2023 Year in Review:
Climate-driven Global Renewable Energy Potential Resources and Energy Demand

WEATHER CLIMATE WATER

WORLD METEOROLOGICAL ORGANIZATION

IRENA
International Renewable Energy Agency

Climate Change Service
climate.copernicus.eu

Authors and contributors:

IRENA: Imen Gherboudj, Amjad Abdulla (ex-IRENA), Michael Renner, Kathleen Daniel, Zafar Samadov
ECMWF C3S: Chiara Cagnazzo, Julien Nicolas
WMO: Roberta Boscolo, Hamid Bastani, Christopher Hewitt, Robert Stefanski
WEMC: Alberto Troccoli, Penny Boorman, Kristian Nielsen
Inside Climate Service SRL: Giovanni Aldrigo, Elena Restivo, Mattia Zaramella, Stefano Cordeddu

Reviewed by: Ute Collier, Kamlesh Dookayka, Toyo Kawabata, Deborah Ayres, Marisol Osman, Ilias Pechlivanidis, Yuhan Zheng, Sajith Wijesuriya, and experts of the WMO Services Commission Study Group on Renewable Energy Transition (SERCOM SG-RENE)

Cover photo: Environmentally friendly installation of photovoltaic power plant and wind turbine farm situated by landfill. Solar panels farm built on a waste dump and wind turbine farm. Renewable energy source, Adobe Stock.

Chair, Publications Board
World Meteorological Organization (WMO)
7 bis, avenue de la Paix
P.O. Box 2300
CH-1211 Geneva 2, Switzerland
Tel.: +41 (0) 22 730 84 03
Email: publications@wmo.int

International Renewable Energy Agency (IRENA)
Masdar City, Abu Dhabi, P.O. Box 236
Email: publications@irena.org

ECMWF Communication Section – Copernicus Team
European Centre for Medium-Range Weather Forecasts, ECMWF
Robert-Schuman-Platz 3,
53175 Bonn, Germany
Email: Copernicus-press@ecmwf.int

NOTE

WORLD METEOROLOGICAL ORGANIZATION

IRENA International Renewable Energy Agency

PROGRAMME OF THE EUROPEAN UNION

Copernicus Europe's eyes on Earth

Climate Change Service climate.copernicus.eu

IMPLEMENTED BY ECMWF

Contents

Foreword 3

Executive summary........ 4

Key messages........ 5

1 Global perspective on renewable energy resources in 2023 7

1.1 Introduction 7

1.2 Key climate observations for 2023 9

1.3 Wind power capacity factor........ 10

1.4 Solar power capacity factor 12

1.5 Hydropower proxy indicator........ 15

1.6 Energy demand proxy indicator........ 17

2 Regional perspective........ 20

2.1 Africa........ 20

2.2 Asia 22

2.3 South America 25

3 Adaptation to climate variability with seasonal climate forecasts........ 27

3.1 Seasonal forecast of wind speed 28

3.2 Seasonal forecast for solar radiation........ 29

3.3 Seasonal forecast for precipitation........ 29

3.4 Seasonal forecast for temperature........ 30

4 Conclusions 32

4.1 Key messages........ 33

5 Methodology 34

5.1 Wind power capacity factor calculation 35

5.2 Solar photovoltaic power capacity factor calculation........ 36

5.3 Hydropower proxy 38

5.4 Energy demand proxy 39

5.5 Seasonal forecast skill measure 41

5.6 Seasonal forecast assessment........ 42

6 References 44

Foreword

The world stands at a pivotal moment in the race to secure a liveable planet for all. As climate change accelerates – propelled by the warmest decade on record – we must act collectively to keep the Paris Agreement climate goal within reach. To keep the long-term global average surface temperature increase well below 2 °C above pre-industrial levels and pursue efforts to limit it to 1.5 °C, we need to make urgent and drastic cuts in greenhouse gas emissions by decisively scaling up renewable energy solutions.

The milestones reaffirmed at COP28, and the global call to triple renewable energy capacity and double energy efficiency by 2030, spotlight the urgency and the feasibility of achieving a low-carbon, climate-resilient economy, backed by technological innovation, policy alignment and climate-informed strategies.

This second edition of the annual Year in Review: Climate-driven Global Renewable Energy Potential Resources and Energy Demand provides an overview of the inextricable link between climate variability/change and renewable energy. Whether it is solar power generation in drier-than-average conditions, wind power generation in regions experiencing shifts from La Niña to El Niño conditions, or hydropower generation in the face of fluctuating precipitation patterns, climate has a direct bearing on both energy supply and demand. Such challenges also present unprecedented opportunities: the integration of climate insights into energy planning yields more reliable power generation, helps anticipate seasonal peaks in demand and strengthens the adaptability of future infrastructure development.

The updated analysis presented here calls for advancing the tools, knowledge and policies for bridging climate science and energy innovation. It also recommends a shift to diversified energy portfolios to ensure energy security and resilience, and the creation of new market structures to account for the flexibility of new and clean power systems.

Collaboration across borders and sectors is essential. The report's findings also illustrate the critical importance of robust data collection and sharing, enabling more nuanced analysis to guide energy planners, policymakers and stakeholders in optimizing resource allocation, improving energy security and strengthening resilience to extreme events, particularly as the global energy transition accelerates.

Jointly produced by the Copernicus Climate Change Service (C3S), operated by the European Centre for Medium-Range Weather Forecasts (ECMWF), the International Renewable Energy Agency (IRENA) and the World Meteorological Organization (WMO), this report exemplifies the strength of collaboration among specialized international institutions coming together to respond the climate change challenge. This is the time to propel a new era of sustainable growth – one where integrated climate services and forward-thinking energy policies forge a more resilient, inclusive and prosperous global community.


Prof. Celeste Saulo
Secretary-General
World Meteorological Organization (WMO)


Francesco La Camera
Director-General
International Renewable Energy Agency (IRENA)


Dr Carlo Buontempo
Director of the Copernicus Climate Change Service at ECMWF

Executive summary

Scaling up renewable energy for a net-zero future

The global energy landscape stands at a pivotal moment, demanding urgent action to meet the climate goals outlined in the 2015 Paris Agreement and reinforced at COP28 in 2023. The UAE Consensus highlighted the critical need to triple the global renewable energy (RE) capacity and double energy efficiency by 2030. Achieving these targets is essential for limiting global temperature rise to 1.5 °C and reaching net-zero emissions by 2050. RE sources – solar, wind and hydropower – are critical for decarbonizing energy systems, ensuring energy security and building climate resilience, all while addressing the challenges of rising global energy demand.

The role of climate in renewable energy

The past two decades have witnessed steady growth in wind and solar power capacity, as well as their share in electricity grids worldwide. These energy sources, along with hydropower, are highly dependent on climatic and physiographic conditions, making an understanding of climate variability and change crucial for optimizing generation and ensuring energy system stability. Climate also plays a significant role in shaping energy demand, particularly for heating and cooling, underscoring the need for integrated analysis of energy supply and consumption patterns across geographic areas.

The climate context in 2023

Climate variability has emerged as a critical factor influencing RE generation and energy demand. The year 2023 marked a transition from La Niña to a mature El Niño phase, affecting key climatic variables such as wind speed, solar radiation, precipitation and temperature. These changes occurred against the backdrop of global warming. In 2023, the global mean near-surface temperature reached 1.45 °C ± 0.12 °C above the 1850–1900 average, making it the warmest year on record at the time, surpassing both 2016 and 2020. Understanding and managing these dynamics is essential for optimizing RE deployment and its generation and meeting growing energy demands sustainably.

Geographic variability in energy indicators

Key energy indicators – wind, solar, hydropower and energy demand – exhibited significant geographic variability in 2023, as shown by percentage deviations from the 1991–2020 climate reference period (see Figure A). Hydropower and energy demand indicators are expressed as proxies based on precipitation and heating/cooling requirements, respectively, and are not directly comparable to wind and solar capacity factor (CF) deviations.

Driven by drier and warmer El Niño conditions, South America experienced a 3.9% increase in solar photovoltaic (PV) CF, leading to an estimated 3.5 TWh/year of additional generation from the region's 50 GW installed capacity. Similarly, East Asia saw a 4.1% positive anomaly in wind power, generating an estimated 45 TWh from its 420 GW of installed onshore capacity, with 95% of this in China. These examples underscore the role of climatic factors in shaping RE generation and the need for adaptive energy planning strategies.

Advancing climate-informed energy planning

Integrating climate information into energy planning is increasingly critical to navigate the challenges of climate variability. Seasonal climate forecasts, supported by advances in climate modelling, as introduced in this report, offer probabilistic insights into resource variability and energy demand patterns, as demonstrated in this report through examples from South America. Such information and tools empower stakeholders to anticipate supply–demand fluctuations, optimize grid operations and enhance energy system resilience.

Hydropower reservoir management, wind farm siting and solar power optimization can benefit significantly from climate-informed decision-making. Seasonal forecasts also enable better preparation for extreme weather events, ensuring energy security and minimizing disruptions.

Policy implications for achieving 2030 targets

Diversified energy portfolios, combining wind, solar and hydropower with emerging technologies such as geothermal and storage, are essential to mitigate the impact of climate variability and change on renewable power generation and management. Regional collaboration and localized solutions will also play a key role in balancing supply–demand dynamics, optimizing cross-border energy flows and building resilient energy infrastructures. Adopting a climate-informed, collaborative approach will accelerate progress toward a sustainable, net-zero future.

Meeting the ambitious 2030 RE targets requires a multi-pronged approach involving technological innovation, policy alignment and climate-informed strategies. Policymakers must leverage tools such as seasonal forecasts, as well as other weather and climate services, to enhance RE system reliability, particularly in regions with higher forecast accuracy, such as tropical areas. This is in keeping with an overall comprehensive and holistic approach to policymaking as it relates to RE promotion, the broader energy transition and climate stabilization efforts. These efforts can succeed only if they combine measures in support of deployment of renewables with their careful integration into energy systems and parallel policies to upgrade and balance electricity grids not just within a particular country, but also within regions.

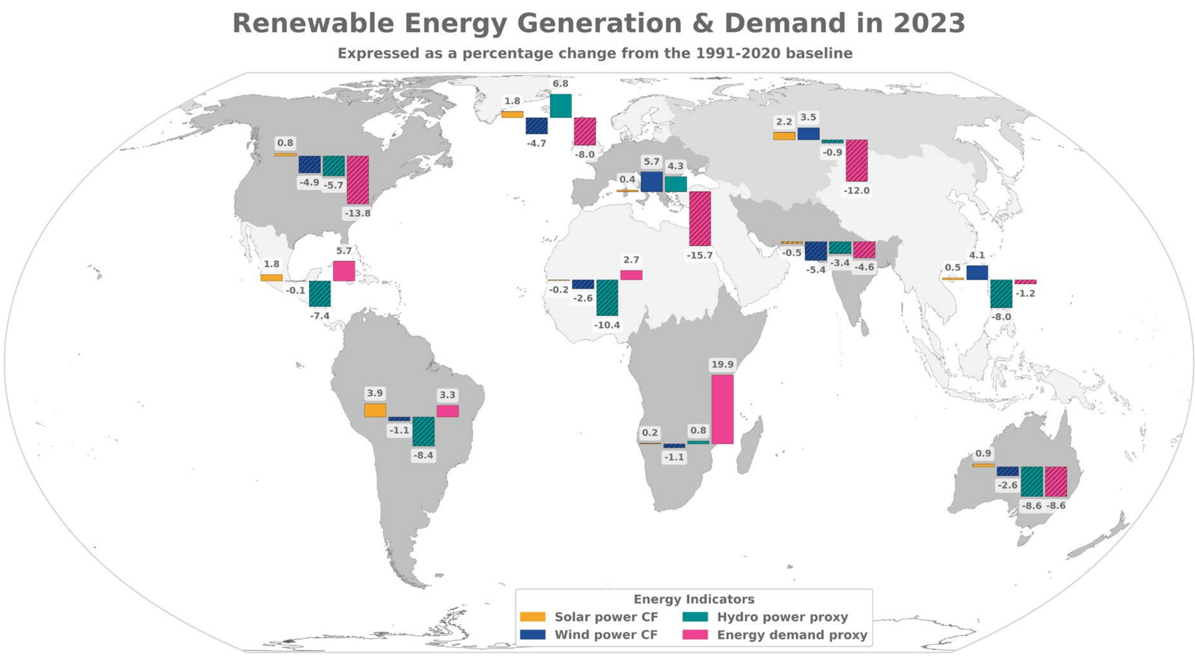

Figure A. Global annual deviations for the four energy indicators – wind, solar, hydropower and energy demand – as presented in this report. Deviations are expressed as percentages for 2023 relative to the 1991–2020 reference period average and are aggregated by region. Hatching is used to highlight negative values for easier identification.

Note: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by WMO, the United Nations, IRENA or the European Union.

Key messages

(1) Climate variability and change significantly affect energy indicators. In 2023, the assessed energy indicators – wind power capacity factor (CF), solar photovoltaic (PV) CF, a hydropower proxy and energy degree days (EDDs) – demonstrate noticeable changes driven by climate variability and change. These effects vary by technology and country, with marked percentage anomalies observed in both annual and monthly averages. While solar PV CF shows annual anomalies that are relatively contained (below 10% compared with the 1991–2020 climate reference period), wind power CF exhibits pronounced variability, exceeding 15% annually in many regions. This underscores the importance of accounting for climate variability and change in energy system planning and operations.

(2) Understanding climate drivers is crucial for energy resilience. The 2023 transition from La Niña to El Niño, two opposite phases of the El Niño–Southern Oscillation (ENSO), highlights the critical role of large-scale climate drivers like ENSO in shaping energy systems. El Niño's drier and warmer conditions significantly influenced energy indicators, with results including increased solar PV generation in South America and enhanced wind power in East Asia. Improved understanding and accurate prediction of these drivers, which account for significant climate variability, allows stakeholders to manage energy resources more effectively, optimize generation and anticipate demand fluctuations, fostering a more resilient and efficient energy transition.

(3) Climate variability information needs to be mainstreamed into energy systems for planning and management. The record-breaking temperatures and climate-driven energy variability in 2023 underscore the need to integrate climate variability into energy planning. This integration can support the establishment of early warning systems to improve energy load management, resource optimization and maintenance scheduling. It can also guide the modernization and expansion of energy infrastructure, fostering innovation across technologies, markets and policies to ensure resilience in a variable climate.

(4) Flexible market structures are crucial for the energy transition. Adapting electricity market structures is essential for ensuring flexibility during the transition from centralized to decentralized power systems. Flexible market designs must facilitate the procurement of the highest-value renewable resources while accommodating flexible solutions. A "dual procurement" system, which supports both renewable resource optimization and deployment of flexible resources, offers a promising approach to achieving this goal.

(5) Resilience should be enhanced through diversification and fostering regional collaboration. Diversified energy portfolios, combining solar, wind, hydropower and emerging technologies, are essential for managing the impacts of climate variability and ensuring energy security. Regional cooperation is vital for balancing energy supply and demand across borders. Collaborative efforts can maximize renewable energy potential, enhance grid stability and build resilient energy systems.

(6) There are huge opportunities for developing countries. Developing countries can harness their renewable energy potential to address energy access challenges while leveraging knowledge of climate variability. For instance, despite abundant renewable energy resources, Africa accounts for only 2% of global installed capacity. By integrating resource potential with climate information, countries can effectively develop renewable energy infrastructure to support industrialization and economic growth, accelerating sustainable development across the continent.

(7) Comprehensive energy data collection and sharing are critical. Systematic and detailed energy data collection and sharing are vital for advancing the understanding of climate variability's impacts on energy supply and demand. While the energy indicators presented here offer a simplified perspective, more representative metrics require access to robust datasets, including detailed information on installed capacity and actual generation. Transparent and harmonized data-sharing practices will enable more accurate modelling and informed decision-making across the energy sector.

1 Global perspective on renewable energy resources in 2023

1.1 Introduction

A key message from the twenty-eighth Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) (COP28) and the resulting UAE Consensus is the reinforcement of the carbon mitigation goals established through international accords, particularly the 2015 Paris Agreement. Notably, the UAE Consensus set an ambitious global target to triple renewable power capacity and double energy efficiency by 2030 (IRENA, 2023). This significant transition toward renewable energy (RE) is crucial for achieving net-zero emissions by 2050. It represents sustained commitment to decarbonizing the energy sector by scaling up clean energy sources, including solar, wind, hydropower, geothermal and marine energy.

Power generation from RE resources (here, specifically wind, solar and hydropower) plays an essential role in the global transition in line with net-zero emission pathways (IRENA, 2022). Given that these resources are strongly influenced by climatic factors, it is essential to understand how the climatic factors impact RE generation. Climate also affects energy demand, particularly in heating and cooling, which is why energy consumption patterns are considered here too.

As in the inaugural 2023 joint WMO–IRENA report (*2022 Year in Review: Climate-driven Global Renewable Energy Potential Resources and Energy Demand*), which reviewed climate conditions in 2022, monitoring and understanding climate variability and change has become increasingly important as the global total installed capacity of wind and solar power – and their share in the electricity grid – has steadily grown over the past two decades.

Wind power installed capacity surpassed 1 000 GW in 2023, a 13% increase compared with 2022 (190% compared with ten years earlier (2014)). Solar power has been growing considerably faster than wind power, with an installed capacity reaching 1 420 GW in 2023, a 32% increase compared with 2022 (680% compared with 2014) (IRENA, 2024a). The 2023 solar power installed capacity has overtaken that of hydropower, which hitherto had the largest installed capacity amongst renewable energies. Specifically, hydropower has grown slightly, with an installed capacity of about 1 410 GW in 2023, an increase of 1% compared with 2022 (20% compared with 2014).

Achieving the 1.5 °C climate target necessitates substantial increases in RE capacities by 2030 and 2050. Specifically, wind power capacity is projected to reach approximately 3 000 GW by 2030 and 8 000 GW by 2050, solar power capacity is expected to expand to about 5 400 GW by 2030 and 18 000 GW by 2050, and hydropower capacity is anticipated to grow to 1 500 GW by 2030 and 2 500 GW by 2050 (IRENA, 2023) (see Table 1). These figures are consistent with the targets established in the UAE Consensus during COP28 in 2023, which emphasized the need to triple RE capacity by 2030. Additionally, the International Renewable Energy Agency (IRENA) reported significant cost reductions in RE technologies between 2010 and 2023, with solar energy costs decreasing by approximately 90% and wind energy costs by about 68% (IRENA, 2024c).

Actual power generation depends on the capacity factors (CFs) – namely the ratio between the average electricity generated by a power system and its nominal rated (or maximum) power. Thus, in terms of power produced and compared with 2021, in 2022 (the latest figures available) hydropower generated 4 470 TWh (a 1% increase), wind power generated 1 840 TWh (13% increase), and solar power generated 1 030 TWh (25% increase) (IRENA, 2024b).

In 2023, total global electricity consumption from all sources, including renewables, reached 29 500 TWh, representing a 3.3% increase compared with 2022 and a significant 26% rise compared with ten years earlier in 2014 (Ember, 2024). This marks a further increase from the 2.5% increase in demand between 2021 and 2022. According to IRENA (2023), total renewable electricity generation in 2022 was 8 440 TWh, up from 7 860 TWh in 2021, meaning renewables met 29.6% of global electricity consumption in 2022, compared with 28.2% in 2021.

In emerging markets and developing economies – which account for nearly 85% of the world's population – energy demand has grown at an average rate of 2.6% per year over the past decade. This increase is driven by a population increase of over 720 million people, a 50% expansion in economic output, and a 40% increase in industrial production. Since 2010, electricity demand has grown at an average annual rate of 2.7%, outpacing the 1.4% per year growth in overall energy demand. Electricity is increasingly replacing fossil fuels in providing heat, mobility and industrial energy needs. Based on current policy settings, global electricity demand is projected to nearly double by 2050, increasing from 26 000 TWh in 2023 to approximately 50 000 TWh. This growth is primarily driven by light industrial consumption, electric mobility, cooling, data centres and the rising adoption of artificial intelligence technologies (IEA, 2024).

Table 1. Summary of global installed capacity for wind power (WP), solar photovoltaic (PV) and hydropower (HP). The corresponding power generation is also shown for 2022 (the latest year for which data are available at the time of writing). The total global energy consumption is reported in the last row.

Sources: IRENA, 2024a, 2024c; IPCC, 2022b; Ember 2024

	2014		2022		2023		2030	2050
	Capacity (GW)	Generation (TWh)	Capacity (GW)	Generation (TWh)	Capacity (GW)	Generation (TWh)	Capacity (GW)	Generation (GW)
WP	350	712	903	2 100	1 020		3 000	8 000
Solar PV	180	193	1 070	1 390	1 420		5 400	18 000
HP	1 180	3 990	1 360	4 470	1 410		1 500	2 500
Total energy consumption		23 400		28 500		29 500		

In this report, the RE generation potential and energy demand are represented by relatively simple and robust indicators, presented at the country level across the globe. Definitions of these indicators are outlined in the sections that follow, covering onshore wind power (referred to simply as wind power),[1] solar photovoltaic (PV) power (also referred to as solar power), hydropower and energy demand[2]. It is important to note that comparing countries can be challenging due to significant differences in size, especially between very large and very small countries. Moreover, for large countries, these averages may not capture regional variations, such as those between locations suitable for energy generation systems and more remote areas. Because the changes in energy indicators reported here are averaged by country, more specific assessments should be conducted at the district or plant level for detailed insights. The information provided in this report serves as a general guide for more localized evaluations.

The primary focus of this publication is to assess the role of climate variability – rather than long-term climate change – on RE potential and energy demand. However, the analysis also examines how 2023 compares to the long-term climate reference period, using the 30-year span 1991–2020 as a baseline. This baseline period, recommended as the standard climatological reference period, helps provide context for understanding deviations, or anomalies, observed in

[1] The focus is on onshore wind power, as results 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] Further details about the computation of the energy indicators are provided in the Methodology section.

2023. Given the significant seasonal variations in CF throughout the year, selected monthly deviations are also assessed, comparing each month in 2023 to the corresponding month in the 30-year reference period (also known as "climatology").

Overall, these deviations provide valuable insights into RE planning, resource management and grid operations by indicating the magnitude and patterns of resource and demand variations. This assessment is intended not only as a retrospective analysis but also to support future decision-making in the energy sector.

In the sections that follow, RE resources and demand are first assessed separately at the global level, and then implications for their interactions are discussed, which is more effectively achieved at the regional (sub-continental) level. Also, indicators are presented as percentage anomalies (for 2023 compared with the base period 1991–2020), but depending on the context, other terms such as "variation", "signal", "change", or simply "anomaly" are also used to denote "percentage anomaly".

1.2 Key climate observations for 2023

In 2023, the global mean near-surface temperature was 1.45 °C ± 0.12 °C above the 1850–1900 average, making it the warmest year on record at the time, surpassing previous record years 2016 and 2020. Monthly global temperature records were particularly notable for ocean temperatures, which remained consistently elevated from April to December, and for land temperatures, which were high from July to November (*State of the Global Climate 2023* (WMO-No. 1347)). The monthly changes in the contributions of various regions to the global temperature anomaly in 2023 showed a notably large impact from warm temperatures over tropical oceans and, especially in the final months of 2023, from the northern hemisphere extratropical land areas (C3S, 2024a, 2024b).

The El Niño–Southern Oscillation (ENSO) influences regional climate patterns worldwide, affecting variables like wind speed, solar radiation, precipitation and temperature. While there are typical regional patterns associated with El Niño and La Niña events, the climate response can vary considerably between individual occurrences.[3]

The transition from a prolonged La Niña phase (2020–2023) to a fully developed El Niño by September 2023 likely contributed to the global temperature rise. However, unusual warming, particularly in the North-east Atlantic, does not align with typical El Niño patterns, suggesting that additional factors are at play. The exact causes of this exceptional warming are still under investigation, as internal climate variability and human-induced forcing do not appear to fully explain the observed rise (Schmidt, 2024). By the end of 2023, a strong El Niño had developed, with the Oceanic Niño Index reaching 2.0 °C during the November–January period – the highest value since the 2015/2016 El Niño.[4]

In addition to ENSO, other climate patterns such as the Indian Ocean Dipole (IOD) and North Atlantic Oscillation (NAO) significantly impacted global weather. A positive IOD, emerging in 2023, exacerbated dry conditions in Australia while contributing to heavy rainfall and flooding in the Horn of Africa, following a prolonged drought in that region from 2020 to early 2023. These climate phenomena carry significant implications for energy systems and resource planning.

[3] These patterns are technically called teleconnections. More information is available at: https://www.weather.gov/fwd/teleconnections.

[4] See for instance the United States National Oceanic and Atmospheric Administration (NOAA) ENSO monitoring portal: https://www.ncei.noaa.gov/access/monitoring/enso.

1.3 Wind power capacity factor

A useful indicator for understanding climate variability relevant to the energy sector is the relative change in the CF (expressed as percentage anomalies) for a given year compared with a reference period. The global monthly wind power CF, as taken from the Weather for Energy (WfE) IEA portal, is computed considering a single 100 m hub height wind turbine and 100 m wind speed at a spatial resolution of 0.25° × 0.25° (IEA; CMCC, 2023).[5] Monthly wind power CF anomalies for 2023 relative to the monthly average for the 1991–2020 reference period are then calculated.

When averaged over the entire year 2023, annual wind power CF anomalies reveal relatively large values and distinct patterns, which affect the generation potential (Figure 1, top). For instance, notable positive variations are seen in Southern Africa, Eastern Asia (including China), Mexico and Central-eastern Europe,[6] with values between 4% and 12%. Specifically, the 4%–8% increase in CF for China, with its installed onshore wind power capacity of over 400 GW (representing about 40% of the global capacity (IRENA, 2024a)), could imply a significant boost in power output, translating to an additional approximately 65 TWh[7] over the year (or 130 Wh a day per person).[8]

On the other hand, many countries saw reductions, or negative variations, in wind resources. This is the case for South Asia, the Middle East, the Horn of Africa and several countries in Western Africa, North America and Northern Europe. In particular, the 4%–8% reduction in CF for India, which has over 40 GW of installed capacity (which is much smaller than China's installed capacity) could still lead to a notable impact on power generation, reducing output by approximately 7 TWh.

It is also interesting to compare how the anomalies evolved in 2023 compared with 2022 (Figure 1, top and bottom, respectively). In many cases, the sign of the anomaly reversed between the two years. This shift is likely due to the predominance of La Niña in 2022 and the transition to El Niño in 2023. This is particularly evident in countries typically influenced by ENSO, such as Australia and the East African countries of Somalia, Ethiopia and Kenya. However, since these values represent an annual average and both phases were present in 2023, these changes require closer examination.

Therefore, June and November have been selected as individual months to assess all four indicators. Another key reason for focusing on individual months is that grid management, energy storage integration, demand response strategies and maintenance typically occur at temporal scales aligned with monthly periods rather than annual ones. Moreover, monthly changes tend to be larger than annual averages due to the greater climate variability over shorter periods (that is, longer averaging periods tend to smooth out the signal). Note that the range of values used in the monthly plots is twice that in the annual plots.

June 2023 marks the transition from the 2022/2023 La Niña to the 2023/2024 El Niño, and – as is typical for such transitions – the climate signal from ENSO is not very strong during this period. The wind power CF anomalies for June 2023, which represent changes compared with the June average for 1991–2020, show a clear spatial distribution with significant negative anomalies in

[5] The wind power conversion model used is highly simplified, 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 2023 with the climatological period 1991–2020, and not to calculate actual values for a specific year. It is worth noting that grid points with CF lower than 0.1 are not considered in country averages (see Methodology section for additional details).

[6] For a discussion about Europeans anomalies in 2023, see also the European State of the Climate 2023: https://climate.copernicus.eu/esotc/2023/renewable-energy-resources.

[7] Assuming an average 0.3 CF, and a 6% increase (average of the 4%–8% range).

[8] Assuming a population for China of 1.4 billion people.

many regions (Figure 2, left). These areas include much of Eastern and Southern Africa (with South Africa being a notable exception), the Middle East, most of South America, North America, South-east Asia, Australia and much of Europe. Apart from South Africa, only a few countries, particularly in Western Africa, exhibit a notable positive anomaly.

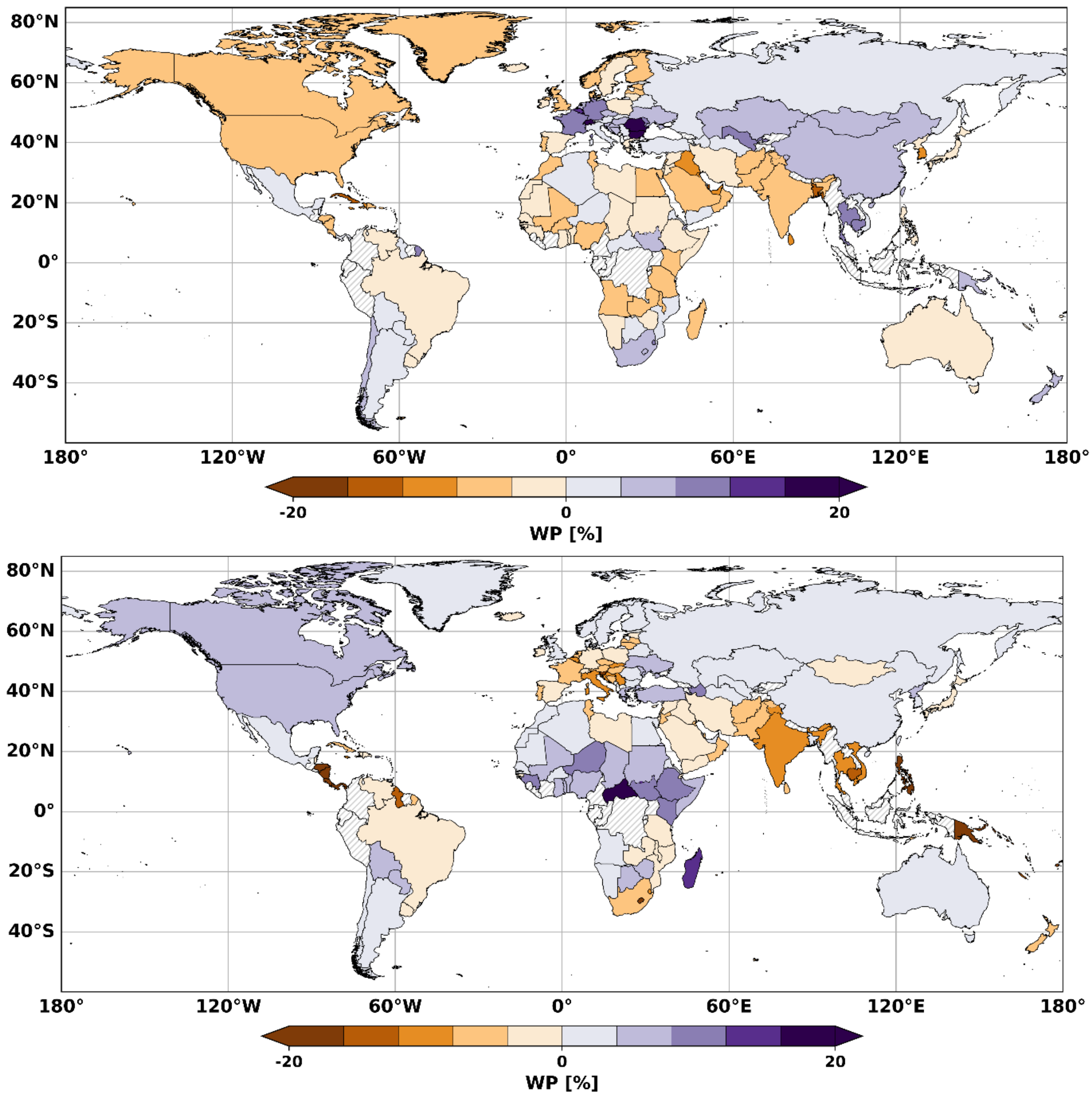

Figure 1. Global anomalies for the wind power (WP) capacity factor annual mean (expressed in %) for 2023 (top) and 2022 (bottom) relative to the average of the 1991–2020 reference period. Hatching indicates countries for which no data are available, due to assumptions made in the computation of wind power capacity factors (see Methodology section).
Note: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by WMO, the United Nations, IRENA or the European Union.

It is worth noting that while there are some similarities in the pattern between the 2023 annual mean anomalies and those observed in June 2023, particularly over Eastern Africa, Brazil and Australia, the magnitude of the June anomalies is notably more pronounced. For example, in Brazil, the anomaly goes from the negative 0%–4% range in the annual mean to the negative 8%–16% range in June 2023.

November 2023 sees the reversal of many anomalies previously observed in June 2023, notably in South America, Southern Africa, much of Asia and large parts of Europe. Except for Southern

Africa, these regions now exhibit strong positive anomalies, with Brazil and Argentina showing increases of 16%–24% and Paraguay exceeding 32%. Notably, China and most of the Central Asia also display strong positive anomalies, while India and Pakistan show negative anomalies. These shifts, particularly between neighbouring countries, suggest potential power balancing, with the “surplus” in China and Central Asia potentially offsetting deficits in South Asia.

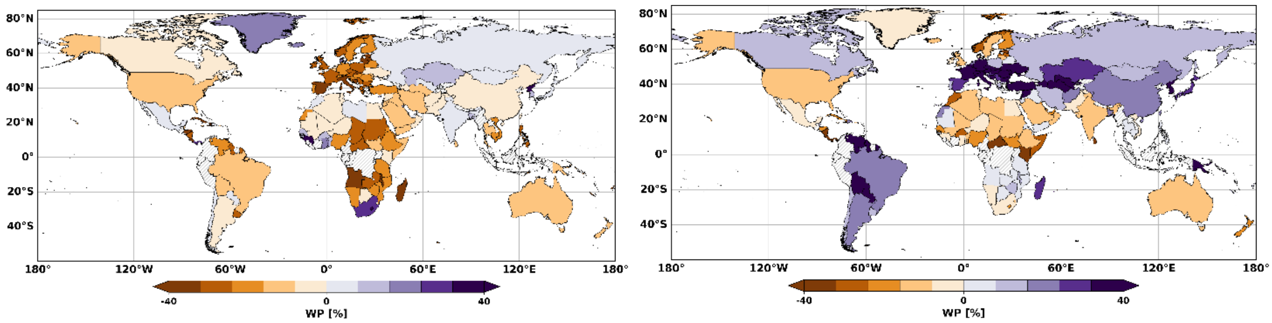

Figure 2. Global anomalies for the wind power (WP) capacity factor annual mean (expressed in %) for June (left) and November (right) 2023 relative to the average of their corresponding month in the period 1991–2020. Note that the range of values is twice that of the annual mean.
Note: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by WMO, the United Nations, IRENA or the European Union.

1.4 Solar power capacity factor

The solar PV power CF, also referred to as solar PV CF, is computed using a straightforward formulation that factors in global solar irradiance, alongside efficiency adjustments due to air temperature near the surface and 10 m wind speed.[9] The main limitation of this approach is that it assumes a constant tilt angle for the PV panels across geographical locations. However, this simplification is not overly impactful, as our focus here is on relative variations rather than absolute CF values.

The global annual anomalies in solar PV CF for 2023, relative to the 1991–2020 baseline, are shown in Figure 3 (top panel). Notably, these anomalies display a smaller range than those for wind power CF (±10% for solar PV CF versus ±20% for WP CF). On an annual basis, solar PV CF variations generally hover close to zero across most countries, within a range of ±2%, with the most significant changes, a positive 4%–6% anomaly, observed in parts of South America, including the Plurinational State of Bolivia, Colombia, the Bolivarian Republic of Venezuela and Brazil. Specifically for Brazil, with an installed capacity of 37 GW in 2023 (IRENA, 2024a), this increase would translate to an additional 3 TWh[10] of energy production annually, or 37 Wh per capita daily.[11]

[9] It is worth noting that grid points with CF lower than 0.1 are not considered in country averages (see Methodology section for additional details).
[10] Assuming an average 0.18 CF and a 5% increase (average of the 4%–6% range).
[11] Assuming a population for Brazil of 215 million people.

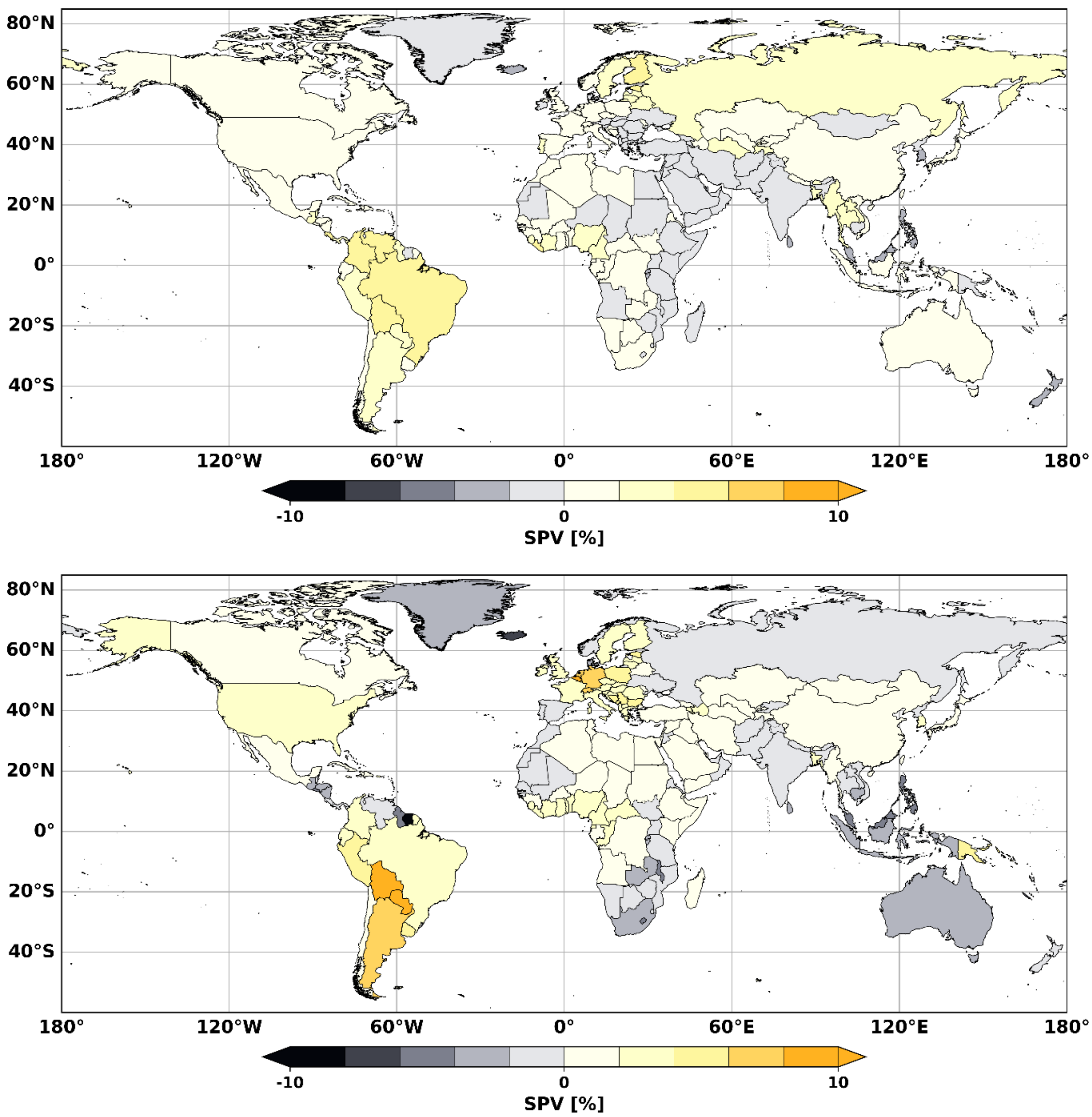

Figure 3. Global anomalies of solar photovoltaic (SPV) power capacity factor annual mean (expressed in %) for 2023 (top) and 2022 (bottom) relative to the average of the 1991–2020 reference period.
Note: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by WMO, the United Nations, IRENA or the European Union.

Large-scale spatial patterns are also evident in solar PV CF anomalies. For example, positive variations are observed across much of South America, several South-east Asian countries, including China, and parts of Western Africa. In contrast, extended regions with negative solar PV CF anomalies stretch from Eastern Africa through the Middle East to India. Negative CF variations are also seen over most of Europe. In Eastern Africa, particularly north of the United Republic of Tanzania, reductions in solar PV CF align with similar reductions in WP CF (Figure 1, top). This suggests a climate pattern, likely induced by ENSO, characterized by increased overcast conditions that impact both solar irradiance and near-surface winds.

From an electricity production perspective, such broad, though modest, regional declines in CF for both wind and solar sources might necessitate compensatory strategies, such as sourcing electricity from alternative generation sources or importing from neighbouring countries.[12] For instance, Eastern Africa could consider importing power from South Sudan (for both wind and solar) or from the Democratic Republic of the Congo (DRC) and Zambia for solar, while regions in Asia with negative CF variations might explore imports from Central Asia (for example, Turkmenistan and Uzbekistan) or neighbouring Pakistan; these are all countries where CF variations are positive.

It is important to note that these considerations are illustrative and do not fully account for: (i) installed capacity or transmission line availability; (ii) actual CF (figures provided show only relative variations); (iii) the availability of alternative sources (refer also to the Hydropower proxy indicator section); and (iv) meteorological conditions critical for load balancing, particularly on sub-daily timescales. Nevertheless, these observations underscore the importance of integrating climate-driven variability into energy policy and planning to enhance grid resilience and optimize cross-border power flows amid changing conditions.

Several differences are noticeable between the solar PV CF patterns in 2023 and those in 2022 (Figure 3, top and bottom, respectively). In some regions, the sign of the CF variations has reversed between the two years, as with wind CF, such as in North America, the Russian Federation, Australia, most of Europe and South-east Asia. In other areas, such as South America (for example, the Plurinational State of Bolivia, Paraguay and Argentina, with annual increases exceeding 6%) and Southern Africa (where Zambia, Mozambique, Botswana and South Africa show reductions of 2%–4%), the sign remains the same, but the magnitude of the change is larger in 2022. This difference is again likely due to 2023 being a transition year between La Niña and El Niño, where climate signals tend to balance each other, compared with 2022, which was influenced by La Niña. These regions – along with Australia, Eastern Africa and South-east Asia, where the sign of the variation has also shifted – are among those most affected by ENSO.

In June 2023, several countries in Central and South America, Asia and Europe experienced a positive anomaly in solar PV CF compared with the June averages during 1991–2020. The findings for Europe were in line with the *European State of the Climate 2023*, though sunnier Southern European countries actually saw a relative decrease in CF. Conversely, large regions across Africa, the Middle East, the United States of America (USA) and Australia showed a negative anomaly for the same month, with several sub-Saharan African countries reaching reductions of 4%–8%. Considering again the balance between wind and solar power CF, there are notable regional contrasts. For example, in large parts of sub-Saharan Africa, where both wind and solar CFs are negative, a shortfall in electricity production is likely. Such a shortfall would be especially concerning in a region already facing significant power shortages and limited or no backup capacity. In contrast, South America shows a compensatory pattern with an overall positive variation in solar PV CF that offsets a negative wind power CF variation.

Stronger overall variations in solar PV CF are observed in November compared with May, though these variations do not necessarily maintain a consistent sign between the two months. For example, large countries like Mexico, the USA, Canada, India and the Russian Federation exhibit a reversal in the sign of their anomalies. The most striking variations are seen in Central and Eastern Africa, largely due to the influence of El Niño, further intensified by the concurrent positive phase of the IOD. While these conditions are beneficial for water resources as they generally bring higher-than-normal precipitation, they naturally also lead to increased cloud cover. This results in significant decreases in solar PV CF, ranging from 12% to 16% in Somalia, Kenya, the Central African Republic and Burundi, and from 8% to 12% in South Sudan, Uganda and the United Republic of Tanzania.

[12] It is important to reiterate that the actual feasibility of cross-border power exchanges depends on factors such as differences in country size, intracountry variations and the availability of transmission infrastructure.

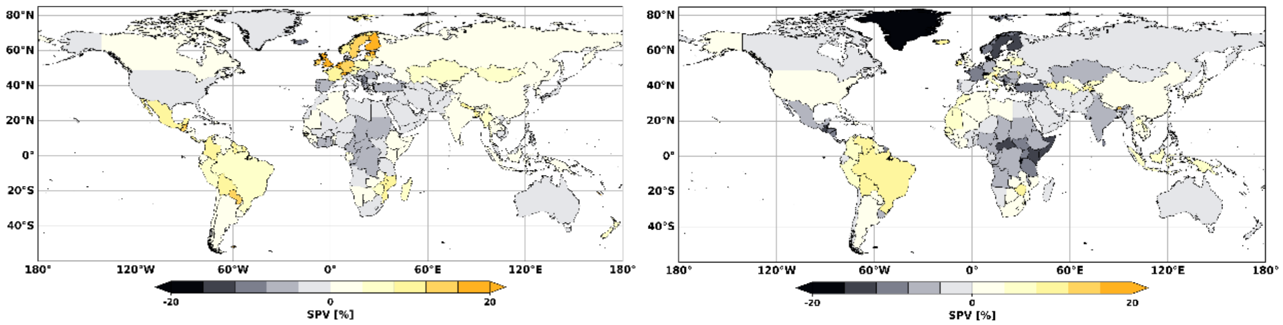

Figure 4. Global anomalies of solar photovoltaic (SPV) power capacity factor annual mean (expressed in %) for June (left) and November (right) 2023 relative to the average for their corresponding month in the period 1991–2020. Note that the range of values is twice that of the annual mean.
Note: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by WMO, the United Nations, IRENA or the European Union.

1.5 Hydropower proxy indicator

The hydropower indicator is represented by a proxy based on a combination of precipitation and the installed capacity of hydropower plants at a given location. Monthly precipitation data are considered only for the sub-country regions where power plants are located, with each plant's installed capacity used to weight the precipitation data accordingly. This hydropower indicator, referred to as installed-capacity-weighted total precipitation (IWP), is calculated as a capacity-weighted country average at the monthly scale. The indicator is based on a rolling three-month average, which includes the two months preceding the target month.[13] Figure 5 (top) shows the IWP averaged over 2023, relative to the 1991–2020 period. Countries with no major hydropower plants are excluded from the indicator, as marked by hatching.

On an annual mean basis, IWP shows widespread reductions in 2023 compared with the 1991–2020 period, particularly across South America, North America, China, the Russian Federation, South Asia and Australia. Notably, Sudan and Namibia experienced reductions exceeding 50%, though these figures are amplified due to their typically low annual rainfall. For example, Sudan received just over 100 mm of rainfall in 2023 (according to ERA5 reanalysis data (Hersbach et al., 2020)) compared with a long-term average of approximately 250 mm, while Namibia received about 200 mm against a long-term average of around 350 mm. These reductions could have significant implications. Sudan, with an installed hydropower capacity of approximately 1 500 MW, relies on hydropower for about 70% of its electricity, though electricity comprises less than 10% of its total energy consumption.[14] This energy supports a large and rapidly growing population, estimated at 48 million in 2023. In contrast, Namibia, with a smaller hydropower capacity of around 350 MW, generates about 60% of its electricity from hydropower, which accounts for roughly 20% of its total energy consumption,[15] serving a much smaller population of approximately 2.5 million. Meanwhile, several countries exhibit positive IWP variations, including Southern African countries, Chile, India, Tajikistan, Uzbekistan and most of the countries of Europe.

Comparing 2023 with 2022 reveals notable changes in regions such as Australia, Southern and Eastern Africa, Central and South America and Central Europe, which reflect the shifting ENSO

---

[13] The choice of this proxy indicator is dictated by the lack of homogenous datasets for power generation for the period covered (1991–2023), which prevents the implementation of a power – or even water inflow – data model (typically a statistical model), as done for instance in https://doi.org/10.3390/en13071786. More details are available in the Methodology section. It is worth noting that any hydropower indicator derived from climate variables has inherent limitations, as hydropower generation is influenced by numerous other factors, such as reservoir management practices, operational constraints, infrastructure capacity and sedimentation.
[14] https://www.iea.org/countries/sudan
[15] https://www.iea.org/countries/namibia

pattern (Figure 5). Thus, similarly to the solar PV CF, the global ENSO influence is also evident in the IWP. This ENSO pattern is particularly pronounced when examining individual months, such as June and November 2023 (see Figure 6, left and right, respectively). Specifically, a positive IWP variation is observed in Australia and South Africa in June 2023 (recalling that this represents an average over the previous three months, and not just the precipitation for that specific month), which is typical of a La Niña pattern, but this changes to a negative anomaly in November 2023. Conversely, many countries show a shift from negative anomalies in June to positive ones in November, especially in tropical regions influenced by El Niño, including countries in South-eastern Africa, and Southern and Western South America. In addition, extratropical countries such as Kazakhstan, the Russian Federation, China and many of the countries of Europe change from negative to positive.

Notably, there are significant increases of 60%–80% in Chile, which has an installed hydropower capacity of 7.5 GW, and 40%–60% in Ethiopia (5 GW installed), Kenya (850 MW installed) and the United Republic of Tanzania (600 MW installed reported, but with the recent addition of the large Julius Nyerere Hydropower Station, which has a capacity exceeding 2 GW).

The Global Water Monitor 2023 summary report (Van Dijk et al., 2024) and the Global Drought Snapshot 2023 (UNCCD, 2024) provide additional useful references on water resource availability and droughts, respectively.

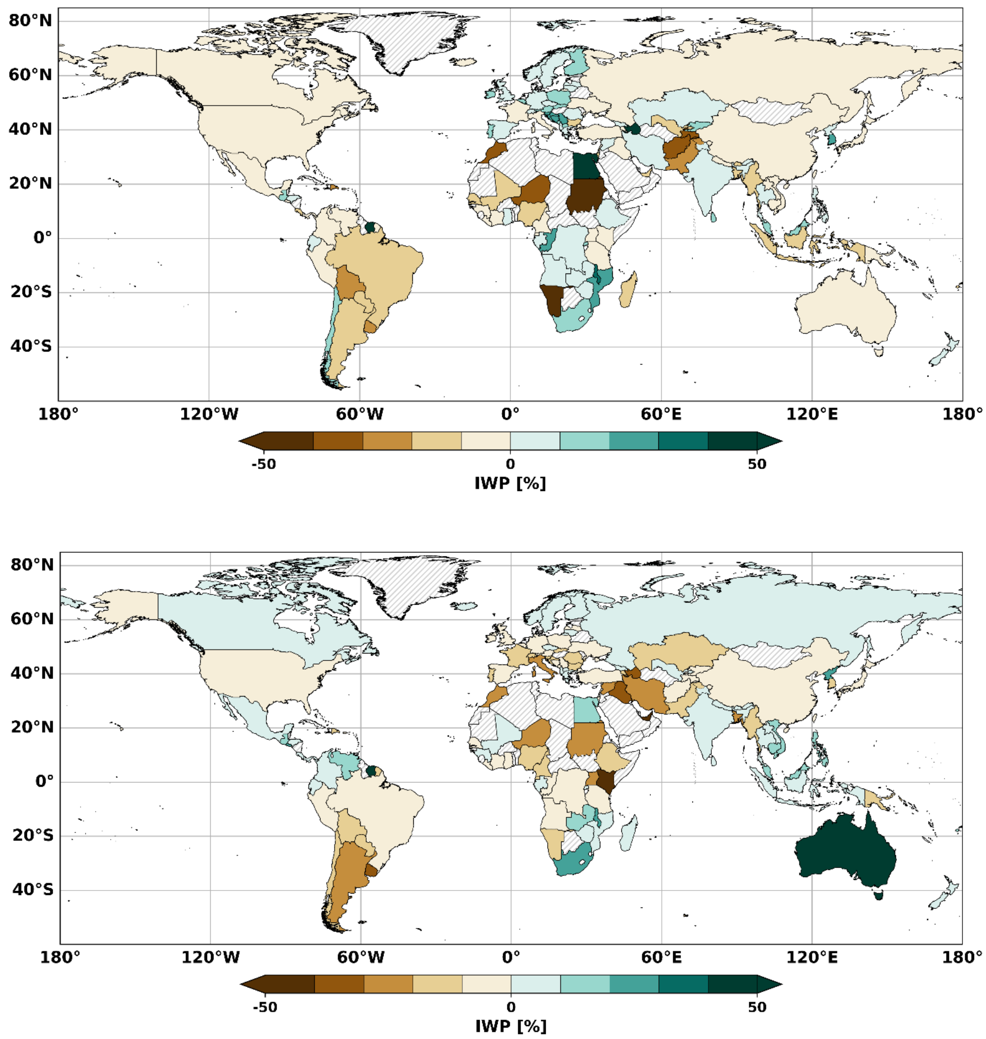

Figure 5. Global anomalies of hydropower proxy annual mean (expressed in %) for 2023 (top) and 2022 (bottom) relative to average of the 1991–2020 reference period. Hatching indicates countries for which no data are available, due to assumptions made in the computation of this proxy (see Methodology section).
Note: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by WMO, the United Nations, IRENA or the European Union.

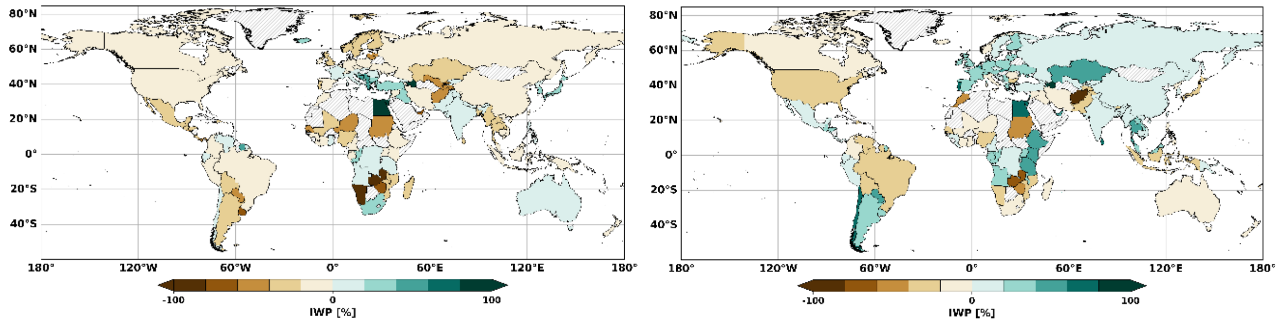

Figure 6. Global anomalies of hydropower proxy annual mean (expressed in %) for June (left) and November (right) 2023 relative to the average of their corresponding month in the period 1991–2020. Note that the range of values is twice that of the annual mean.
Note: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by WMO, the United Nations, IRENA or the European Union.

1.6 Energy demand proxy indicator

The energy demand indicator is represented by a proxy based on two commonly used indicators: cooling degree days (CDDs) and heating degree days (HDDs).[16] Usually, these indicators are used separately as they address different requirements, namely the need for cooling and heating, respectively. However, to streamline the presentation of the energy demand indicator, it is also possible to define energy degree days (EDDs) as the sum of CDDs and HDDs[17] (IPCC, 2021, 2022a; Spinoni et al., 2018). Naturally, CDDs and HDDs (and therefore EDDs) do not capture all uses of electricity (for example, industry, agriculture and transport) as they are more suited to human comfort (heating/cooling in residential or commercial buildings). Moreover, they do not separate electricity demand from the more general energy demand (for example, including gas). However, they provide an indication of energy requirements and are also easy to compute; this is why they are widely used, including by IEA in its WfE data.

The 2023 EDD variations reveal significant regional clusters with substantial reductions in energy demand. For instance, much of Europe, Canada and New Zealand experienced decreases of at least 12% (Figure 7, top). Specifically, Canada recorded approximately 310 EDDs in 2023, compared to the 30-year 1991–2020 average of about 360. In this case, HDDs (which saw a decrease with the milder temperatures in 2023) comprise most of the EDDs, with CDDs accounting for only about 2. Additionally, other extratropical countries (poleward of 30° latitude), such as the Russian Federation (8% to 12%), and the USA (12% to 16%) also show notable reductions. These significant shifts are again largely attributed to decreases in the HDD component, as milder temperatures in 2023, driven particularly by anthropogenic global warming, lessened heating requirements during colder months. More moderate reductions are observed in countries such as China, Mexico, South Africa and Australia.

---

[16] HDDs assess the level of the cold over a specific time period, typically a month, taking into consideration outdoor temperature and average room temperature to infer the need for heating (conversely, CDDs assess the level of heat to infer the need for 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 most countries covering the 1991–2020 baseline period. Several versions of CDD and HDD are available. More details are available in the Methodology section. The individual global gridded CDD and HDD data are based on the ERA5 reanalysis.
[17] The main difficulty with EDDs 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).

There are also notable positive variations in EDDs, particularly across a large part of sub-Saharan Africa and Central America, and more broadly, over much of the tropical region. For example, in DRC, there is an increase of approximate 24% in EDDs, corresponding to an increase of 16 over a 30-year average of 67. This increase is primarily driven by CDDs alone, as HDDs remain close to zero for DRC. These variations again reflect the exceptionally high global temperatures experienced in 2023.

The EDDs in 2022 already displayed a pattern similar to that of 2023, with reductions at high latitudes and increases at low latitudes due to the reasons highlighted above (Figure 7, bottom). However, the higher temperatures of 2023 have significantly amplified these EDD changes. These variations have direct implications for energy consumption, resulting in reduced demand for gas and, in some cases, electricity (as in the case of France) for heating in colder months at higher latitudes, and increased electricity demand for cooling in mid- to low-latitude regions. Balancing these variations with a corresponding energy supply can be challenging, particularly under conditions of large inter-annual fluctuations and long-term changes.

The reduction in HDDs is also seen as a decrease in EDDs for June 2023 at higher latitudes (Figure 8, left). For example, in Zimbabwe and Botswana, there are decreases of around 40 EDDs from their long-term averages of 50 and 90 EDDs, respectively. In both cases, these differences are almost exclusively due to reductions in HDDs, reflecting the milder winter season in these southern hemisphere countries. Even in the northern hemisphere, the reduction in EDDs is similarly driven by lower HDDs. In France, for example, there was a significant drop in HDDs, from an average of over 30 EDDs down to just 3. Conversely, the increases in EDDs observed in China and, to an even greater extent, in Mexico are primarily due to marked increases in CDDs. China saw an increase of nearly 20 CDDs from a base of 110, while Mexico experienced an increase of almost 35 CDDs from a baseline of about 80.

The November 2023 variations are considerably stronger than those observed in June 2023, and in line with the annual 2023 pattern (Figure 8, right). Most extratropical northern hemisphere countries experienced a reduction in EDDs, due to a decrease in HDDs driven by milder autumn temperatures. Scandinavia was an exception, with slightly colder-than-normal temperatures leading to an increase in EDDs. For example, Finland saw its EDDs (equivalent to HDDs in this case) rise by just over 8%, from a baseline of approximately 530 EDDs to around 575.

In the southern hemisphere, widespread warm conditions resulted in increased EDDs, mainly from higher CDDs due to a warmer summer season. For instance, Brazil's EDDs rose by about 45%, from 90 to 130, driven almost entirely by an increase in CDDs (HDDs are minimal in November, around 1 or less). Exceptions to this trend were seen in Eastern Africa and Australia, where higher overcast conditions, influenced by a maturing El Niño phase, led to a reduction in EDDs. In Australia, the number of EDDs decreased by 34%, from a long-term average of 50 down to 33, reflecting a more complex variation than the previous examples. This decrease reflects a combination of a reduction in HDDs (from around 30 to 17) and a decrease in CDDs (from 20 to 16), highlighting the varied climate responses across this large country.

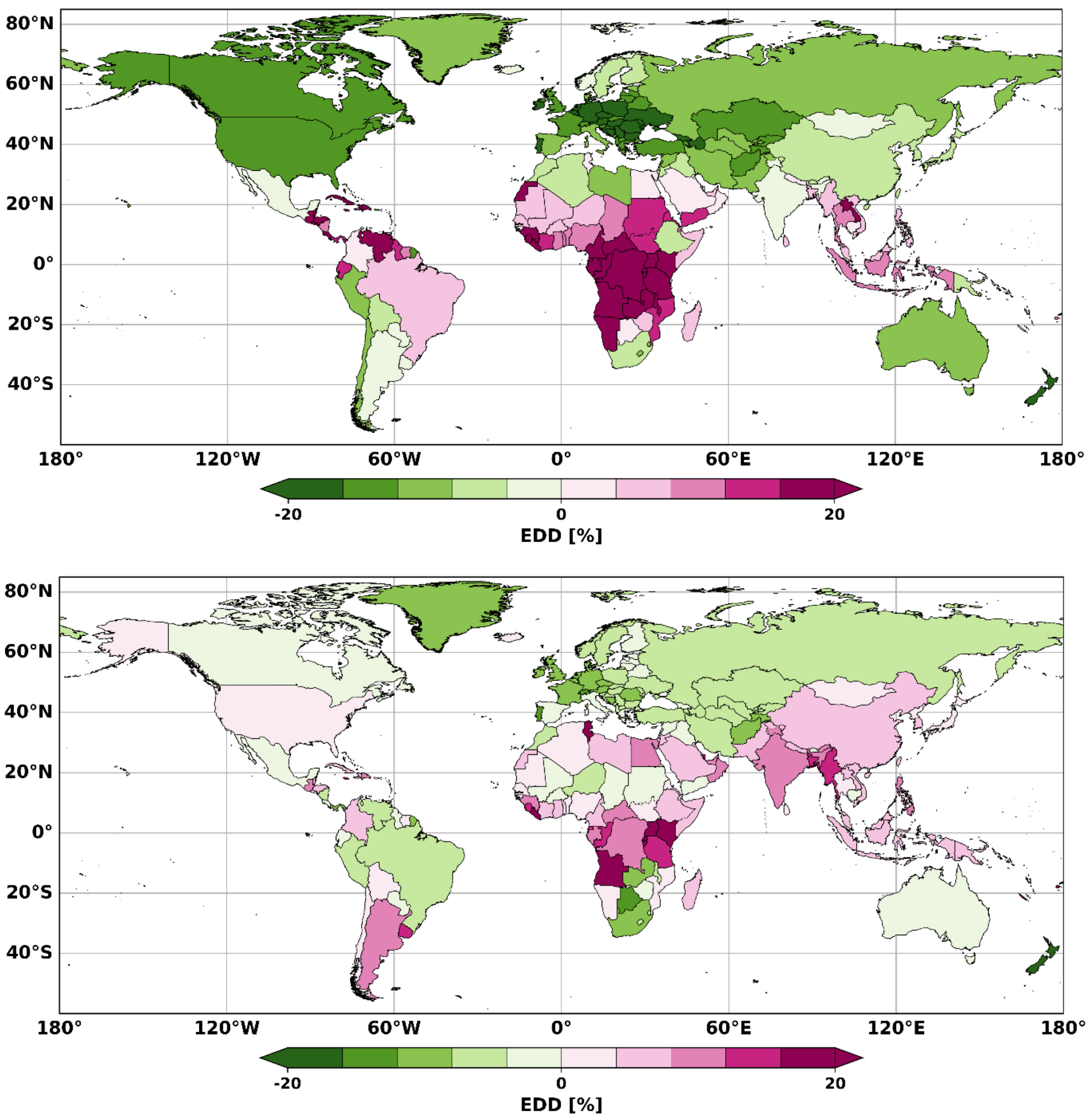

Figure 7. Global anomalies of energy demand proxy (energy degree days (EDDs)) annual mean (expressed as %) for 2023 (top) and 2022 (bottom) relative to the average of the 1991–2020 reference period.
Note: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by WMO, the United Nations, IRENA or the European Union.

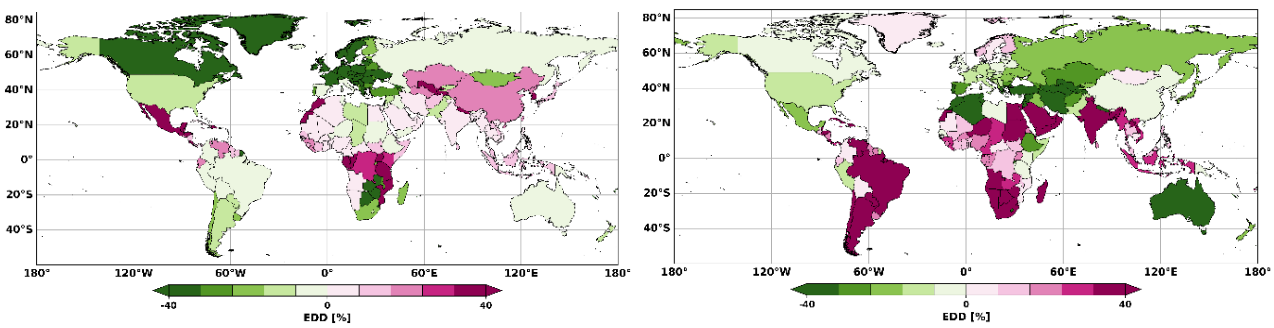

Figure 8. Global anomalies of energy demand proxy (energy degree days (EDDs)) annual mean (expressed as %) for June (left), November (right) 2023 relative to their average corresponding month in the period 1991–2020. Note the range of values is twice that of the annual mean.
Note: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by WMO, the United Nations, IRENA or the European Union.

2 Regional perspective

A more detailed assessment of variability and changes in the four energy indicators is conducted at the regional level for selected parts of three continents: Africa, Asia and South America. In each region, four neighbouring countries were chosen, with the selection kept limited to ensure clarity in the presentation. Monthly changes in 2023, compared to the corresponding month during the 1991–2020 climatology period, are plotted for each energy indicator. This approach visually highlights:

(1) Month-to-month variability, drawing attention to features such as particularly anomalous or near-normal periods within the year;

(2) The 2023 changes compared to each of the 30 years in the reference period, displayed through violin graphs;

(3) Potential surpluses, deficits or compensations in energy supply, which can be observed by comparing all four energy indicators on adjacent stacked plots, also in relation to energy demand.

It is important to note that these intra-annual monthly changes may not directly align with annual averages of the energy indicators discussed in previous sections. This difference arises because: (i) the monthly values in the violin graphs reflect the median rather than the means shown in the previous section, and (ii) the mean annual variations differ visually from the computed means of the individual monthly variations.

Countries were selected based on proximity to each other in order to facilitate potential or actual connectivity via power transmission lines, which is relevant for power-balancing considerations across different energy generation types. Such considerations provide a foundation for energy planning across generation types and countries to meet demand consistently on a monthly basis in this analysis. It is therefore important to consider the three-dimensional space of energy indicators, time (month) and country to optimize energy management. However, and leaving aside the simplified representation of the energy system presented here, a detailed assessment of potential energy resource balancing is beyond the scope of this publication, as it focuses on relative changes in capacity factors (CFs) or proxy indicators rather than actual demand, generation or installed renewable energy (RE) capacity. Thus, the power-balancing discussion remains largely qualitative, serving as a prompt for further analysis.

2.1 Africa

For Africa, four countries within the Southern African Development Community (SADC) were selected for more in-depth analysis (Figure 9): Mozambique (green), United Republic of Tanzania (yellow), Malawi (red) and Zambia (blue). These countries are also part of the Southern African Power Pool (SAPP), with the United Republic of Tanzania additionally being part of the Eastern Africa Power Pool.

Figure 9 encapsulates extensive information, which we will briefly discuss, noting that only general indications can be given regarding practical applications due to the multiple layers of interpretation involved. Essentially, Figure 9 presents the four energy indicators by month in 2023 for these countries. Referring back to the 2023 annual average variations, these four countries exhibit the following behaviour: the wind power CF variation is negative on average, except for Mozambique (Figure 1, top); the solar photovoltaic (PV) CF variation is marginally negative, with a slight positive variation in Zambia (Figure 3, top); the variation of the hydropower proxy is positive, except in the United Republic of Tanzania (Figure 5, top); and the energy demand deviation is positive, with particularly strong positive values for Malawi and the United Republic of Tanzania (Figure 7, top).

Monthly variations and patterns

Monthly variations reveal patterns that are not evident in annual averages or specific months previously examined (June and November). For example, Zambia's solar PV CF in January 2023 was notably low, with the maximum value of the distribution negative (indicated by the entire violin graph being below zero) and reductions exceeding 30% compared to any of the 30 reference years. Meanwhile, Mozambique and the United Republic of Tanzania showed median values that were positive for the same month, albeit only by a few percent. January 2023 coincided with La Niña conditions, which typically produce a distinctive teleconnection pattern in this region. This pattern is characterized by a bipolar shape with a transition zone around the southern United Republic of Tanzania and northern Malawi. It usually results in opposite signals for the United Republic of Tanzania and Zambia, while Malawi, being smaller and located in the transition zone, exhibits higher variability. A similar pattern is observed in November and December during the El Niño phase, where the signals from the United Republic of Tanzania and Zambia reverse compared to January. February, however, diverges somewhat from the expected La Niña influence.

Balancing energy indicators in November and December

Focusing on November and December – two months affected by El Niño – provides insight into the inter-country balance across all indicators. For the United Republic of Tanzania, wind power CF was close to normal in November but considerably lower than normal in December, making it insufficient to compensate for reductions in solar PV CF. However, the hydropower indicator was higher than normal, consistent with increased precipitation during El Niño. With the United Republic of Tanzania's large installed hydropower capacity of approximately 2 600 MW (including the Julius Nyerere Hydropower Station), generation from this source could offset the contributions from wind and solar power (even though these are currently minimal, with 2 MW and 20 MW, respectively (IRENA, 2024a)). This occurs against a backdrop of slightly lower-than-normal demand (EDDs) in November and slightly higher-than-normal demand in December.

Regional dynamics and power balancing

Demand was close to normal in November but exceptionally high in December for both Malawi and Zambia, with 2023 values exceeding those of any year in the reference period for Zambia. While Malawi's hydropower indicator showed positive anomalies in November, in Zambia and Malawi the hydropower indicator was significantly negative in December, exacerbating the challenge of meeting demand. To address the increased demand, electricity could be sourced from:

- **Solar power**: Zambia showed higher-than-normal solar PV CF for both November and December, while Malawi's solar PV CF was higher than normal in December.
- **Wind power**: Generally all three countries experienced above-normal wind power CFs across both months.
- **Hydropower**: The United Republic of Tanzania's positive hydropower anomaly could compensate for deficits in the neighbouring countries, if transmission connectivity permits.

These monthly variations highlight the intricate interplay between energy supply indicators and demand. While largely qualitative in nature, this analysis underscores the importance of regional energy planning, particularly in balancing RE sources across borders and managing supply–demand dynamics under varying climate conditions.

2.2 Asia

For Asia, four neighbouring countries in the Middle East were selected (Figure 10): United Arab Emirates (UAE) (green), Qatar (yellow), Oman (red) and Yemen (blue). Based on 2023 annual average variations, the wind power CF anomaly was generally negative across the region, except for Yemen (Figure 1, top). The solar PV CF anomaly was marginally negative for all countries (Figure 3, top), while the hydropower proxy anomaly, available only for the UAE, was negative (Figure 5, top). EDD deviation was positive for all countries, with Yemen displaying particularly high values (Figure 7, top).

Inter-annual variability and climatic influences
Significant demand variability was observed in January, with all countries except Oman exhibiting large fluctuations compared to the reference period (Figure 10, bottom). The highly oblong shapes of the violin plots, in some cases extending beyond the plotted area, highlight this variability. These changes are primarily driven by unusually low EDD values for January 2023. For instance, Qatar's EDDs dropped dramatically to nearly zero from an average of 25, and the UAE experienced a similar decline from an average of 8.5 to nearly zero. Oman, in contrast, showed a more modest reduction from 8.5 to 4. These reductions can be attributed to higher-than-average temperatures, which significantly reduced nominal HDDs. The globally standardized HDD thresholds may not fully account for local climatic conditions, highlighting the importance of region-specific analyses. While these percentage changes are notable, a deeper examination is required to better understand their underlying drivers and implications.

Relationships between demand and renewable energy indicators
November and December highlighted notable interconnections between energy demand and RE production, even for this region, with elevated demand deviating from historical averages. In Qatar, the EDDs for December dropped to zero from an average of 8, rendering ratio-based analyses indeterminate, as indicated by the absence of the corresponding violin plot in Figure 10.

Against an increased demand, wind and solar power indicators were largely negative across the four countries analysed. However, Yemen experienced a slight positive variation in solar PV output in December, which could partially meet the increased local demand but would likely fall short of supporting export potential.

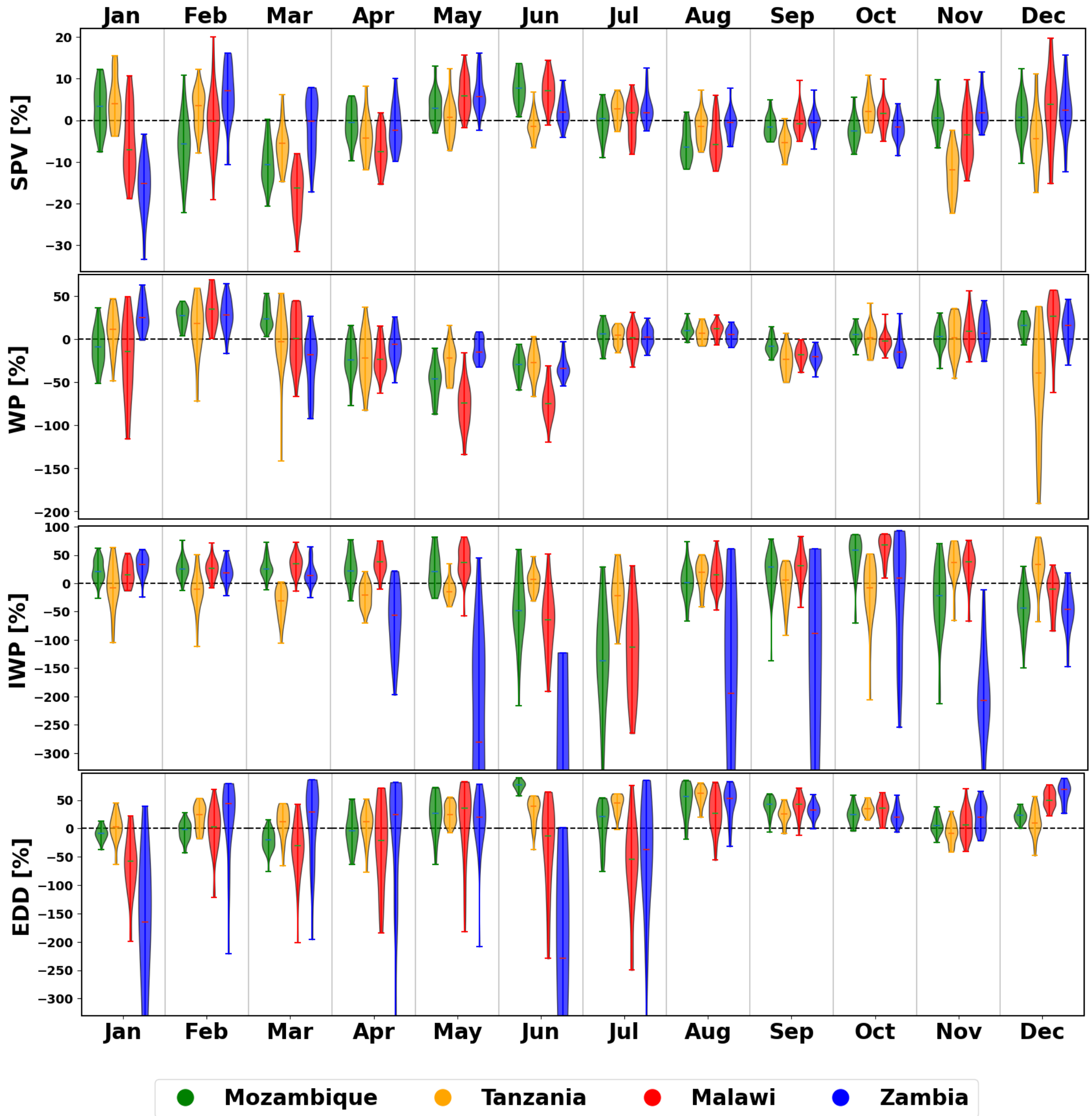

Figure 9. The four energy indicators – solar PV capacity factor (SPV), wind power (WP) capacity factor, installed-capacity-weighted total precipitation (IWP) (hydropower proxy), and energy degree days (EDD) (energy demand proxy) – are displayed by month for 2023 across four countries in Africa. The violin graphs illustrate the range of percentage variations for each month in 2023 compared to the corresponding month across the reference period, 1991–2020 (each violin comprises 30 values). The median of the 30-year distribution is highlighted by a short horizontal line within the violin. Some violins have been trimmed to improve readability due to extended ranges. This representation makes it possible to easily compare demand variations with supply variations, for each month, to ease energy management within and across countries. Note that large percentage variations may occur when denominators are small.

In contrast, the UAE showed a significantly positive hydropower proxy, though from a low baseline. Notably, among the four countries the UAE is the only one with hydropower potential, supported by the recent construction of the Hatta pumped storage hydroelectric plant. This project, still under construction in 2024, has a planned capacity of 250 MW.[18] While it promises to enhance energy resilience in the future, actual generation data for wind, solar and hydropower will be essential for a comprehensive assessment of RE's capacity to meet demand.

[18] https://www.dewa.gov.ae/en/about-us/strategic-initiatives/hatta-project

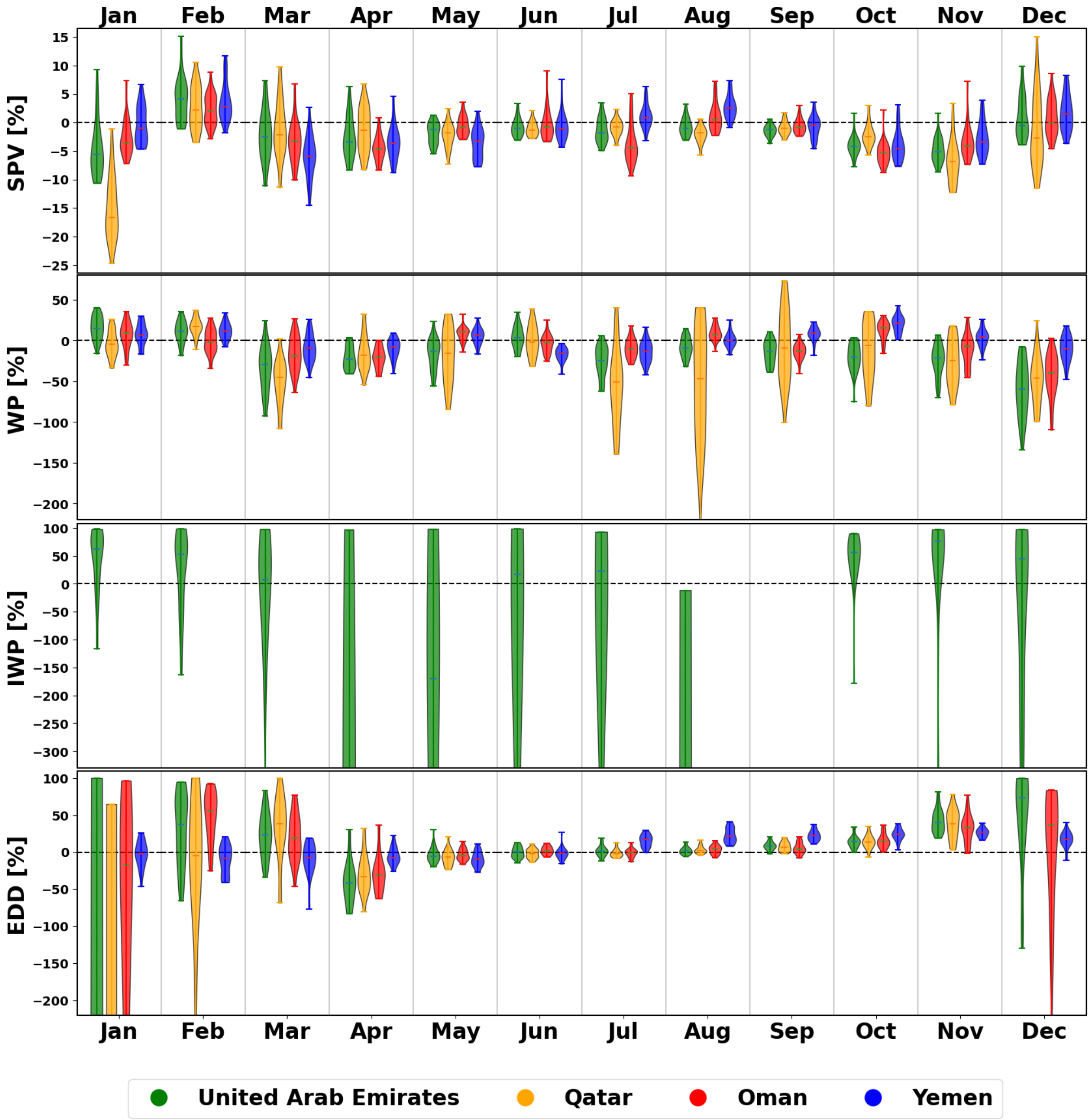

Figure 10. The four energy indicators – solar PV capacity factor (SPV), wind power (WP) capacity factor, installed-capacity-weighted total precipitation (IWP) (hydropower proxy), and energy degree days (EDD) (energy demand proxy) – are displayed by month for 2023 across four countries in Asia. Note that Qatar, Bahrain and Yemen do not have the hydropower indicator (see Methodology for details).

The interactions between climate variability and energy systems in the Middle East remain complex and regionally specific. Higher-than-average temperatures in January reduced heating demand, while meeting the increased demand in November and December posed significant challenges for RE production. Yemen's modest solar PV gains underscore the resilience challenges in the region, whereas the UAE's hydropower potential illustrates the value of diversifying energy sources to manage demand volatility effectively. These findings highlight the need for further regional analysis to refine climate variable thresholds, improve prediction of inter-annual variability, and optimize energy systems under future climate scenarios. A deeper understanding of these dynamics is crucial to addressing the region's unique energy and climate challenges effectively.

2.3 South America

For South America, the selected neighbouring countries (Figure 11) are Chile (green), Colombia (yellow), Peru (red) and Brazil (blue). Annual average variations in 2023 revealed diverse RE trends. Wind power CFs, available only for Brazil and Chile, were positive for Chile (4%–8%) but slightly negative for Brazil (0%–4%) (Figure 1, top). Solar PV CF was consistently positive across all four countries (Figure 3, top), while the hydropower proxy exhibited variability – negative for Brazil (10%–20%) but notably positive for Chile (10%–20%) (Figure 5, top). EDD deviations followed similar regional contrasts, with Brazil showing a 7% increase, marginally positive deviations for Colombia, and considerably negative values for Peru and Chile (8%–12%) (Figure 7, top). In Brazil, the increase in EDDs was driven by higher CDDs (+8), while HDDs decreased slightly (–2). In contrast, the EDD declines in Chile and Peru were primarily due to reduced HDDs. Peru, however, saw a partial offset from a rise in CDDs (from an average of 18 to 26).

Renewable energy responses to El Niño
Revisiting November and December, during the El Niño peak, EDDs increased in all countries except for Peru, while Colombia saw only a marginal increase. During those two months, Brazil recorded its highest number of EDDs in 2023 (violin plot entirely positive), with a median increase of 20%–30%. In contrast, Peru experienced its lowest number of EDDs in 2023 during those months (violin plot entirely negative), with a median reduction of about 20%. Brazil's population of 220 million (compared to Peru's 34 million, Chile's 20 million and Colombia's 52 million) significantly amplified its weight in the region's overall energy demand and likely influenced related dynamics.

To meet Brazil's higher demand, RE would have played a critical role. Solar PV CF was significantly above average (violin plot entirely positive in November and mostly positive in December), with a median increase nearing 10%, especially in November. Wind power CF also rose by a few percentage points. However, the hydropower proxy for Brazil dropped by 30%–40%, presenting challenges given that hydropower supplies around 60% of its electricity.[19] Despite this drop, Brazil's contributions from wind (13.5% of electricity generation) and solar (7.2%) would have partially offset the hydropower shortfall.

Regional variations in energy trends
Colombia's slightly higher-than-average demand in November was likely met by increased solar PV, which compensated for minor hydropower reductions. In December, solar PV CF decreased slightly (1%–2%), while the hydropower proxy returned to near-average levels, resulting in only modest challenges for the energy system.

Chile's considerably higher demand in November – nearly 40% above normal – was met by a substantial increase in the hydropower proxy (about 50%, with hydropower providing nearly 27% of the country's electricity)[20] and an 8% rise in wind power CF (which contributes nearly 11%). These gains offset a minor reduction in solar PV CF, which accounts for a substantial 20% of Chile's electricity generation.

In Peru, lower-than-normal demand (approximately 20% below average) likely created a production surplus. This surplus was supported by a 10% increase in the hydropower proxy, which dominates Peru's electricity mix at 50%.[21] The approximately 5% decline in solar PV CF in December had negligible impact due to solar PV's minimal contribution to Peru's overall energy supply.

[19] https://www.iea.org/countries/brazil. Note that these are 2022 figures.
[20] https://www.iea.org/countries/chile. Note that these are 2022 figures.
[21] https://www.iea.org/countries/peru. Note that these are 2022 figures.

These observations underscore the pivotal role of El Niño in shaping energy demand and RE production across the region. While solar and wind provided essential buffers during peak demand in some countries, the variability in hydropower highlights the vulnerability of energy systems heavily reliant on this resource. A diversified energy portfolio, coupled with regional collaboration, could bolster resilience and ensure stability during future climate-driven events.

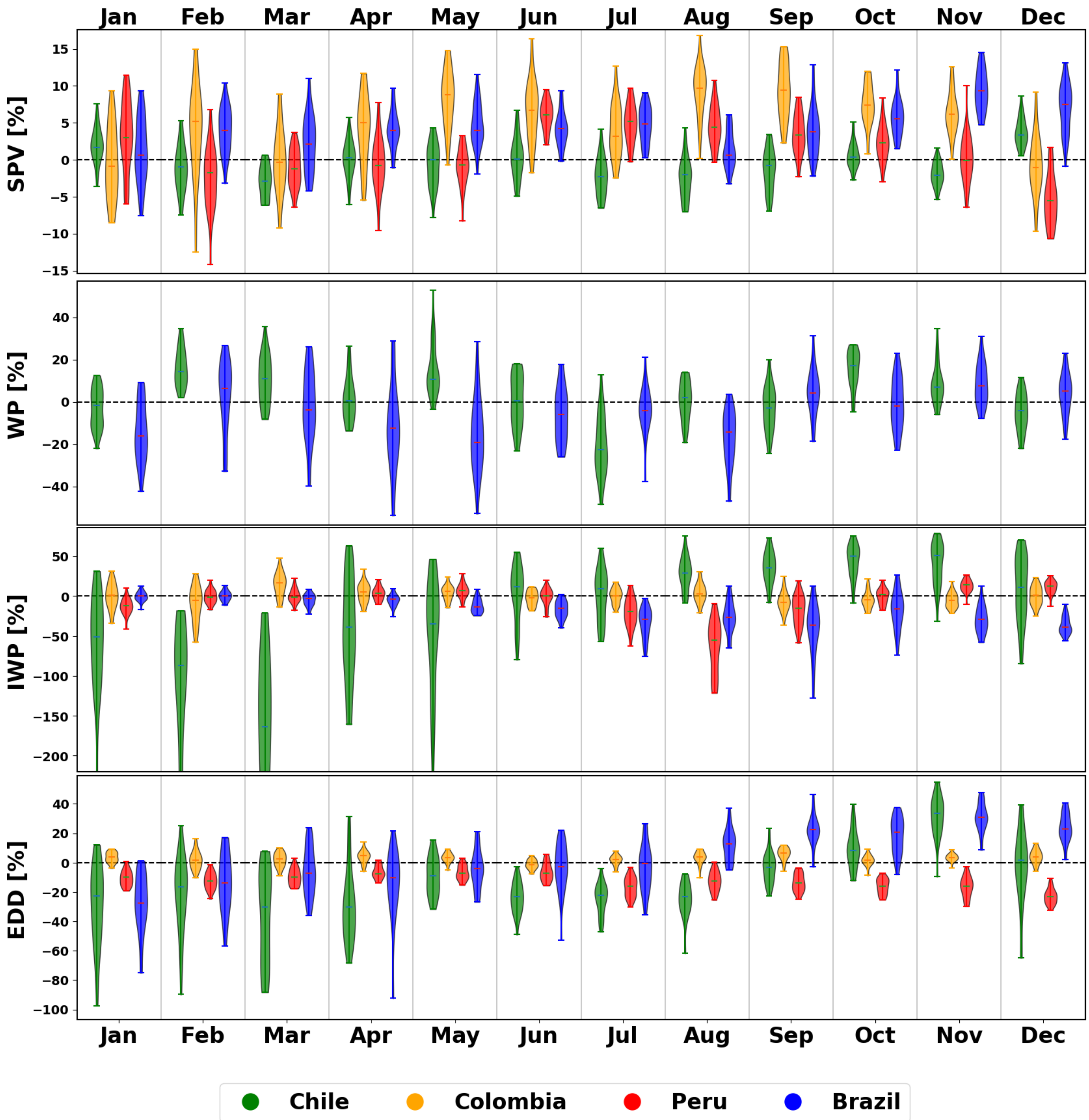

Figure 11. The four energy indicators – solar PV capacity factor (SPV), wind power (WP) capacity factor, installed-capacity-weighted total precipitation (IWP) (hydropower proxy), and energy degree days (EDD) (energy demand proxy) – are displayed by month for 2023 across four countries in South America. Note that Colombia and Peru do not have the wind power indicator (see Methodology for details).

3 Adaptation to climate variability with seasonal climate forecasts

Seasonal climate forecasts have emerged as a critical tool for the energy sector, enabling stakeholders to anticipate and adapt to climate variability on timescales ranging from months to seasons (see, for example, White et al., 2022). As the global energy transition accelerates, the ability to predict seasonal climate conditions has profound implications for ensuring energy security, optimizing renewable energy (RE) production and enhancing resilience to extreme weather events. For instance, understanding predicted precipitation patterns, including their probability and uncertainty, can inform hydropower reservoir management, while temperature forecasts can guide grid operators in preparing for spikes in cooling or heating demand. By integrating seasonal forecasts into energy planning, policymakers and industry leaders can make more informed decisions, ultimately supporting the reliability and sustainability of energy systems.

This section aims to illustrate the potential applications of seasonal forecasts as a valuable tool for energy planning and management. It does so by presenting examples of seasonal forecasts relevant to 2023 and evaluating the performance of the model used to produce these forecasts.

The relevance of seasonal forecasts lies in their potential to bridge the gap between short-term weather forecasts and long-term climate projections. They provide probabilistic insights into key climate variables, such as temperature, precipitation, solar radiation and wind patterns, that directly affect RE resources. Wind and solar power production, for example, are highly sensitive to atmospheric conditions, while hydropower generation depends on streamflow levels influenced by seasonal 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 via the Copernicus Climate Change Service,[22] 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 (Troccoli, 2010; Troccoli et al., 2018; IRENA, 2023).

Seasonal climate forecasting is a specialized field with many complex facets that are not intuitive.[23] Given the wide range of options for generating and presenting forecasts – encompassing different forecast models, lead times, verification metrics, regions, seasons and months – this section focuses on a specific model (the ECMWF System 5),[24] metric (the continuous ranked probability skill score (CRPSS), see Methodology for details), region (South America) and target month (November 2023).

To better illustrate the signals from a seasonal forecast, climate variables are used in place of energy indicators. While climate data are available globally on a regular 1° grid,[25] energy indicators are typically averaged over countries. However, wind and solar power capacity factors (CFs) can, in principle, also be presented on the same regular grid as climate data. Although it

---

[22] https://climate.copernicus.eu/seasonal-forecasts

[23] Concepts such as initial conditions, ensemble members and their generation, model bias, probabilistic forecasting and lead times contribute to the complexity of this area. This section touches upon a few key concepts to aid in understanding the material presented.

[24] The ECMWF System 5, the latest seasonal forecasting system from ECMWF, is widely regarded as one of the best models in the world. However, there are dozens of global seasonal forecast systems, and some outperform ECMWF's system in specific regions or during certain months. Importantly, it has been empirically proven that combining outputs from multiple models generally yields better results than relying on any single model alone.

[25] This is the common grid used by C3S for all eight models currently available via the Climate Data Store: https://cds.climate.copernicus.eu.

is possible to analyse seasonal forecast maps based on country averages, examining gridded maps offers a more pedagogical and insightful approach to understanding the spatial patterns and dynamics of the forecasts. Accordingly, we assess four climate variables aligned with their corresponding energy indicators: wind speed for wind power, solar radiation for solar power, precipitation for hydropower and temperature for energy degree days (EDDs).

3.1 Seasonal forecast of wind speed

South America is strongly influenced by the El Niño–Southern Oscillation (ENSO). During active ENSO phases, whether positive (El Niño) or negative (La Niña), seasonal forecasts are generally more skilful. Figure 12 (right) presents a map of the seasonal forecast for wind speed at 10 m height for November 2023, based on forecasts initiated on 1 October 2023. The forecast consists of a 51-member ensemble, and a common approach to display a single map while retaining probabilistic information is to show the most likely category. This method avoids collapsing the ensemble into a single value (such as the mean or median). Instead, it highlights the probabilities of wind speeds falling into the upper or lower terciles, represented by separate colour palettes. For most of South America, the forecast indicates a higher probability of wind speeds being in the upper tercile (stronger winds, shown in green tones) than in the lower tercile.

To compare the forecast with the observed event, as represented by the ERA5 reanalysis, the other two maps display results from ERA5 for November 2023. The first map (Figure 12, left) shows the anomaly, calculated as the difference between November 2023 wind speeds and the average for the reference period (1993–2016).[26] The map indicates that wind speeds were indeed higher than average over most of the continent. To facilitate a fairer comparison with the "most likely category" forecast, the middle map (Figure 12, centre) categorizes the observed anomalies into the three terciles (upper, middle or lower). The map confirms that most of South America experienced wind speeds in the upper tercile, consistent with stronger-than-normal conditions. This aligns with the deviation shown by the wind power CF[27] (Figure 2, right), in line with the findings of Bett et al. (2022),[28] although it should be noted that there is a slight difference in reference periods: 1991–2020 for wind power CF and a little shorter period, 1993–2016, for the seasonal forecast retrospective data, as provided via the C3S Climate Data Store. For an assessment of the seasonal forecast model for the selected event, please refer to Section 6.6.

[26] This reference period is determined by the availability of seasonal retrospective forecast data from the C3S Climate Data Store.
[27] Wind power CF is related to wind speed (typically at 100 m height) via the standard power curve conversion (see also the Methodology section).
[28] Bett et al. (2022) found that for seasonal and regional averages (for example, over a country), wind and solar photovoltaic (PV) power generation are both very highly correlated with the average wind speed and solar irradiance, respectively.

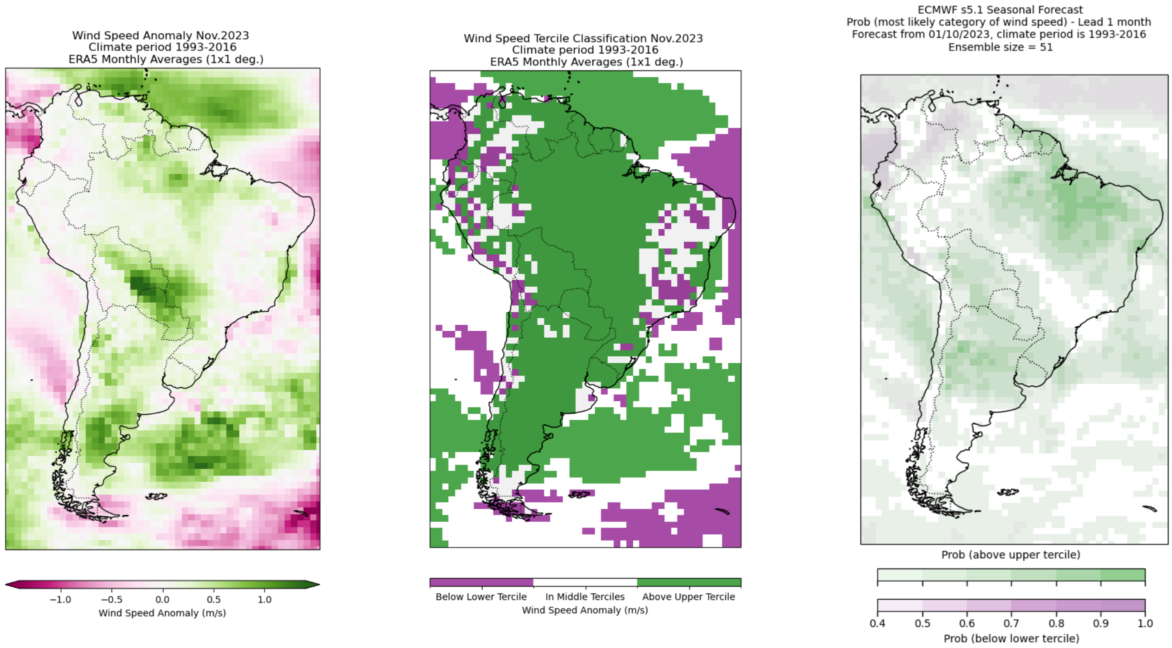

Figure 12. Maps of wind speed focusing on South America (from a global model) for November 2023. The panels show (left) the observed anomaly based on the ERA5 reanalysis, (centre) the tercile classification derived from ERA5, and (right) the most likely tercile category from the seasonal forecast at a lead time of one month (forecast initiated on 1 October 2023).
Note: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by WMO, the United Nations, IRENA or the European Union.

3.2 Seasonal forecast for solar radiation

As shown in Figure 13, solar radiation, which is closely linked to solar power, shows a strong signal in the seasonal forecast for the upper tercile, particularly over much of Brazil. In contrast, a lower tercile signal is more prominent over Peru, southern Brazil and Uruguay (Figure 13, right). This pattern is broadly reflected in the ERA5 anomaly (Figure 13, left), which is further supported by the ERA5 tercile classification in the middle panel (Figure 13, centre). This observed pattern aligns with the solar photovoltaic (PV) CF variation depicted in Figure 4, right. Again, the strong positive signal in most of the eastern region of the continent, coupled with a negative signal in the west, can be attributed to El Niño being close to its mature phase.

3.3 Seasonal forecast for precipitation

For precipitation, which is closely related to the hydropower proxy, the seasonal forecast signal closely mirrors that of solar radiation but with a reversed sign (Figure 14, right). Accordingly, the most likely category is the lower tercile (indicating dry conditions) for most of the continent, while the upper tercile (indicating more precipitation) is observed over Peru, southern Brazil and Uruguay. This pattern aligns with the ERA5 anomaly (Figure 14, left) and the ERA5 tercile classification (Figure 14, centre). It is also broadly consistent with the hydropower proxy (Figure 6, right), though it is important to note that the proxy represents a three-month average for precipitation (in this case, September, October and November), making it not directly comparable to the value for November alone shown here.

3.4 Seasonal forecast for temperature

Seasonal forecasts for temperature are generally more skilful than those for other variables. This is due to lower overall high-frequency variability compared to other climate variables, such as wind speed, and the influence of the global warming trend. The forecast for November 2023 for South America (Figure 15, right) indicates a strong predominance of the upper tercile as the most likely category, consistent with global warming. However, areas of lower terciles are observed in the southern part of the continent. This pattern aligns with the ERA5 anomaly (Figure 15, left) and the ERA5 tercile classification (Figure 15, centre). However, the alignment with the corresponding EDD variation (Figure 8, left) is less pronounced, owing to the non-linear relationship between temperature and the EDD definition. While there is strong positive variation for Brazil and other countries in the centre and north-west of the continent across both EDDs and the seasonal forecast (as well as ERA5), the sign of the variation differs for EDDs compared to the seasonal forecast (and ERA5) in some regions. For instance, ERA5 shows positive variations for Peru, but EDDs show negative variations, whereas the opposite is true for Chile and Argentina. This mismatch is likely due to the non-linearities inherent in the EDD definition.

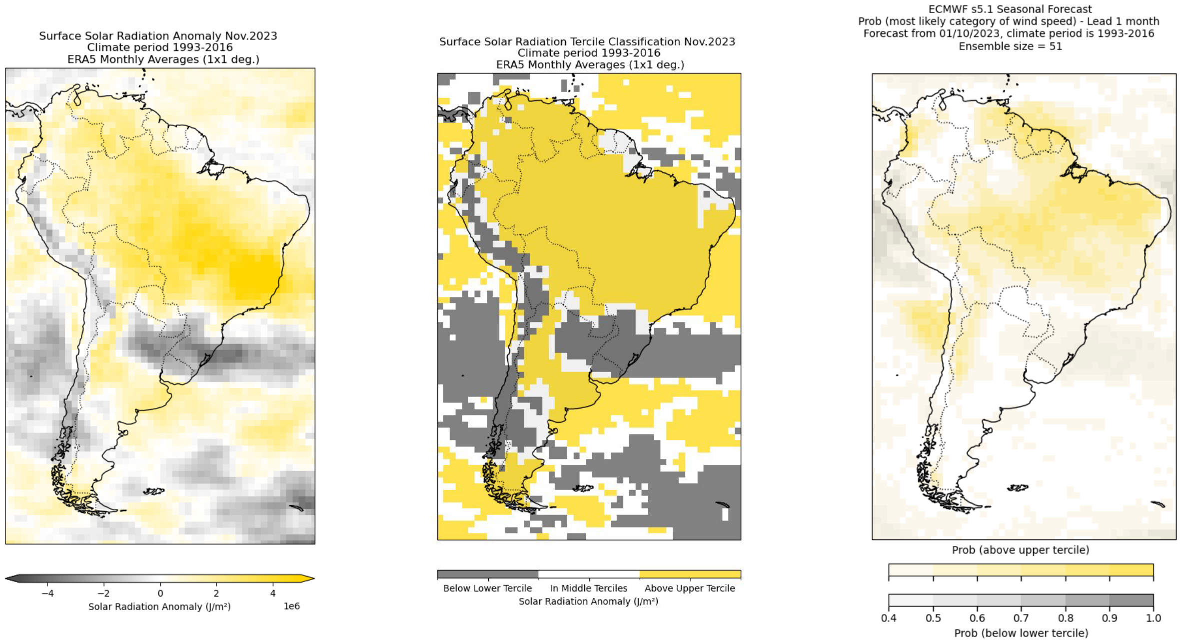

Figure 13. Maps of solar radiation focusing on South America (from a global model) for November 2023. The panels show (left) the observed anomaly based on the ERA5 reanalysis, (centre) the tercile classification derived from ERA5, and (right) the most likely tercile category from the seasonal forecast at a lead time of one month (forecast initiated on 1 October 2023).

Note: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by WMO, the United Nations, IRENA or the European Union.

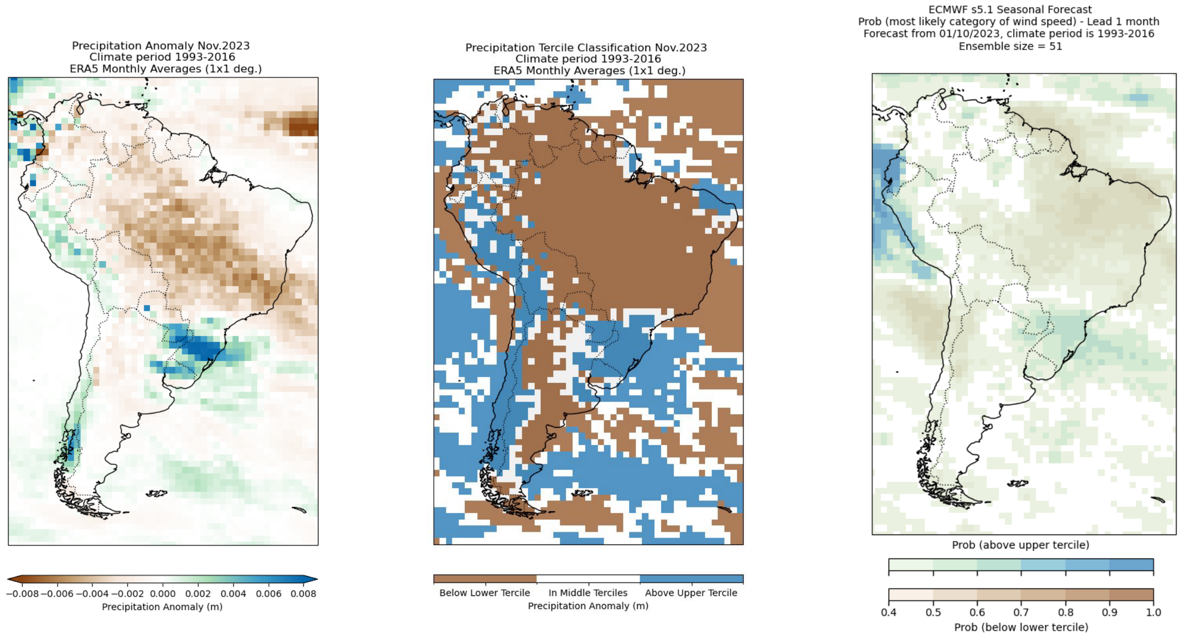

Figure 14. Maps of precipitation focusing on South America (from a global model) for November 2023. The panels show (left) the observed anomaly based on the ERA5 reanalysis, (centre) the tercile classification derived from ERA5, and (right) the most likely tercile category from the seasonal forecast at a lead time of one month (forecast initiated on 1 October 2023).
Note: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by WMO, the United Nations, IRENA or the European Union.

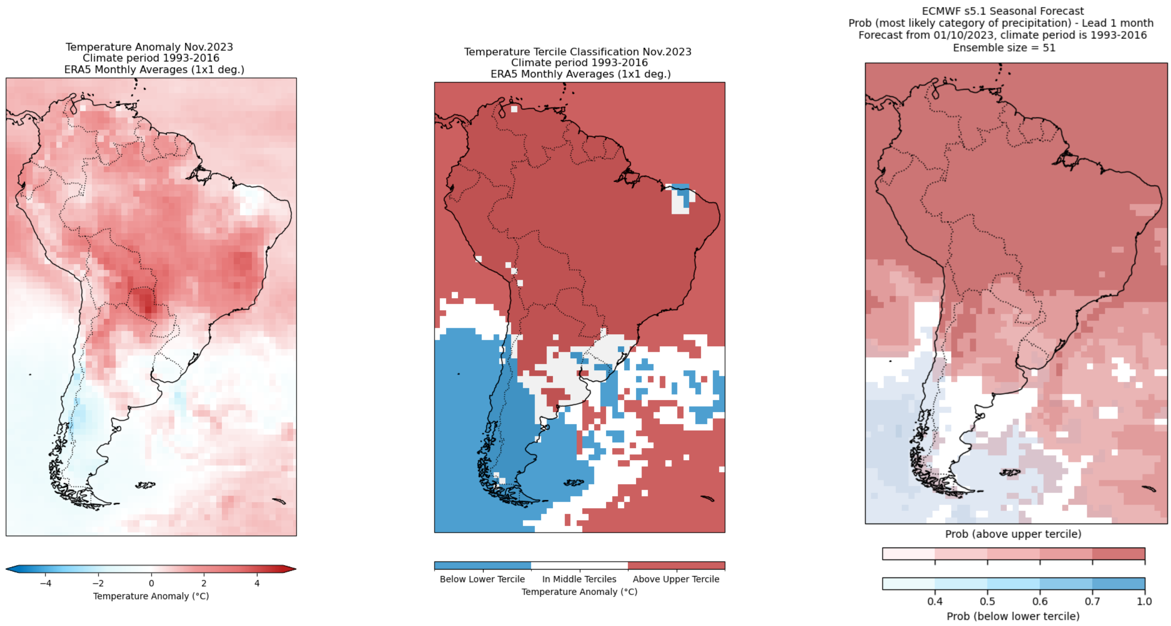

Figure 15. Maps of air temperature focusing on South America (from a global model) for November 2023. The panels show (left) the observed anomaly based on the ERA5 reanalysis, (centre) the tercile classification derived from ERA5, and (right) the most likely tercile category from the seasonal forecast at a lead time of one month (forecast initiated on 1 October 2023).
Note: The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by WMO, the United Nations, IRENA or the European Union.

4 Conclusions

The Influence of climate variability on renewable energy
Climate variability, driven by phenomena such as El Niño and La Niña, has a profound impact on renewable energy (RE) generation and demand. In 2023, the mature El Niño phase demonstrated the dual influence of climatic drivers on energy systems. Enhanced solar radiation improved solar photovoltaic (PV) capacity factors (CFs) in parts of South America, while reduced precipitation hindered hydropower generation in critical regions. These effects, occurring against the backdrop of global climate change and warming, highlight the urgent need for robust, adaptable energy systems capable of mitigating climate-driven risks.

The variability and changes in wind, solar and hydropower potential underscore the necessity of integrating climate considerations into energy planning. Countries heavily reliant on a single energy source, such as hydropower, are particularly vulnerable to these impacts. A diversified approach to energy planning, combined with regional cooperation, can mitigate these risks, stabilize energy supplies and strengthen resilience.

The value of seasonal climate forecasts
Seasonal climate forecasts hold significant potential for improving energy planning and management. By providing probabilistic insights into key variables such as temperature, precipitation, wind speed and solar radiation, these tools allow stakeholders to anticipate resource variability and optimize energy system operations. For instance, hydropower reservoir management benefits from accurate precipitation forecasts, while wind and solar farm operators can adjust operations based on forecasted wind speed and solar radiation patterns.

Despite their utility, the adoption of seasonal forecasts in the energy sector remains limited. Barriers such as insufficient awareness, lack of technical capacity, and integration challenges must be overcome to fully realize their value. Capacity-building initiatives, collaborative research and tailored tools are essential to bridge these gaps and foster broader and more inclusive adoption of climate-informed energy planning.

Detection, observation, monitoring, analysis and forecasting
While existing datasets and models provide a strong foundation for creating effective energy services and forecasts, gaps in data quality and coverage remain. Improvements could focus on better representing physical processes relevant to wind and solar power. For instance, enhanced model resolution, improved use of forecast ensembles and increased observation coverage could deepen our understanding of climate anomalies – such as El Niño – and their dynamics (*Integrated Weather and Climate Services in Support of Net Zero Energy Transition* (WMO-No. 1312)). Accurately assessing and understanding the key climate drivers and associated atmospheric patterns is critical for providing advanced warnings and enabling proactive energy management (as well as supporting other sectoral applications).

Data sharing also plays a key role in improving forecast accuracy and energy system modelling. Observations are fundamental for initializing numerical weather predictions, assessing climate models and calibrating post-processing techniques. However, many regions, particularly in developing countries, remain under-observed for critical variables like wind speed at various heights and solar radiation.

In the energy domain, data sharing on generation and installed capacity is equally crucial. High-quality and consistent energy data are essential for modelling power production and capacity factors accurately. Yet, gaps and inconsistencies persist due to commercial sensitivities and irregular reporting practices. Even in regions with robust data-sharing frameworks, such as the European Network of Transmission System Operators for Electricity (ENTSO-E) Transparency Portal, discrepancies in reported capacities highlight the need for more frequent and accurate updates. Addressing these gaps is essential for advancing RE systems globally.

Policy recommendations for a resilient energy future
Diversifying energy portfolios to include a mix of solar, wind, hydropower, emerging technologies and storage will be crucial for managing climate variability and ensuring energy security. Achieving the ambitious targets of tripling RE capacity by 2030 and reaching net-zero emissions by 2050 requires a multifaceted approach. Policymakers must integrate climate information into national energy strategies, ensuring that tools like seasonal forecasts are effectively utilized to enhance resilience and reliability.

This is in keeping with an overall comprehensive and holistic approach to policymaking as it relates to RE promotion, the broader energy transition and climate stabilization efforts. These efforts can succeed only if they combine measures in support of deployment of renewables with their careful integration into energy systems and parallel policies to upgrade and balance electricity grids not just within a particular country, but also within regions. Technical measures need to be accompanied by policies to ensure viable supply chains. Considerations such as the security and stability of energy supplies need to be paired with policies to ensure that communities and countries share in the socioeconomic benefits of the energy transition. And the transition must be based on the understanding that human and environmental well-being are intrinsically linked. Not only is the energy system central to the function of the overall economy, but the economy is inextricably embedded in the planet's climate and ecosystems.

Regional collaboration is equally critical for balancing supply–demand dynamics, optimizing cross-border energy flows and fostering shared resilience to climate risks. The international community must prioritize investment in climate-resilient energy infrastructure, leveraging partnerships that capitalize on shared knowledge and resources. By embracing these strategies, countries can accelerate the transition to sustainable, low-carbon energy systems, ensuring a resilient and equitable energy future.

4.1 Key messages

(1) Climate variability and change significantly affect energy indicators. In 2023, the assessed energy indicators – wind power capacity factor (CF), solar photovoltaic (PV) CF, a hydropower proxy and energy degree days (EDDs) – demonstrate noticeable changes driven by climate variability and change. These effects vary by technology and country, with marked percentage anomalies observed in both annual and monthly averages. While solar PV CF shows annual anomalies that are relatively contained (below 10% compared with the 1991–2020 climate reference period), wind power CF exhibits pronounced variability, exceeding 15% annually in many regions. This underscores the importance of accounting for climate variability and change in energy system planning and operations.

(2) Understanding climate drivers is crucial for energy resilience. The 2023 transition from La Niña to El Niño, two opposite phases of the El Niño–Southern Oscillation (ENSO), highlights the critical role of large-scale climate drivers like ENSO in shaping energy systems. El Niño's drier and warmer conditions significantly influenced energy indicators, with results including increased solar PV generation in South America and enhanced wind power in East Asia. Improved understanding and accurate prediction of these drivers, which account for significant climate variability, allows stakeholders to manage energy resources more effectively, optimize generation and anticipate demand fluctuations, fostering a more resilient and efficient energy transition.

(3) Climate variability information needs to be mainstreamed into energy systems for planning and management. The record-breaking temperatures and climate-driven energy variability in 2023 underscore the need to integrate climate variability into energy planning. This integration can support the establishment of early warning systems to improve energy load management, resource optimization and maintenance scheduling. It can also guide the modernization and expansion of energy infrastructure, fostering innovation across technologies, markets and policies to ensure resilience in a variable climate.

(4) Flexible market structures are crucial for the energy transition. Adapting electricity market structures is essential for ensuring flexibility during the transition from centralized to decentralized power systems. Flexible market designs must facilitate the procurement of the highest-value renewable resources while accommodating flexible solutions. A "dual procurement" system, which supports both renewable resource optimization and deployment of flexible resources, offers a promising approach to achieving this goal.

(5) Resilience should be enhanced through diversification and fostering regional collaboration. Diversified energy portfolios, combining solar, wind, hydropower and emerging technologies, are essential for managing the impacts of climate variability and ensuring energy security. Regional cooperation is vital for balancing energy supply and demand across borders. Collaborative efforts can maximize renewable energy potential, enhance grid stability and build resilient energy systems.

(6) There are huge opportunities for developing countries. Developing countries can harness their renewable energy potential to address energy access challenges while leveraging knowledge of climate variability. For instance, despite abundant renewable energy resources, Africa accounts for only 2% of global installed capacity. By integrating resource potential with climate information, countries can effectively develop renewable energy infrastructure to support industrialization and economic growth, accelerating sustainable development across the continent.

(7) Comprehensive energy data collection and sharing are critical. Systematic and detailed energy data collection and sharing are vital for advancing the understanding of climate variability's impacts on energy supply and demand. While the energy indicators presented here offer a simplified perspective, more representative metrics require access to robust datasets, including detailed information on installed capacity and actual generation. Transparent and harmonized data-sharing practices will enable more accurate modelling and informed decision-making across the energy sector.

5 Methodology

To understand 2023 patterns of power potential anomalies, the 1991–2020 period is used as a baseline in all cases. This period is officially designated as the new climatological normal (*2022 State of Climate Services: Energy* (WMO-No. 1301)).

All calculations for wind, solar 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. Precipitation is used as a proxy for hydropower, but it is weighed according to the number of hydropower plants and their size in a particular area.

Once the power generation (or its proxy) for each of the three renewable energy sources is calculated, their co-variability and their role in the energy mix are explored in a qualitative way. The generation indicators are also compared 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 the energy indicators are based on climate data from the ERA5 reanalysis (Hersbach et al., 2020; IPCC, 2021). 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, means that 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° × 0.25° over the whole globe), which is normally not the case with observations.

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 that are not suitable or have restrictions for power plant construction (such as natural reserves, steep slopes) are excluded.

Display
Maps at a global level are presented as country averaged data. Also, timeseries of monthly averages for 2023 for selected countries are displayed.

5.1 Wind power capacity factor calculation

The wind power capacity factor data used were those available in the Weather for Energy (WfE) portal calculated by IEA/Euro-Mediterranean Centre for Climate Change (CMCC) for 1991–2020 and 2023. They represent 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 capacity factor at 100 m from WfE:

- Spatial resolution: 0.25° × 0.25° latitude/longitude
- Coverage: Global
- Temporal resolution: Monthly
- Temporal period: 1991–2020 and 2023

Wind mask

- This product is produced under the C3S Energy project[29] and is considered time-invariant
- Spatial resolution: 0.25° × 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.

[29] https://climate.copernicus.eu/operational-service-energy-sector

Formula used by WfE

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

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)
T: time considered, for example, 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 Vestas V110-2 MW[30]

Workflow

The wind power capacity factor (CF) is masked prior to calculations. With these data the following are calculated: (i) capacity factors for "non-restricted" grid points for the period 1991–2020 and 2023; (ii) capacity factors averaged over countries (Natural Earth Admin 0 regions (ADM0)), considering the non-restricted areas.

(1) Mask wind capacity factor data using the wind mask (see below for description) in addition to a land-sea mask (that masks out all oceans).

  (a) Consider grid points for each country (after applying mask) and retain only the points for which the climatological CF is above the threshold of 0.1, to avoid including areas where wind power is unlikely to be developed.

  (b) Retain the country if the number of grid points above the threshold is greater than 20% of all grid points for that country and there are at least two grid points, otherwise the country is not considered (that is, set to NA).

(2) Calculate anomalies for 2023 using 1991–2020 as baseline (monthly means).

(3) Anomaly = monthly mean for 2023 – monthly mean for the period 1991 to 2020.

(4) Aggregate by country taking only grid points above CF threshold.

(5) Generate global anomaly maps aggregated by country (shape file).

(6) Generate regional anomaly maps (selected WMO regions) using gridded data clearly showing masked areas (as this is also useful information for the user).

5.2 Solar photovoltaic power capacity factor calculation

Solar photovoltaic (PV) power potential capacity factor is based on monthly averages of downward solar irradiance, air temperature at 2 m and 10-m wind speed. PV capacity factor mainly accounts for the solar irradiance resource, but it also takes into account the influence that other atmospheric variables may have on the efficiency of the PV cells, which diminishes as their temperature increases (Jerez et al., 2015). So, the effect of temperature and wind speed is also considered.

[30] The Vestas V110-2 MW is a turbine 110 m high that can start generating at a low wind speed of 3 m/s, producing a good capacity and yield at low- and medium-wind sites.

The calculation of PV capacity factor follows the method in Jerez et al. (2015). Only power capacity over land is evaluated and, in this case, urban areas are not masked, as PV can be installed there. An even distribution of PV panels is assumed in all unmasked areas. Similarly to wind, anomalies for 2023 are calculated and data are aggregated by country to explore the energy mix complementarity of each region.

Base data

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

- Spatial resolution: 0.25° × 0.25° latitude/longitude
- Coverage: Global
- Temporal resolution: Monthly
- Temporal period: 1991–2020 and 2023

Air temperature at 2 m from ERA5 reanalysis data:

- Spatial resolution: 0.25° × 0.25° latitude/longitude
- Coverage: Global
- Temporal resolution: Monthly
- Temporal period: 1991–2020 and 2023

Wind speed at 10 m from ERA5 reanalysis data:

- Spatial resolution: 0.25° × 0.25° latitude/longitude
- Coverage: Global
- Temporal resolution: Monthly
- Temporal period: 1991–2020 and 2023

Solar mask

- This product, produced by WEMC (C3S Energy project), is considered time-invariant
- Spatial resolution: 0.25° × 0.25° latitude/longitude
- Coverage: Global
- Binary layers accounting for:
  - Protected areas
  - Topographic conditions with high elevations and high slopes
  - Polar areas

Workflow

(1) Calculate solar power capacity, assuming an even distribution over land of PV panels.

(2) Mask solar capacity factor data using the restricted areas mask and the land-sea mask.

   (a) Consider grid points for each country (after applying mask) and retain only the points for which the climatological CF is above the threshold of 0.1, to avoid including areas where solar PV power is unlikely to be developed.

(b) Retain the country if the number of grid points above the threshold is greater than 20% of all grid points for that country and there are at least two grid points, otherwise the country is not considered (that is, set to NA).

(3) Calculate anomalies for 2023 using the same baseline and formulas as for wind.

(4) Aggregate by country taking only grid points above CF threshold.

(5) Generate global anomaly maps aggregated by country (shape file).

(6) Generate regional anomaly maps (selected WMO regions) using gridded data clearly showing masked areas (as this is also useful information).

5.3 Hydropower proxy

The calculation of the proxy hydropower capacity factor is based on monthly averages of ERA5 precipitation data. As the installed capacity of this renewable energy is more stable over time, global hydropower plant location data were used, with everything else masked out. However, only installations from recent years (for example, 2021–2023) were considered, to avoid issues with uneven coverage over the reference period and also to have results more representative of future hydropower installed capacity (assuming changes will be minor); however, knowledge of new power plants may also be included in view of a potential use of projection data, as otherwise those grid cells would not be considered (for example, the planned large hydropower plant in Malawi).

The installed capacities of existing power plants were used as weights for the proxy calculation based on precipitation over defined sub-country areas, according to Natural Earth Admin 1 regions (ADM1). Several countries have very low precipitation values, and any increase/decrease causes high values in the percentage change calculations. Therefore, data are aggregated over a three-month period, namely the month considered together with the two preceding months (to mimic accumulation of water for hydropower).

Base data

Precipitation from ERA5:

- Spatial resolution: 0.25° × 0.25° latitude/longitude
- Coverage: Global
- Temporal resolution: Monthly averages
- Temporal period: 1991–2020 and 2023

Plant locations and Installed capacity

We use the hydropower plant locations database from the Global Energy Monitor Global Hydropower Tracker, which is a comprehensive and up-to-date database:

- Spatial resolution: lat./long. datapoints
- Coverage: Global

Workflow

(1) For each grid cell or area (as defined by the ADM1 shape files), assign weights based on the area's aggregated installed capacity.

(2) Calculate new monthly moving average values using a three-month window.

(3) Aggregate precipitation data at ADM1 level (or other agreed upon aggregation area).

(4) Compute the country's weighted-average precipitation based on the installed capacity weights (the normalization factor is taken as the country average, considering all the ADM1 for that particular country).

(5) Calculate anomalies for 2023 using the same baseline and formulas as for other energy indicators.

(6) Generate anomaly maps aggregated by country for the different WMO regions.

5.4 Energy demand proxy

To provide an assessment of the balance or imbalance between demand and renewable energy, in the context of energy mix, the report considers an energy demand proxy.

Given the sparsity and disparity of energy demand data at monthly resolution for 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 (EDDs) indicator – the sum of cooling degree days (CDDs) and heating degree days (HDDs)[31] – was selected as a proxy for energy (electricity) demand. EDDs have been defined and used in various studies in Europe (Spinoni et al., 2018) and globally (Spinoni et al., 2021). Having only a single demand indicator, EDDs, rather than two, CDDs and HDDs, makes it possible to simplify the presentation and discussion.

Global CDD and HDD data are freely available from the IEA/CMCC Weather for Energy Tracker from 1979 to near real time (IEA; CMCC, 2023). Multiple realizations of CDD and HDD are provided. Unlike the previous report (*2022 Year in Review: Climate-driven Global Renewable Energy Potential Resources and Energy Demand*), this report adopts a different definition for CDDs (and consequently for EDDs), while maintaining the same definition for HDDs, to align with the broader range of products now offered by the C3S Energy Service (see Table 2). Specifically, the CDD definition used here is CDDThold21.

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, 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 indicator is 5 (26 °C – 21 °C). If the daily mean air temperature is 22 °C, for that day the CDD value is 0.

Similarly 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 this 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

[31] HDD assesses the severity of the cold in a specific time period taking into consideration outdoor temperature and average room temperature to infer the need for heating (conversely, CDD assesses the severity of the heat to infer the need for cooling). The number of days the temperature is above or below a predefined threshold is then counted.

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 ≥ $T_{threshold}$: HDD = 0

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

The HDD definition of HDDThold18 (IEA, 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 indicator is 6 (18 °C – 12 °C), whereas if the daily mean air temperature is 16 °C, for that day the HDD value is 0.

As with the IEA/CMCC dataset, gridded data are weighted by population, as population location and growth have an effect on changing energy demand, and then country averages are calculated.

Table 2. Selected indices for CDD and HDD

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 indicator is 5 (26 °C – 21 °C). If the daily mean air temperature is 22 °C, for that day the CDD value 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 HDDThold18**

Note: See also the Weather for Energy Tracker.

Population data

Provided by CMCC:[32]

- Spatial resolution: 0.25° × 0.25° latitude/longitude
- Coverage: Global
- Temporal resolution: Annual
- Temporal period: 1991–2020 and 2023

Base data

Use HDDThold18 and CDDthold21 datasets (see Table 2):

- Spatial resolution: 0.25° × 0.25° latitude/longitude
- Units: Degree days

[32] Their data are derived from the Center for International Earth Science Information Network (CIESIN), Columbia University, 2018, Gridded Population of the World, Version 4 and GHS population grid from the Joint Research Centre (IEA; CMCC, 2023). Data are interpolated to estimate yearly population values from 2000 to 2023.

- Coverage: Global
- Temporal resolution: Monthly averages
- Temporal period: 1991–2020 and 2023

Workflow

(1) Data are only masked with the land-sea mask.

(2) The CDD and HDD are weighted by population.

(3) EDD values are obtained from CDD and HDD using the formula:

EDDh21Thodl18 = CDDhum21 + HDDThold18.

(4) Anomalies are calculated using the same formula as above.

(5) Data are aggregated by country to be compared to the energy mix derived from the three renewable energy sources.

5.5 Seasonal forecast skill measure

A wide variety of metrics are available for assessing seasonal forecasts, ranging from deterministic metrics (which use the ensemble mean) to probabilistic metrics that leverage the full ensemble. For this analysis, a probabilistic measure was selected, which is more appropriate for probabilistic forecasts like seasonal forecasts. Specifically, the continuous ranked probability skill score (CRPSS) was adopted. CRPSS is a metric that evaluates forecast skill by comparing the cumulative squared probability error – known as the ranked probability score (RPS) – of the actual forecasts with the RPS derived from climatology-based forecasts. The RPS quantifies the extent to which forecasts successfully discriminate between different observed outcomes and identifies systematic biases in location and confidence levels. A positive RPSS indicates that the RPS for the forecasts is lower than that for climatology forecasts, signifying improved forecast performance (Table 3). 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 (for example, the upper tercile).

Table 3. Summary of the main features of the continuous ranked probability skill score (CRPSS)

Metric	Answers the question	Range	Characteristics
Continuous ranked probability skill score (CRPSS)	What is the relative improvement of the probability forecast over climatology in predicting the category that the observations fall into?	–Infinity to 1; 0 indicates no skill when compared to the reference forecast. **Perfect score:** 1	Measures the improvement of the multi-category probabilistic forecast relative to a reference forecast (usually the long-term or sample climatology); strictly proper; takes climatological frequency into account; unstable when applied to small data sets; CRPSS is a generalization of RPSS, whereby the thresholds are continuous rather than discrete.[33]

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

5.6 Seasonal forecast assessment

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, November 2023. This is why it is essential to assess the quality of the model beforehand, as this provides an indication of whether, and to what extent, the forecast can be trusted. To achieve this, skill metrics are applied to retrospective forecasts, which, in this case, cover the period 1993–2016.

Wind speed

As mentioned, the continuous ranked probability skill score (CRPSS) was chosen as the metric. Figure 16 displays the CRPSS averaged across four countries: Brazil, Colombia, Peru and Chile. Specifically, the figure illustrates the model's skill in predicting Novembers at increasing lead times, with forecasts initiated on 1 October (lead time 1), 1 September (lead time 2), and so on. Generally, the accuracy, or skill, of the seasonal forecast model decreases as the lead time increases. However, there are exceptions, partly due to the limited sample size (24 years, while relatively long, is insufficient for a fully robust climatology). More specifically, the seasonal forecasts for November show positive skill mainly for the first month, with the skill dropping considerably thereafter. This is an expected behaviour, as wind speed is subject to a high level of variability, making seasonal forecasting challenging.

It is also important to note that this is the average skill, encompassing years of both neutral ENSO phases and active ENSO phases. As noted earlier, during active ENSO phases (El Niño or La Niña), the signal tends to be stronger, leading to generally higher forecast accuracy. Additionally, forecast skill tends to be higher in the tropics compared to the extratropics, contributing to the heterogeneity observed in the country-aggregated results. Since the skill shown in Figure 16 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 November 2023 shown in Figure 12 (right). With experience, users can better evaluate and interpret the reliability of upcoming seasonal forecasts. This is why it is important to begin exploring and adopting seasonal forecasts as a valuable tool for planning and decision-making, recognizing that proficiency develops over time through consistent use and analysis.

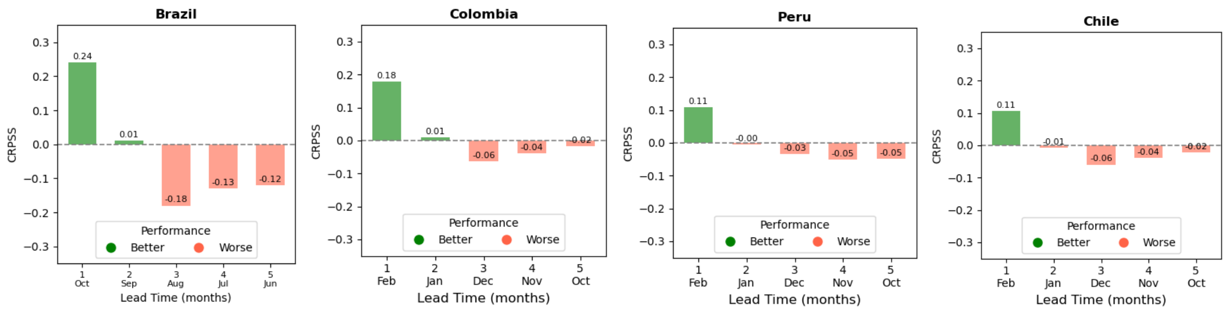

Figure 16. Assessment of the seasonal forecast using the continuous ranked probability skill score (CRPSS) for wind speed, targeting November over the testing period 1993–2016, and focusing on the same four countries analysed in the regional perspective (Section 2.3): Brazil, Colombia, Peru and Chile. The histogram bars represent the skill of the forecast initiated on 1 October (lead time 1) (leftmost), 1 September (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.

Solar radiation

Regarding the November skill, solar radiation forecasts for Brazil, Colombia, and Chile exhibit positive skill at most lead times (Figure 17). However, the forecasts for Colombia show atypical behaviour at lead time 1, warranting further investigation. The forecasts for Peru, once again, show little to no skill across all lead times. One of the reasons of this limited skill can be attributed to a combination of the country's steep orography and strong oceanic currents near its coast, which are not fully considered by the ocean component of the seasonal forecast models.

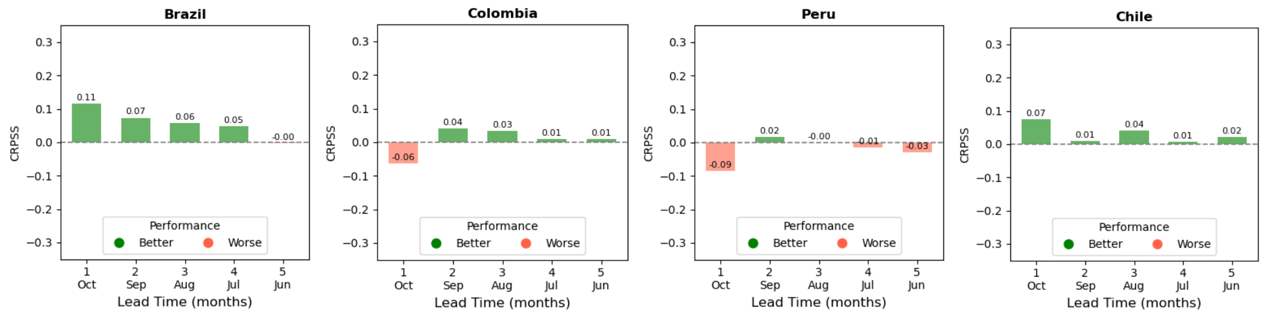

Figure 17. Assessment of the seasonal forecast using the continuous ranked probability skill score (CRPSS) for solar radiation, targeting November over the testing period 1993–2016, and focusing on the same four countries analysed in the regional perspective (Section 2.3): Brazil, Colombia, Peru and Chile. The histogram bars represent the skill of the forecast initiated on 1 October (lead time 1) (leftmost), 1 September (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.

Precipitation

For November, precipitation forecast skill is positive for most lead times in Brazil, Colombia and Chile, indicating that forecasts made 4–5 months in advance are more accurate than relying on climatological values (Figure 18). In contrast, forecasts for Peru consistently exhibit negative skill across all lead times.

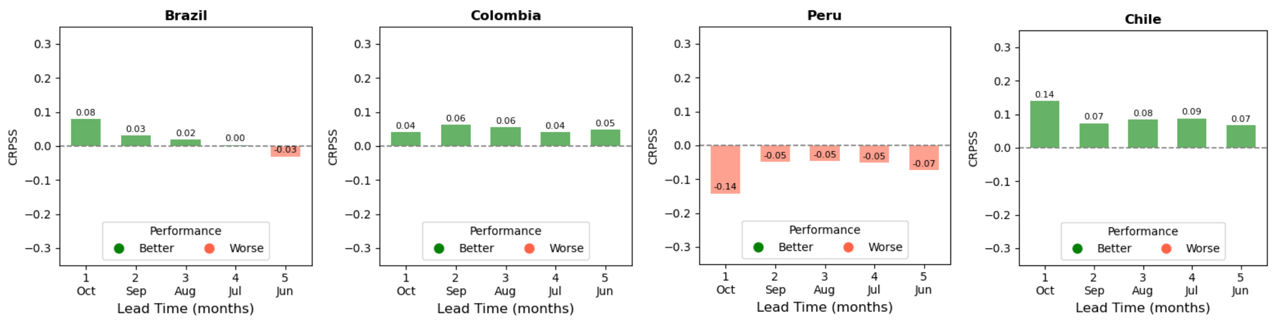

Figure 18. Assessment of the seasonal forecast using the continuous ranked probability skill score (CRPSS) for precipitation, targeting November over the testing period 1993–2016, and focusing on the same four countries analysed in the regional perspective (Section 2.3): Brazil, Colombia, Peru and Chile. The histogram bars represent the skill of the forecast initiated on 1 October (lead time 1) (leftmost), 1 September (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.

Temperature

The seasonal forecast model skill for temperature in November shows positive results for Brazil (up to lead time 4) and especially for Colombia, which exhibits higher skill values and positive results across all lead times (Figure 19). However, the skill for Chile and Peru is less promising. Forecasts for Peru, as in previous analyses, show negative or zero skill at all lead times, likely influenced by the effects of steep orography and complex ocean circulation patterns, as previously mentioned. Similar factors may contribute to the poor performance of the seasonal forecast for Chile. Notably, in Chile's case, lead time 1 demonstrates a positive skill.

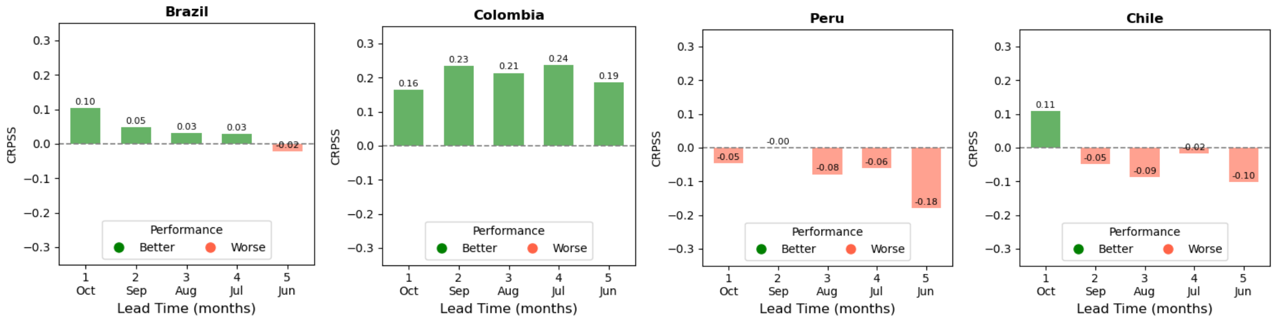

Figure 19. Assessment of the seasonal forecast using the continuous ranked probability skill score (CRPSS) for air temperature, targeting November over the testing period 1993–2016, and focusing on the same four countries analysed in the regional perspective (Section 2.3): Brazil, Colombia, Peru and Chile. The histogram bars represent the skill of the forecast initiated on 1 October (lead time 1) (leftmost), 1 September (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.

6 References

Bett, P. E.; Thornton, H. E.; Troccoli, A. et al. A Simplified Seasonal Forecasting Strategy, Applied to Wind and Solar Power in Europe. *Climate Services* **2022**, *27*, 100318. https://doi.org/10.1016/j.cliser.2022.100318.

Copernicus Climate Change Service (C3S). *European State of the Climate 2023*; C3S, 2024a. https://climate.copernicus.eu/ESOTC/2023.

Copernicus Climate Change Service (C3S). *Global Climate Highlights 2023*; C3S, 2024b. https://climate.copernicus.eu/global-climate-highlights-2023.

Ember. *Global Electricity Review 2024*; Ember, 2024. https://ember-energy.org/app/uploads/2024/05/Report-Global-Electricity-Review-2024.pdf.

Hersbach, H.; Bell, B.; Berrisford, P. et al. The ERA5 Global Reanalysis. *Quarterly Journal of the Royal Meteorological Society* **2020**, *146* (730), 1999–2049. https://doi.org/10.1002/qj.3803.

International Energy Agency (IEA). *World Energy Outlook 2024*; IEA: Paris, 2024. https://www.iea.org/reports/world-energy-outlook-2024.

International Energy Agency (IEA); Euro-Mediterranean Centre for Climate Change (CMCC). *Weather for Energy Tracker: Users Guide*; April 2023 Edition; IEA: Paris, 2023. https://iea.blob.core.windows.net/assets/d8558cd7-5a1a-4ef6-9c24-6d639f54be7d/IEA_CMCC_Weather_for_Energy_Tracker_-_Users_Guide.pdf.

Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Masson-Delmotte, V.; Zhai, P.; Pirani, A. et al., Eds.; Cambridge University Press: Cambridge, United Kingdom, 2021. https://www.ipcc.ch/report/ar6/wg1.

Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Pörtner, H.-O.; Roberts, D. C.; Tignor, M. M. B. et al., Eds.; Cambridge University Press: Cambridge, United Kingdom, 2022a. https://www.ipcc.ch/report/ar6/wg2.

Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Shukla, P. R.; Skea, J.; Slade, R. et al., Eds.; Cambridge University Press: Cambridge, United Kingdom, 2022b. https://www.ipcc.ch/report/ar6/wg3.

International Renewable Energy Agency (IRENA). *RE-organising Power Systems for the Transition*; IRENA: Abu Dhabi, 2022. https://www.irena.org/publications/2022/Jun/RE-organising-Power-Systems-for-the-Transition.

International Renewable Energy Agency (IRENA). *World Energy Transitions Outlook 2023: 1.5°C Pathway*; Volume 1; IRENA: Abu Dhabi, 2023. https://www.irena.org/Publications/2023/Jun/World-Energy-Transitions-Outlook-2023.

International Renewable Energy Agency (IRENA). *Renewable Capacity Statistics 2024*; IRENA: Abu Dhabi, 2024a. https://www.irena.org/Publications/2024/Mar/Renewable-capacity-statistics-2024.

International Renewable Energy Agency (IRENA). *Renewable Energy Statistics 2024*; IRENA: Abu Dhabi, 2024b. https://www.irena.org/Publications/2024/Jul/Renewable-energy-statistics-2024.

International Renewable Energy Agency (IRENA). *Renewable Power Generation Costs in 2023*; IRENA: Abu Dhabi, 2024c. https://www.irena.org/Publications/2024/Sep/Renewable-Power-Generation-Costs-in-2023.

Jerez, S.; Tobin, I.; Vautard, R. et al. The Impact of Climate Change on Photovoltaic Power Generation in Europe. *Nature Communications* **2015**, *6* (1), 10014. https://doi.org/10.1038/ncomms10014.

Schmidt, G. Climate Models Can't Explain 2023's Huge Heat Anomaly — We Could Be in Uncharted Territory. *Nature* **2024**, *627* (8004), 467–467. https://doi.org/10.1038/d41586-024-00816-z.

Spinoni, J.; Vogt, J. V.; Barbosa, P. et al. Changes of Heating and Cooling Degree-Days in Europe from 1981 to 2100. *International Journal of Climatology* **2018**, *38* (S1), e191–e208. https://doi.org/10.1002/joc.5362.

Spinoni, J.; Barbosa, P.; Füssel, H.-M. et al. Global Population-Weighted Degree-Day Projections for a Combination of Climate and Socio-Economic Scenarios. *International Journal of Climatology* **2021**, *41* (11), 5447–5464. https://doi.org/10.1002/joc.7328.

Troccoli, A. Seasonal Climate Forecasting. *Meteorological Applications* **2010**, *17* (3), 251–268. https://doi.org/10.1002/met.184.

Troccoli, A., Ed. *Weather and Climate Services for the Energy Industry*; Palgrave Macmillan, 2018. https://doi.org/10.1007/978-3-319-68418-5.

White, C. J.; Domeisen, D. I. V.; Acharya, N. et al. Advances in the Application and Utility of Subseasonal-to-Seasonal Predictions. *Bulletin of the American Meteorological Society* **2022**, *103* (6), E1448–E1472. https://doi.org/10.1175/BAMS-D-20-0224.1.

United Nations Convention to Combat Desertification (UNCCD). *Global Drought Snapshot 2023: The Need for Proactive Action*; UNCCD: Bonn, 2024. https://reliefweb.int/report/world/global-drought-snapshot-2023-need-proactive-action-enru.

Van Dijk, A. I. J. M.; Beck, H. E.; Boergens, E. et al. *Global Water Monitor 2023: Summary Report*; Global Water Monitor, 2024.

World Meteorological Organization (WMO). *2022 State of Climate Services: Energy* (WMO-No. 1301). Geneva, 2022.

World Meteorological Organization (WMO). *Integrated Weather and Climate Services in Support of Net Zero Energy Transition* (WMO-No. 1312). Geneva, 2023.

World Meteorological Organization (WMO). *State of the Global Climate 2023* (WMO-No. 1347). Geneva, 2024.

World Meteorological Organization (WMO); International Renewable Energy Agency (IRENA). *2022 Year in Review: Climate-driven Global Renewable Energy Potential Resources and Energy Demand*. WMO: Geneva, 2023. https://www.irena.org/Publications/2023/Dec/2022-Year-in-Review-Climate-driven-Global-Renewable-Energy-Potential-Resources-and-Energy-Demand.

For more information, please contact:

World Meteorological Organization

7 bis, avenue de la Paix – P.O. Box 2300 – CH 1211 Geneva 2 – Switzerland

Strategic Communications Office

Tel.: +41 (0) 22 730 83 14

Email: cpa@wmo.int

wmo.int

International Renewable Energy Agency

Masdar City, Abu Dhabi, P.O. Box 236

Email: publications@irena.org

www.irena.org

European Centre for Medium-Range Weather Forecasts

Reading, UK | Bologna, Italy | Bonn, Germany

Email: copernicus-press@ecmwf.int

https://climate.copernicus.eu/

JN 2554