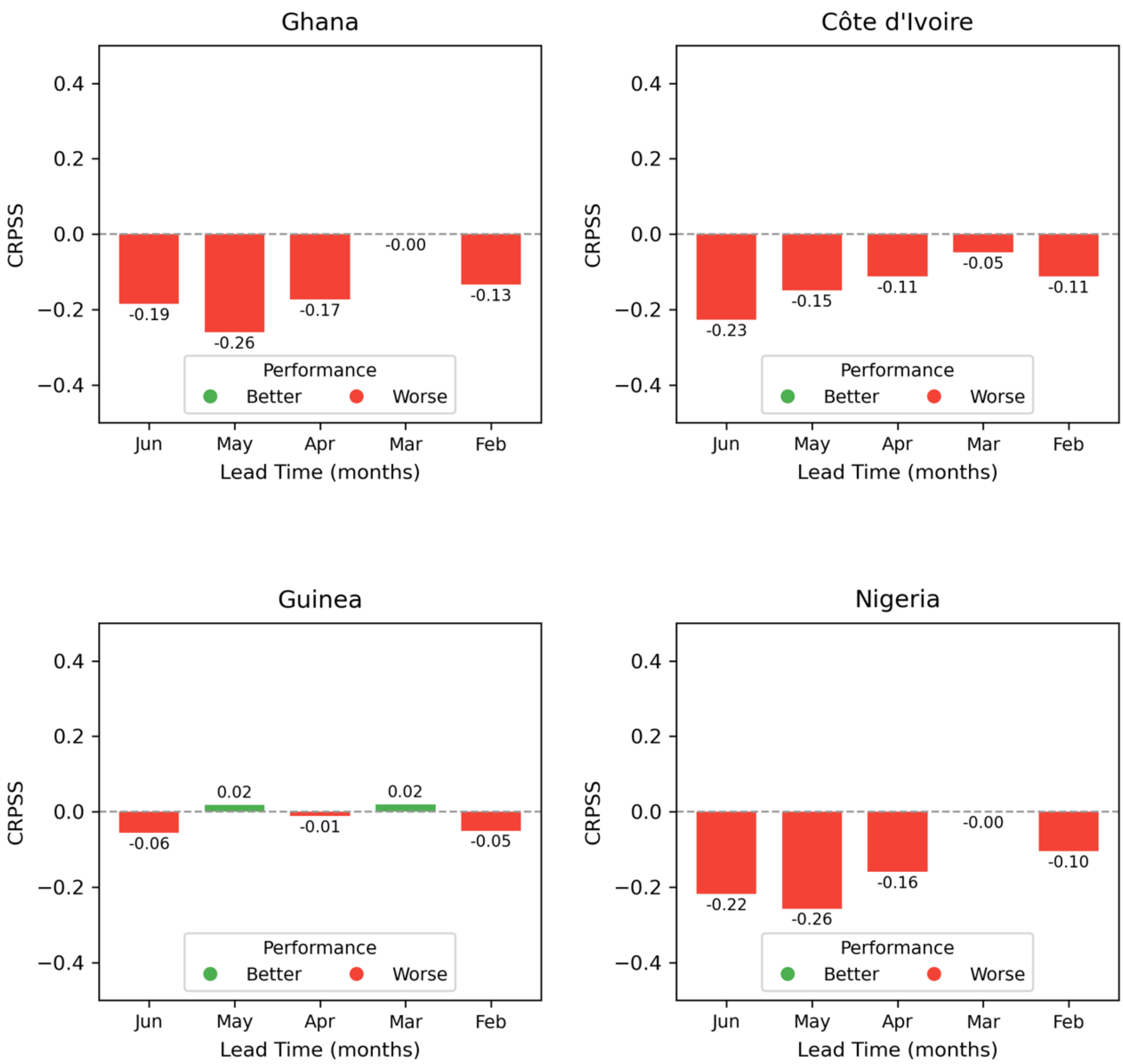


Figure 18. Assessment of the seasonal forecast using the Continuous Ranked Probability Skill Score (CRPSS) for wind speed, targeting July over the testing period 1993–2016, and focusing on the same four countries analysed in the regional perspective (Section 2.1): Ghana, Côte d'Ivoire, Guinea and Nigeria. The histogram bars represent the skill of the forecast initiated on 1 June (lead time 1, left-most), 1 May (lead time 2) and so on. Positive values indicate that the seasonal forecast model performs better, on average (over the testing period), than the climatological reference, while negative values (red) suggest that climatology may provide a more accurate forecast.

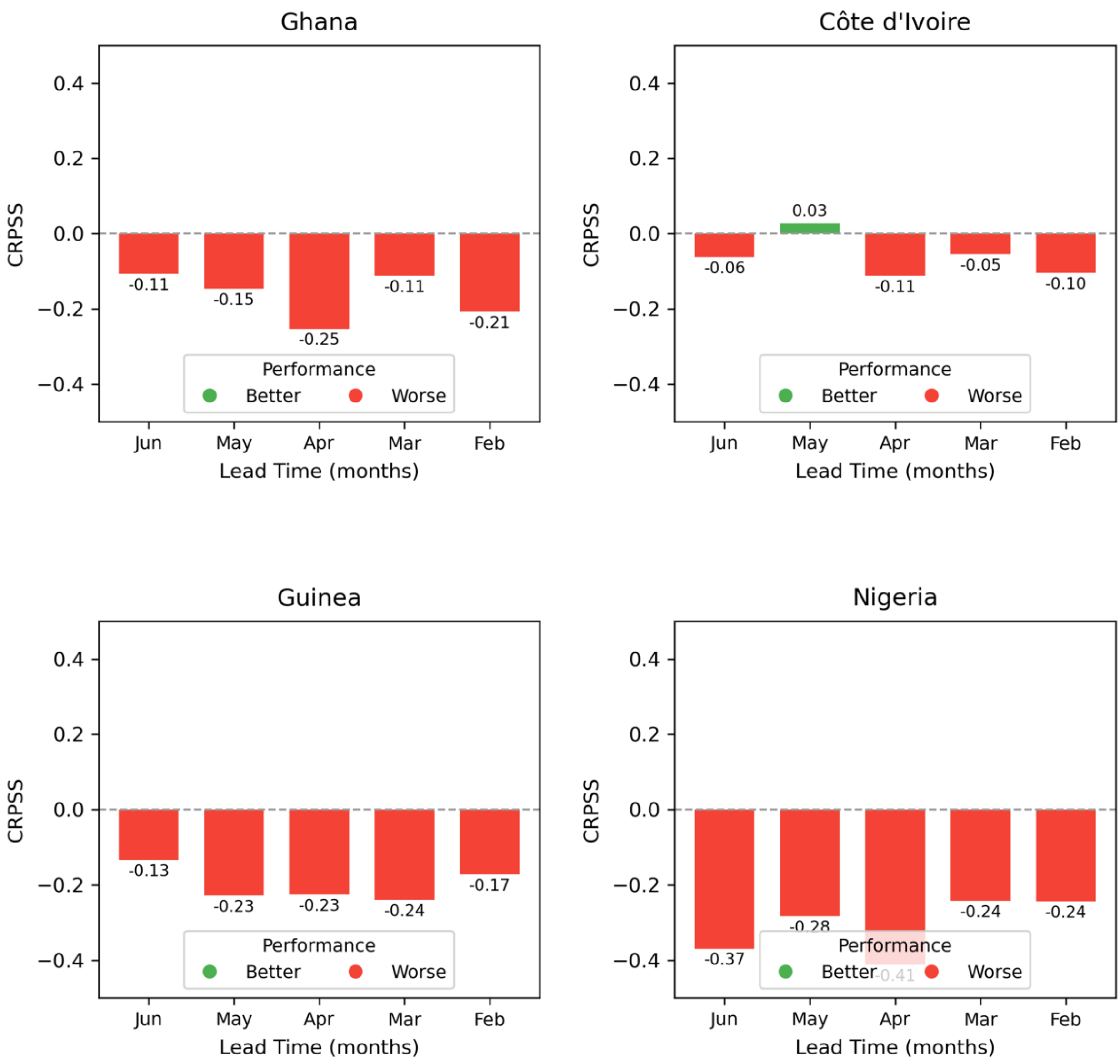


Figure 19. As in Figure 18, but for solar PV capacity factor

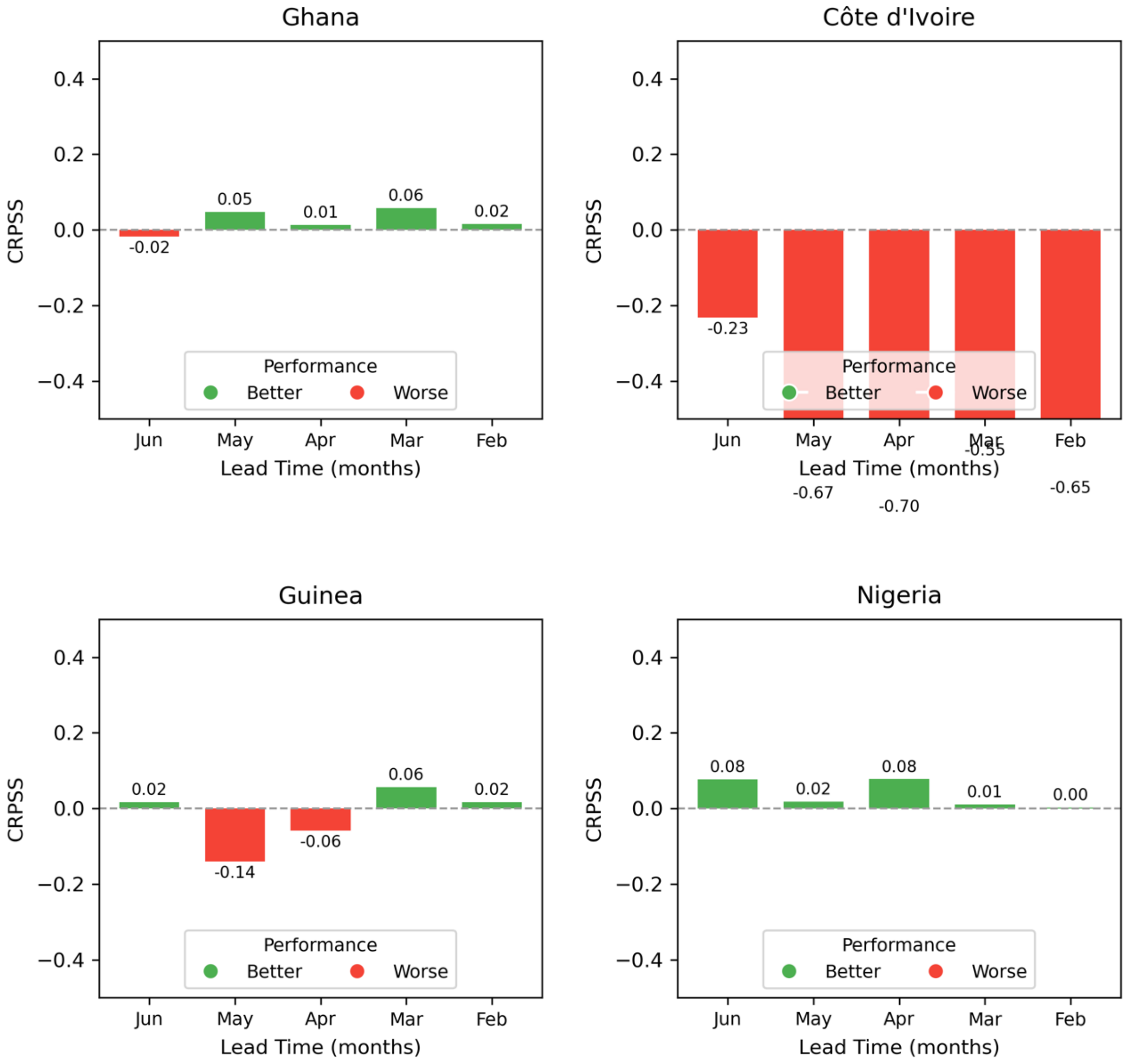


Figure 20. As in Figure 18, but for the hydropower proxy

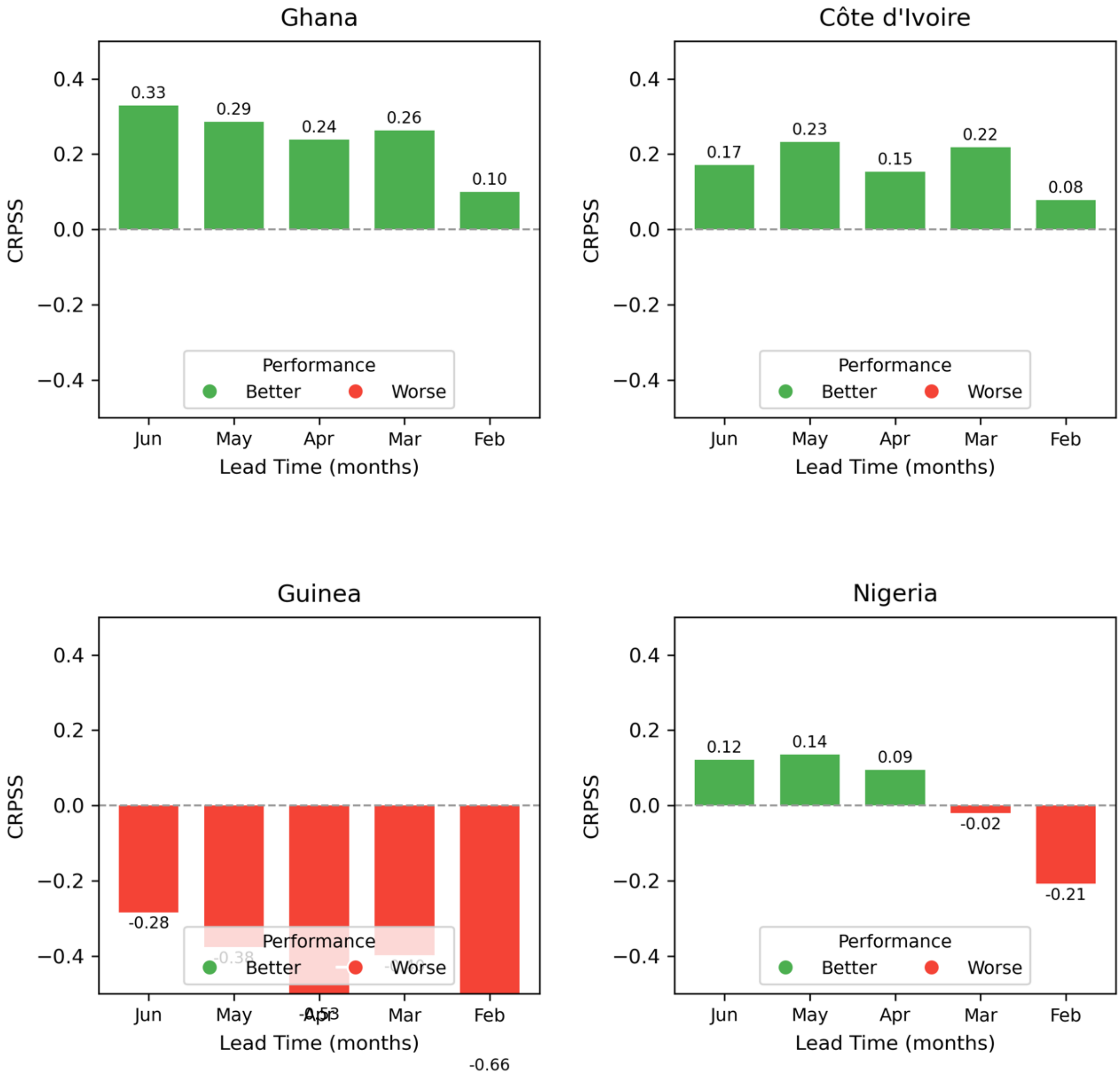
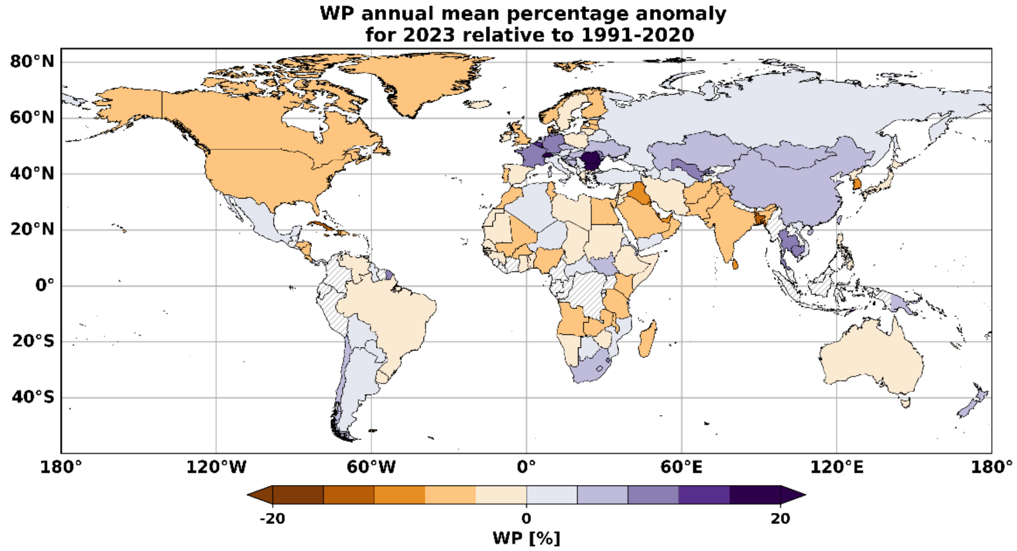


Figure 21. As in Figure 18, but for the energy demand proxy, namely the Energy Degree Days (EDD)

Appendix 3. Additional figures



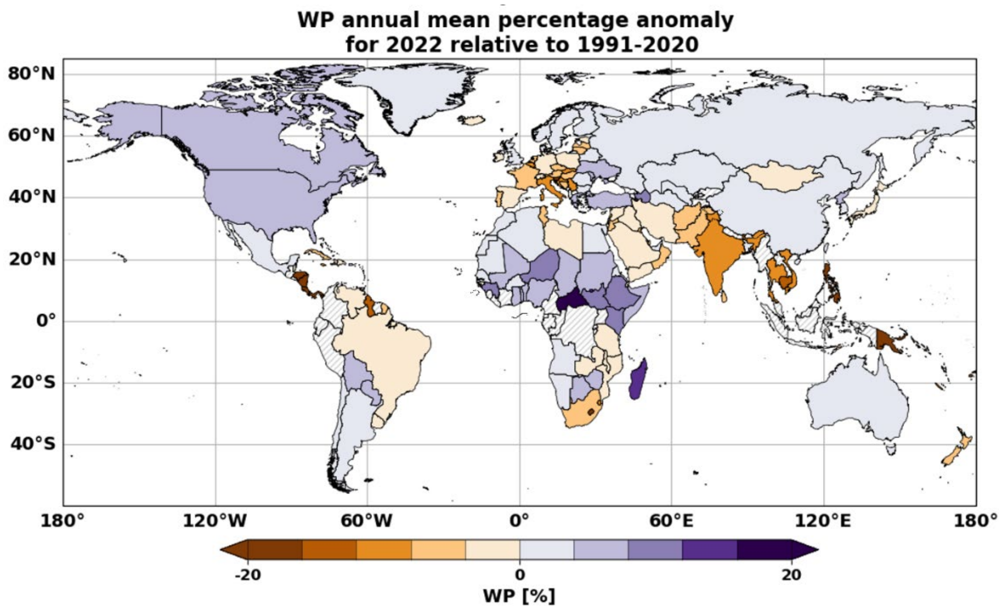
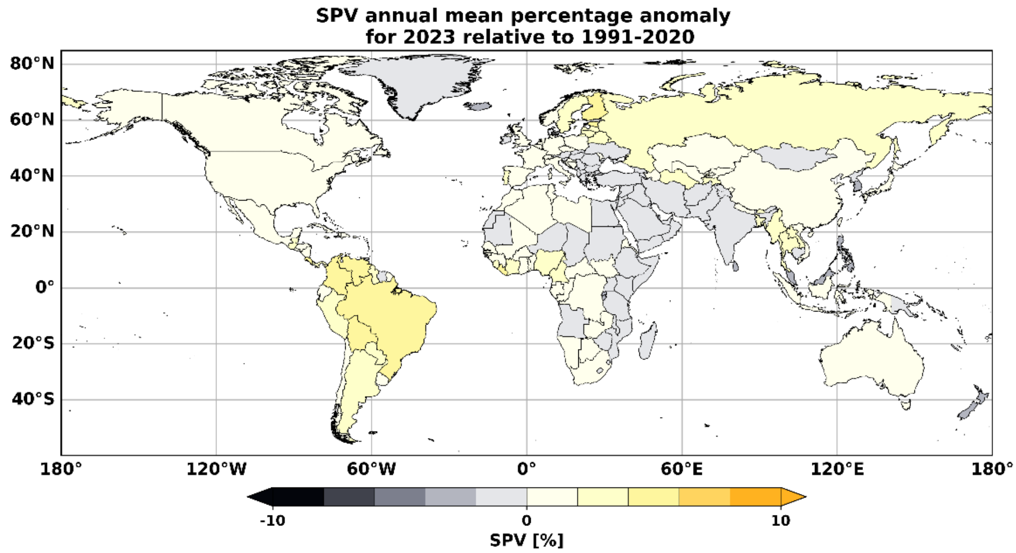


Figure 22. Global annual anomalies for the wind power capacity factor (expressed in %) for 2023 (left) and 2022 (right) relative to the average of the 1991–2020 reference period. Hatching indicates countries for which no data is available, due to assumptions made in the computation of wind power capacity factors (see WMO–IRENA, 2023; WMO-IRENA-C3S, 2024).

The boundaries and names shown and the designations used in this map do not imply official endorsement or acceptance by WMO or the United Nations.



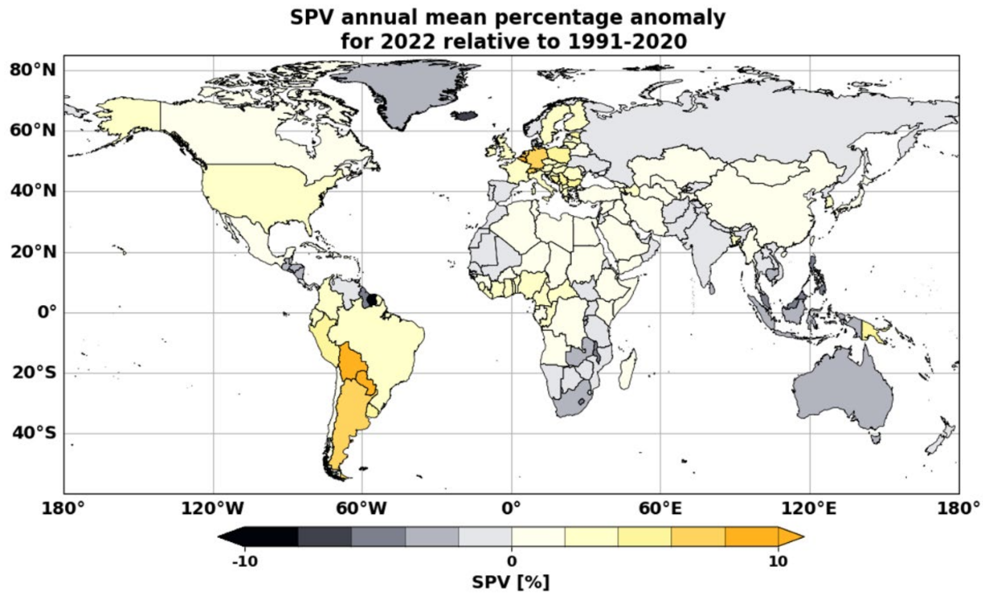
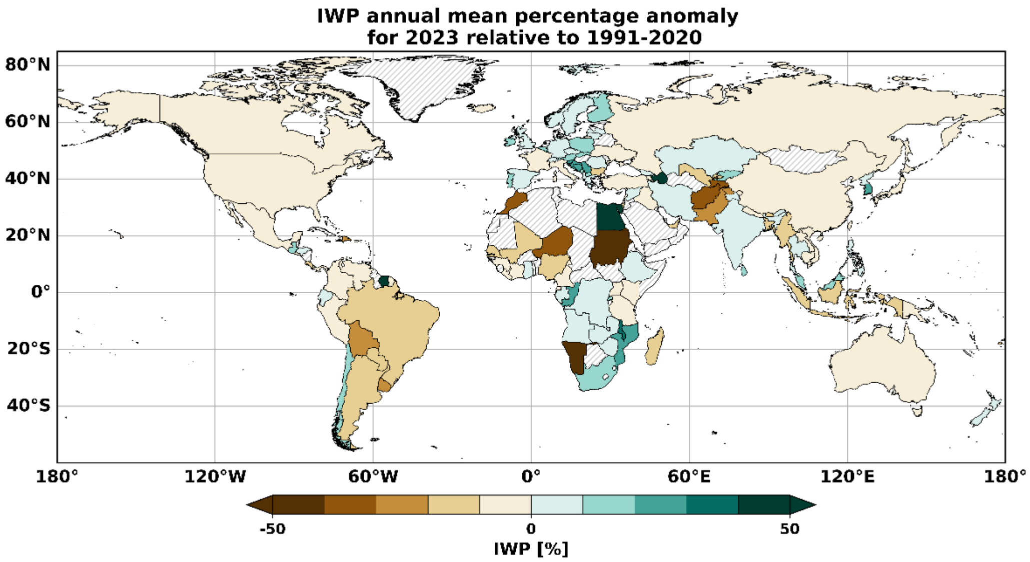


Figure 23. Global annual anomalies of solar PV power capacity factor (expressed in %) for 2023 (top) and 2022 (bottom) relative to 1991–2020 (see WMO–IRENA, 2023; WMO–IRENA–C3S, 2024)

The boundaries and names shown and the designations used in this map do not imply official endorsement or acceptance by WMO or the United Nations.



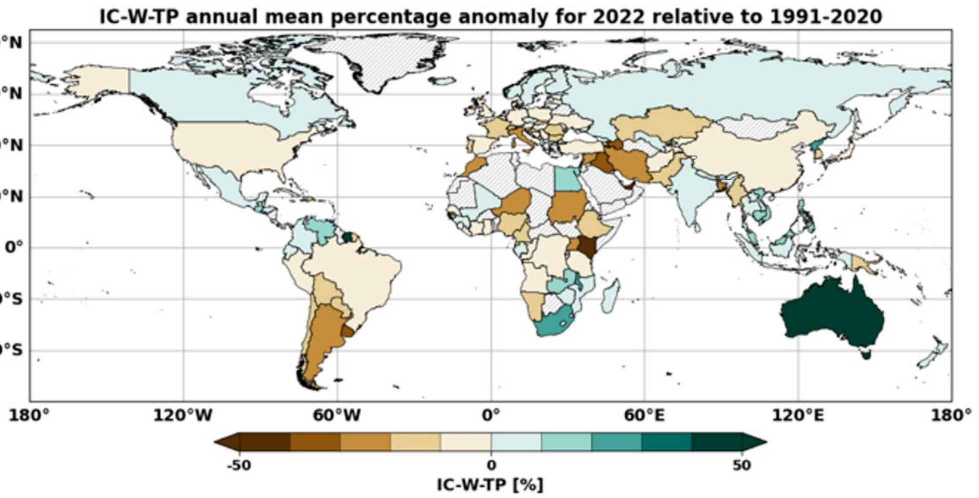
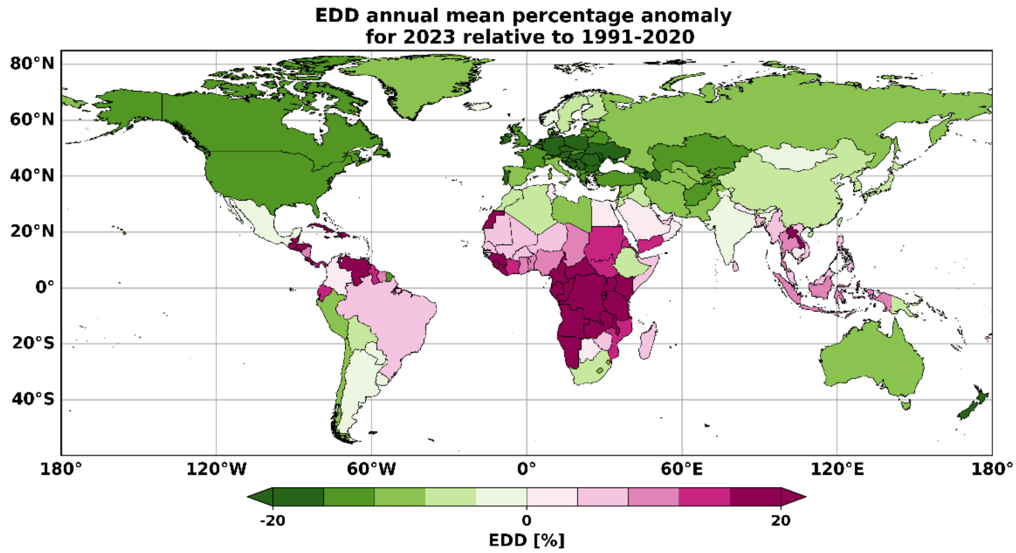


Figure 24. Hydropower proxy annual mean percentage anomaly for 2023 (top) and 2022 (bottom) relative to 1991–2020. Hatching indicates countries for which no data is available, due to assumptions made in the computation of this proxy (see WMO–IRENA, 2023; WMO–IRENA–C3S, 2024).

The boundaries and names shown and the designations used in this map do not imply official endorsement or acceptance by WMO or the United Nations.



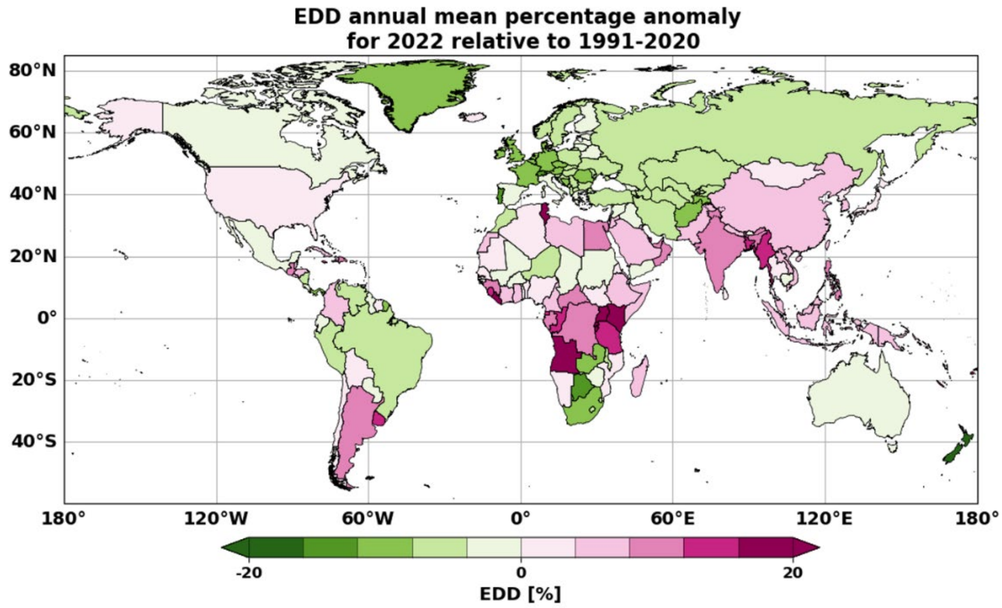


Figure 25. Energy Degree Days (EDD) annual mean percentage anomaly for 2023 (top) and 2022 (bottom) relative to 1991–2020 (see WMO–IRENA, 2023; WMO–IRENA–C3S, 2024)

The boundaries and names shown and the designations used in this map do not imply official endorsement or acceptance by WMO or the United Nations.

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