2022 Year in Review:
Climate-driven Global Renewable Energy Potential Resources and Energy Demand

WEATHER CLIMATE WATER

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METEOROLOGICAL
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International Renewable Energy Agency

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.

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Contents

Foreword

The data and analysis in this report represent a significant milestone in fulfilling the joint commitment by the World Meteorological Organization (WMO) and the International Renewable Energy Agency (IRENA) to advance the understanding of renewable energy resource potential, and its intricate relationship with climate variability and change.

Renewable energy, primarily driven by the dynamic forces of solar radiation, wind and water, has surged to the forefront of global power generation. This global energy transition is a powerful catalyst for mitigating climate change, safeguarding our planet and ensuring a prosperous future for generations to come.

The numbers speak for themselves. In 2022, 83% of new power generation capacity was from renewable energy. Such robust expansion represents considerable progress in achieving the goals of the Paris agreement to limit global surface temperature increase to 1.5 °C above pre-industrial levels and substantially reduce energy-related greenhouse gas emissions by 2030. To meet the 1.5 °C goal, global renewable power capacity must triple by 2030, while energy efficiency improvements must double.

This report highlights the inherent links between renewable energy sources and weather and climate conditions. The critical nexus between climate variability and renewable energy requires a comprehensive understanding of how meteorological variables impact the potential capacity of wind, solar and hydropower. Climate influences not only energy supply but also demand, particularly in the context of heating and cooling.

This publication explores these intricate connections in detail, at both the global and regional levels, by considering anomalous behaviours of energy indicators (onshore wind power, solar photovoltaic (PV) power, hydropower and energy demand proxies – called “energy degree days”) occurring in 2022, and comparing them to the current 30-year standard climatology reference period (1991–2020). The changes in these indicators for 2022 compared to the 30-year climatological average offer a valuable insight into the role of climate in renewable energy supply and demand.

Beyond climate trends, the analysis emphasizes the importance of considering climate variability in the contexts of renewable energy operations, management, planning and investment. The key messages of this report represent an invitation to policymakers, scientists and stakeholders to address the synergy between meteorology and renewable energy. It is at this intersection that IRENA and WMO expertise sets the stage for a rigorous evaluation that will empower policymakers, energy planners, resource managers and grid operators to grasp the magnitude and patterns of observed variations in clean energy supply and demand.

This effort also supports the reorganization of power systems into a “dual procurement” structure, which can effectively optimize the acquisition of high-value variable renewable resources and the flexible deployment of resources. It is also aligned with the activities taking place within the Early Warnings for All initiative, which is co-led by WMO. By assisting the understanding of relevant climate drivers and their associated large-scale atmospheric patterns, stakeholders can better anticipate climate-related impacts on renewable power generation and demand.

We extend our gratitude and appreciation to the lead authors from both organizations for their exceptional efforts in compiling this report, as well as to all the experts and contributors for their unwavering support and valuable inputs. We hope that this report will mark the inaugural edition of a series of such publications in the years to come.

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Executive summary

Renewable energy (RE) dominates new capacity additions, driven by solar and wind. The global total installed capacity of renewable power, and its share in the electricity grid, has been steadily increasing over the past two decades. Today, some 30%[1] of global power generation is renewable, due to rapid deployment in the past decade. In 2022 alone, 83% of new capacity was renewable, with solar and wind accounting for most additions. Such an increase is key to achieving decarbonized energy systems by 2050, with an accompanying steep and decisive decline of fossil fuel consumption.

More decisive actions are needed to further accelerate the transition of energy systems to dramatically reduce the greenhouse gases emissions of the energy sector by 2030 in line with 1.5 °C pathways. To achieve the most ambitious climate target of the Paris Agreement, global RE capacity needs to be tripled and the rate of energy efficiency improvements doubled by 2030.

Power generation from renewables, such as solar, wind and hydropower, which are addressed in this report, is both driven and impacted by climatic factors. These resources play an essential role in the global energy transition. But these RE resources are largely driven by climatic factors, so it is critical to understand the effects of climate variability and changes in relevant variables on RE generation. On the other hand, climate also impacts energy demand, especially related to heating and cooling.

The present report analyses the year 2022 compared with 30-year climatology data to offer insights into the effects of climate variability and change on selected technologies and energy demand. The effects of climate variability and change are presented by evaluating the changes in four energy indicators, namely, wind power capacity factor (CF), solar photovoltaic (PV) CF, a hydropower proxy and an energy demand proxy (called energy degree days, EDD) for 2022, compared with the standard 30-year average, 1991–2020. This comparison allows us to identify specific inter-annual features that occurred in 2022, with respect to "average" conditions. The main measure considered is the percentage anomaly (for 2022 compared with 1991–2020).

This assessment is an initial step towards a more rigorous evaluation on the role of climate on RE supply and demand. Such information can be used both as a retrospective analysis and to aid future decision-making. Ultimately, policymakers, energy planners and resource managers, as well as grid operators, will need comprehensive data and analysis to fully understand the magnitude and patterns of observed variations in resources and demand.

Key insights have been identified:

(i) **All assessed indicators show noticeable changes due to effects of climate variability and change, albeit differing by technology and country.** The four energy indicators assessed (wind power CF, solar PV CF, a hydropower proxy and the energy demand proxy EDD), presented as country averages, display marked percentage anomalies for both annual and monthly averages. Aside from solar PV, which displays limited variability of less than 10% on average annually, the overall inter-annual and intra-annual variability is pronounced; for instance, it is larger than 15% for wind power CF for many countries.

(ii) **Improving our understanding of climate drivers and their interactions with renewable resources is vital for resilience and the efficiency of energy systems and their transition**. It is critical to consider key climate drivers such as the El Niño Southern Oscillation (ENSO), as these normally explain a large portion of the observed

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[1] REN21, Renewables 2023 Global Status Report: Energy Supply, https://www.ren21.net/gsr-2023/modules/energy_supply/01_energy_supply.

variability; accurately predicting them makes it possible to manage energy resources more efficiently than would be possible without such knowledge.

(iii) **Mainstreaming climate variability, in addition to climate change, should be a priority for improved operation, management and planning of energy resources**. This could lead to the establishment of early warning systems to help better manage energy load, resources and maintenance. Moreover, this can inform energy infrastructure modernization and expansion, and trigger the necessary innovation across technologies, markets and policies.

(iv) **Adapting market structures is central to providing the necessary flexibility during the transitional phase from centralized to decentralized power systems.** Power system organizational structures that allow both the procurement of the highest value set of variable renewable resources and the deployment of flexibility resources are necessary. A "dual procurement" system can be an effective avenue in this regard.

(v) **Developing countries, especially in Africa where energy access remains a key priority, can adapt their systems to harness renewable potential with the benefit of knowledge on climate variability**. RE is particularly underdeveloped in Africa, which accounts for only 2% of global capacity despite its abundant potentials. RE is essential to support the continent's development and industrialization. For effective implementation and utilization of RE, it is important to combine knowledge of potential resources and existing infrastructures, but also climate variability as discussed here.

(vi) **Comprehensive and systematic energy data collection and sharing are essential to improving knowledge and understanding of the impact of climate variability and change on energy supply and demand**. The energy indicators presented here are simplified with respect to actual, more representative ones. The computation of more accurate indicators requires more general and systematic sharing of energy data, including installed capacity and actual generation.

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1 Global perspective on renewable energy resources and demand in 2022

1.1 Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), decarbonizing energy systems by 2050 will require a steep and decisive decline in fossil fuel consumption. Concrete actions are needed in the near term (2030 time horizon) to transition our energy systems from carbon-intensive to renewable, clean sources. To achieve the most ambitious climate target of the Paris Agreement, global renewable energy (RE) capacity needs to be tripled and the rate of energy efficiency improvements doubled by 2030 (IRENA, 2023c).

Power generation from RE resources (here specifically wind, solar and hydropower) plays an essential role in the global transition in line with 1.5 °C energy pathways. As these RE resources are largely driven by climatic factors, it is critical to understand the effect of the variability of relevant climate variables on renewable energy generation. Climate influences demand for electricity, and energy consumption more generally, especially in relation to heating and cooling; this is why demand is also considered here.

Considering climate factors, such as climate variability, is all the more important given that global total installed capacity of wind and solar power, and its share in the electricity grid, has been steadily increasing over the past two decades. Wind power reached nearly 900 GW of capacity in 2022, a 9% increase compared with 2021 (and a 200% increase compared with ten years earlier, 2013). Solar power has been growing faster than wind power, with installed capacity reaching 1 055 GW in 2022, a 22% increase compared with 2021 (650% compared with 2013) (IRENA, 2023a). Hydropower currently has a larger installed capacity than either wind or solar power, with about 1 400 GW in 2022, an increase of 2% compared with 2021 (22% compared with 2013). By 2030, wind power installed capacity is expected to reach about 3 000 GW (8 000 GW by 2050), solar power about 5 400 GW (18 000 GW by 2050), and hydropower 1 500 GW (2 500 GW by 2050) (IRENA, 2023c). It is worth noting that from 2010 to 2019, there was a sustained decrease in the unit cost of solar energy (−85%) and wind energy (−55%) (IPCC, 2022b).

Actual power generation depends on the capacity factors (CF) – 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, in 2021 (the latest figures available) hydropower generated 4 400 TWh, wind power 1 840 TWh, and solar power 1 030 TWh (IRENA, 2023b).

The total global electricity consumption, from all sources, including renewables, was 28 500 TWh in 2022, a 2.5% increase compared with 2021 (and a 25% increase compared with ten years earlier, 2013) (EMBER, 2023). According to IRENA (2023b) the percentage of electricity consumption met by RE was 27.8% in 2022, up from 27.6% in 2021. According to the International Energy Agency (IEA) (2023), demand is expected to grow by slightly less than 2% in 2023. This moderation in growth compared with previous years is strongly driven by declining electricity demand in advanced economies, which are dealing with the ongoing effects of the global energy crisis and slower economic growth. In 2024, as expectations for the economic outlook improve, global electricity demand growth is forecast to rebound to 3.3%.

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 2021 (the latest year for which data are available at the time of writing). The total global energy consumption is reported in the last row.

	2013		**2021**		**2022**		**2030**	**2050**
	Capacity (GW)	Generation (TWh)	Capacity (GW)	Generation (TWh)	Capacity (GW)	Generation (TWh)	Capacity (GW)	Capacity (GW)
WP	300		824	1 840	900		3 000	8 000
Solar PV	140		860	1 030	1 055		5 400	18 000
HP	1 140		1 360	4 400	1 400		1 500	2 500
Total energy consumption		22 800		27 800		28 500		

For this publication, the RE generation potential and demand are represented using relatively simple indicators, which are presented mainly at the country level over the whole globe. A brief definition of these indicators is presented in the following sections on onshore wind power (for simplicity, this will be referred to as wind power), solar photovoltaic (PV) power (also referred to as solar power), hydropower, and energy demand.[2] Because the main focus of this publication is on assessing the role of climate variability on the RE potential and energy demand, the report mainly considers anomalous behaviours of these indicators in 2022 in comparison with the current 30-year standard climatology reference period (1991–2020). In other words, the publication will highlight the main deviations that occurred in 2022 with respect to 1991–2020 in order to inform RE planners and resource managers, as well as grid operators, about the magnitude and patterns of observed variations in resources and demand. Such an assessment can be useful both as a retrospective analysis and to aid future decision-making.

In the following sections, RE resources and demand are first assessed separately at the global level, and then implications for their interactions are discussed, which is most effectively done at the regional (continental) level. Also, indicators are presented as percentage anomalies (for 2022 compared to 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 Wind power capacity factor

A useful indicator of climate variability is the relative change of the CF (anomalies expressed as a percentage) for a given year compared with a reference period. The global monthly wind power CF, as taken from the IEA Weather for Energy (WfE) 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).[3] Monthly wind power CF anomalies for 2022 relative to the monthly average for the 1991–2020 reference period are then calculated.

When averaged over the entire year 2022, annual wind power CF anomalies display some relatively large values and noticeable patterns, which affect the generation potential (Figure 1). For instance, several countries in Europe experienced a reduction of 10% or more in CF (negative anomalies) (see *European State of the Climate 2022*[4]). Strong reductions in CF are also seen in Central America and Papua New Guinea (more than 16%), while a moderate decline in CF is observed in several countries in South and South-East Asia, and South Africa (between 4% and 8%). At the same time, increases of 8% or more in CF (positive anomalies) are observed in several countries throughout the world, including some countries in sub-Saharan Africa,

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[2] Further details about the computation of the energy indicators are provided in the annex.

[3] 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 2022 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 the annex for additional details).

[4] https://climate.copernicus.eu/esotc/2022/wind-solar-energy-resources

Madagascar, the Plurinational State of Bolivia, Paraguay, Republic of Korea and the Democratic People's Republic of Korea. In addition, North America, host of 163 GW of installed capacity in 2022, which is a sizeable 18% of the global capacity (IRENA, 2023a), experienced a 4%–8% increase compared to the long-term reference average.

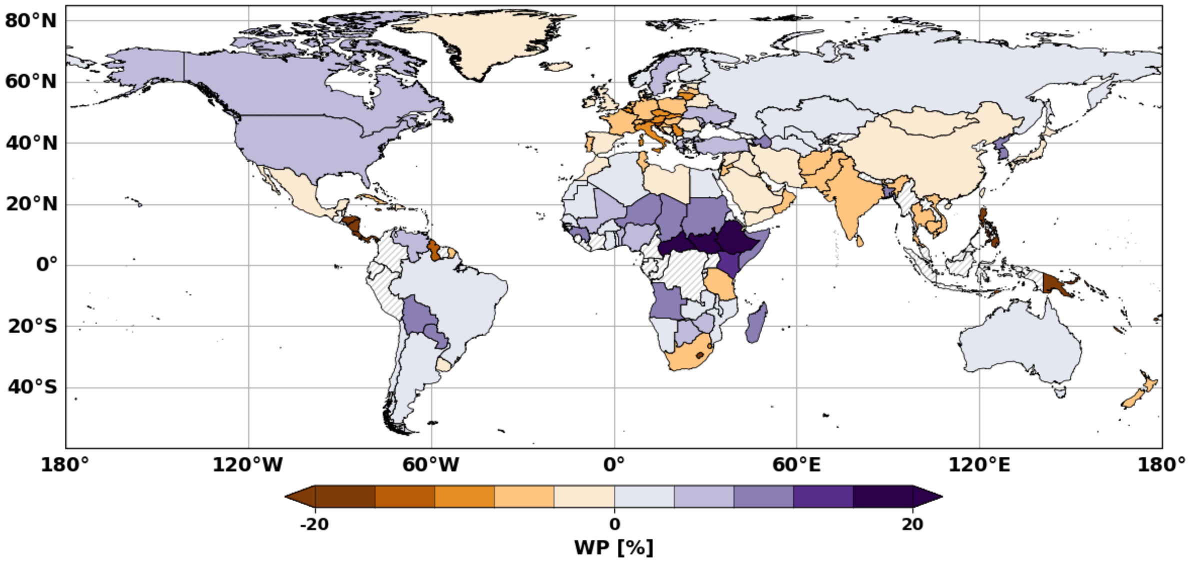

Figure 1. Global anomalies of wind power (WP) capacity factor annual mean (expressed in %) for 2022 relative to the average of the 1991–2020 reference period

Two main considerations emerge from the global 2022 annual mean anomalies in wind power CF: (i) even when averaged over a year, variations can be sizeable – changes larger than 5%–10%, in either direction, would be considered important in terms of power resource allocation and management; and (ii) spatial patterns emerge with country clusters displaying consistently lower resources (for example, Europe) or higher resources (North America, South America, sub-Saharan Africa). Such patterns point to possible balancing of electricity on a continental or intercontinental scale subject to the presence of necessary power networks to exchange electricity between countries or continents. For instance, the higher production in North America could compensate the reduction in CF in Mexico.

It is also important to consider individual months, as resource operation and management is performed at temporal scales commensurate to monthly periods rather than on an annual basis, noting that at monthly timescales we expect to see larger anomalies due to the greater variability in wind speed for these shorter periods. For instance, wind power CF anomalies for May 2022 relative to the May 1991–2020 reference period show stronger signals than for the annual mean (Figure 2; note that the scale range is double that in Figure 1). This is observed in a large part of Europe, where there is high negative variation, but this time with considerably higher values (larger than 24% for some countries). However, several other countries which on annual average had positive values are now showing marked negative variations. This is the case for Argentina, Paraguay and Australia, among others. On the other hand, for places like Mexico, a large portion of South Asia and South-East Asia the variation is reversed, with wind power CF for May 2022 in Mexico being more than 8% higher than the climatological average for May.

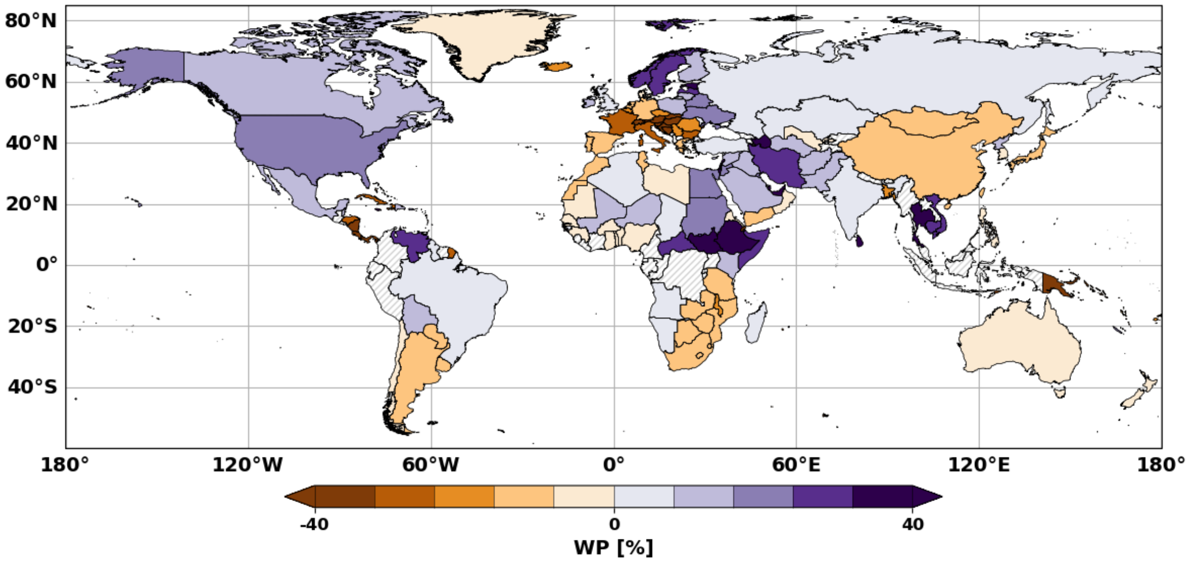

Figure 2. Global anomalies of wind power (WP) capacity factor annual mean (expressed in %) for May 2022 relative to the average for May in 1991–2020. Note that the range of values is twice that of the annual mean in Figure 1.

Some strong anomalies are also seen in November 2022, with a notable reversal in sign for countries such as China and Argentina from negative in May to positive in November, and in the opposite direction for the Russian Federation, India and especially South-East Asia, the latter with a swing larger than 50% (Figure 3). The changes in sign, especially for neighbouring countries, again points to potential power balancing, with, for instance, the "surplus" in China potentially offsetting the deficit in South-East Asia. From an atmospheric point of view, it is interesting to note that in equatorial areas where the Walker circulation operates – this is an East–West vertical motion of air driven by differences in heat distribution between land and ocean – some of the observed changes can be linked to inter-annual climate drivers such as El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). This is the case for instance for Kenya, Ethiopia and Somalia, where large positive anomalies can be related to air subsidence in that region driven by the La Niña conditions present in 2022, noting that La Niña typically peaks in the October to February period in the Pacific Ocean, with slightly delayed impacts in other parts of the globe. The ascendent branches of the same zonal Walker circulation, where strong convective processes occur, can be linked to the reductions of wind power CF in Papua New Guinea and Northern South America.

For consistency the same two months, May 2022 and November 2022, are considered for the following three energy indicators, namely for solar PV power, hydropower and energy demand.

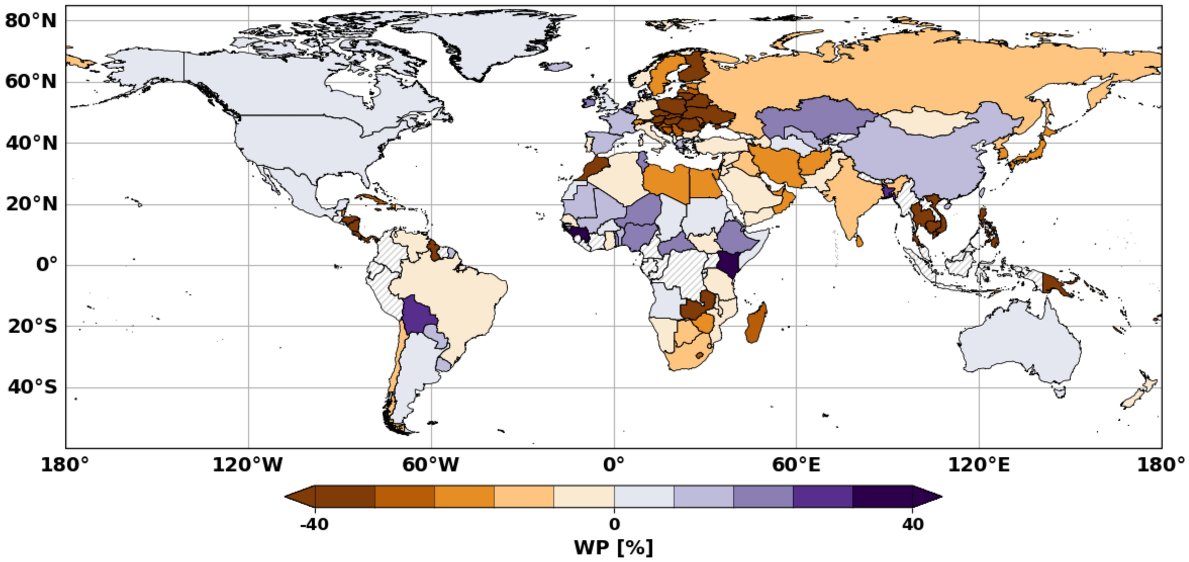

Figure 3. Global anomalies of wind power (WP) capacity factor annual mean (expressed in %) for November 2022 relative to the average for November in 1991–2020. Note that the range of values is twice that of the annual mean in Figure 1.

1.3 Solar power capacity factor

The solar photovoltaic (PV) power CF is computed using a relatively simple formulation which, in addition to the required global solar irradiance, also accounts for efficiency effects due to variations in air temperature near the surface and 10-m wind speed.[5] The main drawback of this approach is the use of a constant tilt angle for the computation regardless of the PV panel's geographical location. However, this shortcoming is not too major as we are only concerned with relative variations.

The global annual anomalies in solar PV CF for 2022 relative to 1991–2020 are shown in Figure 4. The range of these anomalies is lower than that for the wind power CF (±15% compared with ±20%). Moreover, the overall variations are considerably smaller than those for wind, with the largest changes observed in the Plurinational State of Bolivia, Paraguay and Argentina, with an increase of between 3% and 6%. At the global scale an overall balance of positive and negative variations emerges, even if it is difficult to estimate the overall mean solar PV CF variation due to factors such as the relative size of countries. At the continental scale, in particular, there appear to be interesting features, for example with the positive variations in Asian countries like China, Turkmenistan and Uzbekistan potentially counterbalancing the reduction in South Asia and South-East Asia even if the changes in either direction are weak (±3%). Clearly, these observations are speculative, since in the areas mentioned, only China, India and Viet Nam currently have a sizeable installed capacity (as of 2022) with 392 GW, 62 GW and 18 GW, respectively (IRENA, 2023a). Moreover, the actual location of transmission lines has not been taken into account to be able to indicate how power could be transmitted across boundaries in practice.

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[5] It is worth noting that grid points with CF lower than 0.1 are not considered in country averages (see the annex for additional details).

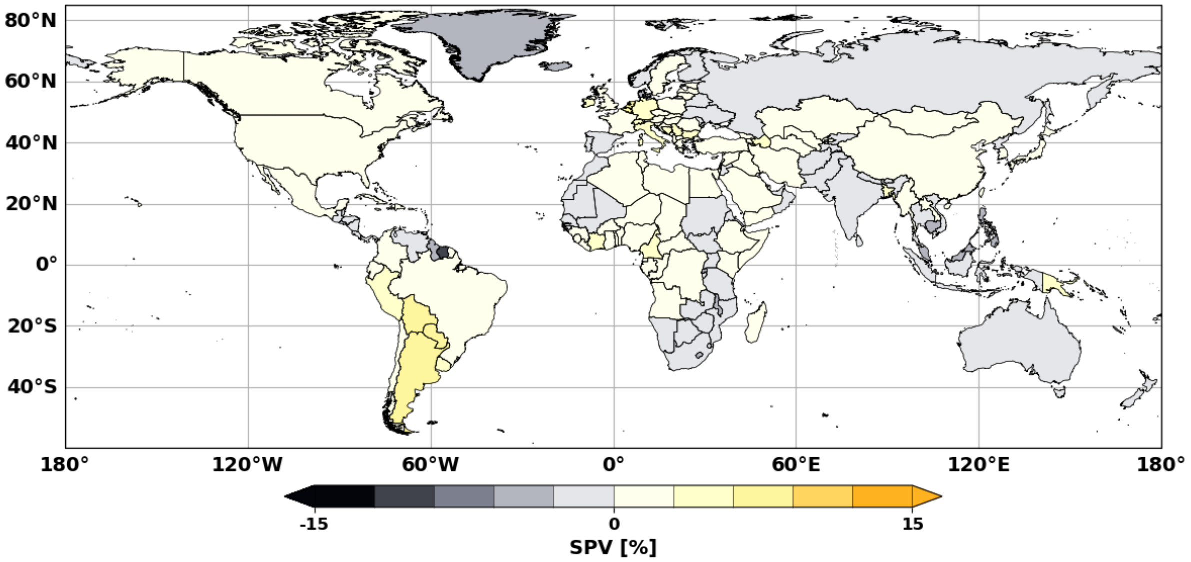

Figure 4. Global anomalies of solar photovoltaic (SPV) power capacity factor annual mean (expressed in %) for 2022 relative to the average of the 1991–2020 reference period.

In May 2022 (Figure 5), several countries in South America, Africa and Europe (the latter in line with the *European State of the Climate 2022*) experienced a positive anomaly compared to the corresponding average for May in 1991–2020 (note again that the range of values in the figures for individual months is twice that in the annual average). The general pattern in these continents is similar to that present in the annual average, but positive anomalies seem to be more widespread (for example, the Bolivarian Republic of Venezuela, the United Republic of Tanzania and Spain have now turned positive), even if the values are rather modest, with the largest values ranging from 6% to 12%. At the same time, a large part of Asia displays a negative anomaly in May 2022, with South-East Asia reaching reductions of between 12% and 18%. In this situation, intracontinental transmission of solar power would be challenging. It is also worth noting that in May 2022, China had both wind power and solar PV power CFs with a negative anomaly, again making compensation between wind and solar power difficult.

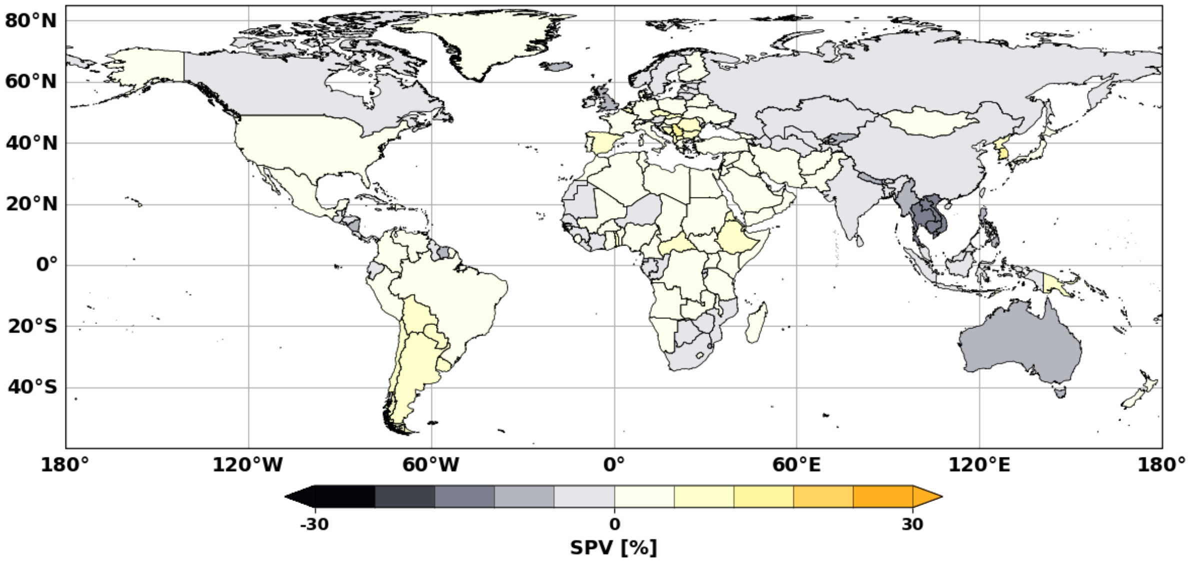

Figure 5. Global anomalies of solar photovoltaic (SPV) power capacity factor annual mean (expressed in %) for May 2022 relative to the average for May in the 1991–2020 reference period. Note that the range of values is twice that of the annual mean in Figure 4.

More negative anomalies in solar PV power CF are observed in November (Figure 6) than in May, with the main notable exception of India, Bangladesh, Myanmar, the Lao People's Democratic Republic and Viet Nam, which became moderately positive, and the Plurinational State of Bolivia and Paraguay, which accentuated their positive variation (18%–24%). Particularly in the tropical area, the November 2022 pattern is consistent with La Niña conditions,[6] which were present over most of 2022[7] (even if La Niña normally peaks during the austral summer, see, for example, the National Oceanic and Atmospheric Administration (NOAA) ENSO monitoring portal[8]). La Niña manifests itself as increased cloud cover (and precipitation) over countries in the Western Pacific (for example, Australia), in Southern Africa (for example, South Africa, Zimbabwe and Botswana), and in North-eastern South America, with corresponding reduced solar PV power CF. At the same time, La Niña is associated with subsidence conditions in Eastern Africa (Somalia, Ethiopia and Kenya) and in Western South America (Ecuador, Peru, the Plurinational State of Bolivia and Paraguay). It is to be noted that by and large these same La Niña patterns, or teleconnections, are noticeable in May 2022.[9]

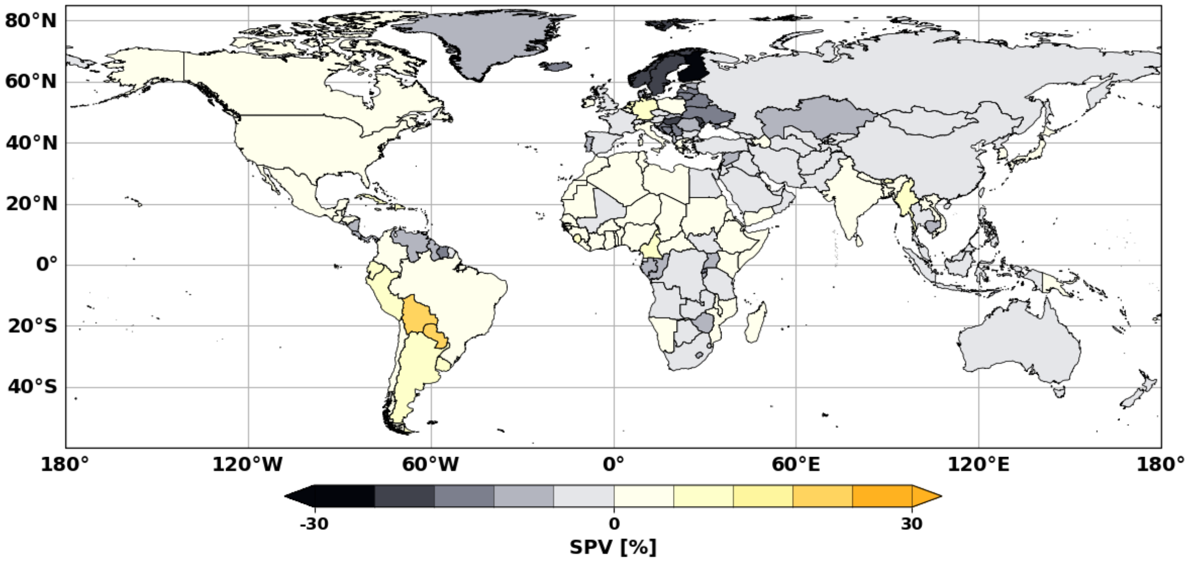

Figure 6. Global anomalies of solar photovoltaic (SPV) power capacity factor annual mean (expressed in %) for November 2022 relative to the average for November in the 1991–2020 reference period. Note that the range of values is twice that for the annual mean in Figure 4.

1.4 Hydropower proxy indicator

The hydropower indicator is represented by a proxy based on a combination of precipitation and hydropower installed capacity at a given location. Monthly precipitation is considered only for sub-country areas in which power plants are present, with their installed capacity used as weights for the precipitation. Thus, this hydropower indicator, also referred to as installed-capacity-weighted total precipitation or IC-W TP, is computed as a precipitation-weighted country average at the monthly scale.[10] The indicator averaged over 2022, relative to 1991–2020, can be seen in Figure 7. According to the definition adopted, the indicator is not calculated

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[6] The pattern is technically called teleconnection. More information is available at: https://www.weather.gov/fwd/teleconnections.

[7] The year 2022 was the third La Niña year in a row.

[8] https://www.ncei.noaa.gov/access/monitoring/enso

[9] A more rigorous assessment would need to ascertain to what extent the observed variations are due to La Niña, or ENSO more generally.

[10] This choice is dictated by the lack of homogenous datasets for power generation for the period covered (1991–2022), which prevents the implementation of a power data model (typically a statistical model), as done for instance in https://doi.org/10.3390/en13071786. More details are available in the annex.

for countries with no hydropower plant; this is indicated by hatching in the figures. Because this hydropower indicator is based on precipitation, the pattern of anomalies for 2022 closely resembles that of the solar PV CF (Figure 4).

The IC-W TP presents clusters of countries with a reduction in mean values for 2022 compared with the 1991–2020 average. This is apparent for a large part of South America, Eastern Asia, Central and Eastern Africa and Western Europe. In the latter case, the reduction is linked to the strong drought which affected Western Europe, particularly its southern part, over much of 2022. At the same time, Scandinavia, which has a very high installed capacity (nearly 55 GW among Norway, Sweden and Finland), experienced a positive variation. This is a case where power balancing through transmission of electricity could occur, for instance via the 1 400 MW interconnector linking Norway with the United Kingdom of Great Britain and Northern Ireland – the North Sea Link.

There are also several countries for which the IC-W TP shows a positive anomaly, as in the case of Canada, Mexico, the Russian Federation, India, Nepal, South Africa and Australia, in addition to the Scandinavian countries mentioned above. Most of these countries would have benefitted from the increase in IC-W TP given their overall high hydropower installed capacity.

As was the case for solar PV CF, the global La Niña pattern is evident in the IC-W TP. This is also apparent in the anomalies for the individual months of May and November 2022 (see Figure 8 and Figure 9, respectively). Specifically, the positive IC-W TP signals in Australia, South Africa, Mozambique and Northern South America, together with the negative signal in Eastern Africa (especially in Somalia, Kenya, Uganda and the United Republic of Tanzania), and Southern South America (Peru, Chile, Bolivarian Republic of Venezuela, Plurinational State of Bolivia, Paraguay, Argentina) clearly reflect such a pattern.

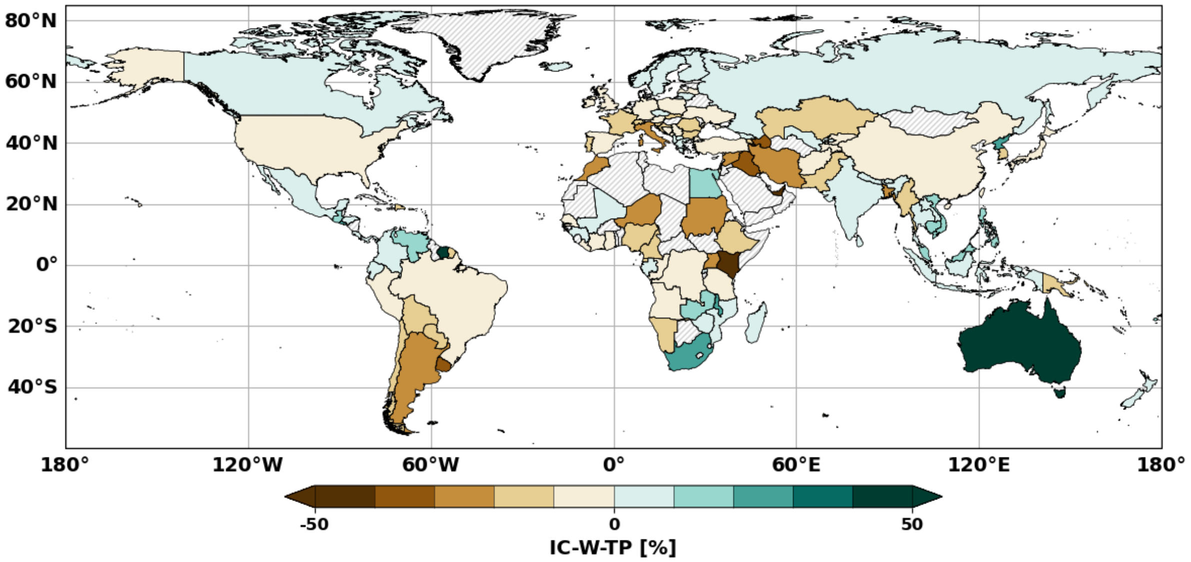

Figure 7. Global anomalies of hydropower proxy annual mean (expressed in %) for 2022 relative to the average of the 1991–2020 reference period. Note: IC-W TP stands for installed-capacity-weighted total precipitation.

Aside from the consistent La Niña pattern in May and November 2022, a specific feature in May 2022 (Figure 8) is the shift from negative to positive variations for the United States of America, Spain, Kazakhstan and China. Notable inversions from positive to negative, albeit with moderate values on either side, are seen for Mexico, India and Scandinavian countries (Norway displays the strongest reduction). Major notable changes in November 2022 (Figure 9), particularly with respect to the annual average, are the negative anomaly for Canada and Sweden, and the positive one for much of Western Europe.

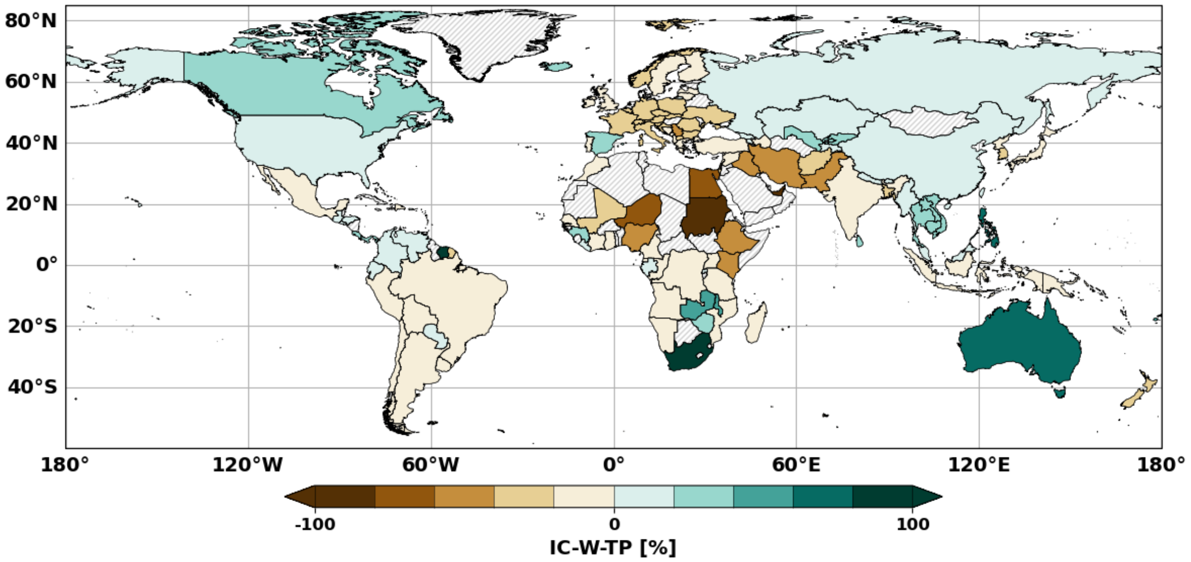

Figure 8. Global anomalies of hydropower proxy annual mean (expressed in %) for May 2022 relative to the average for May in the 1991–2020 reference period. Note that the range of values is twice that for the annual mean in Figure 7. Note: IC-W TP stands for installed-capacity-weighted total precipitation.

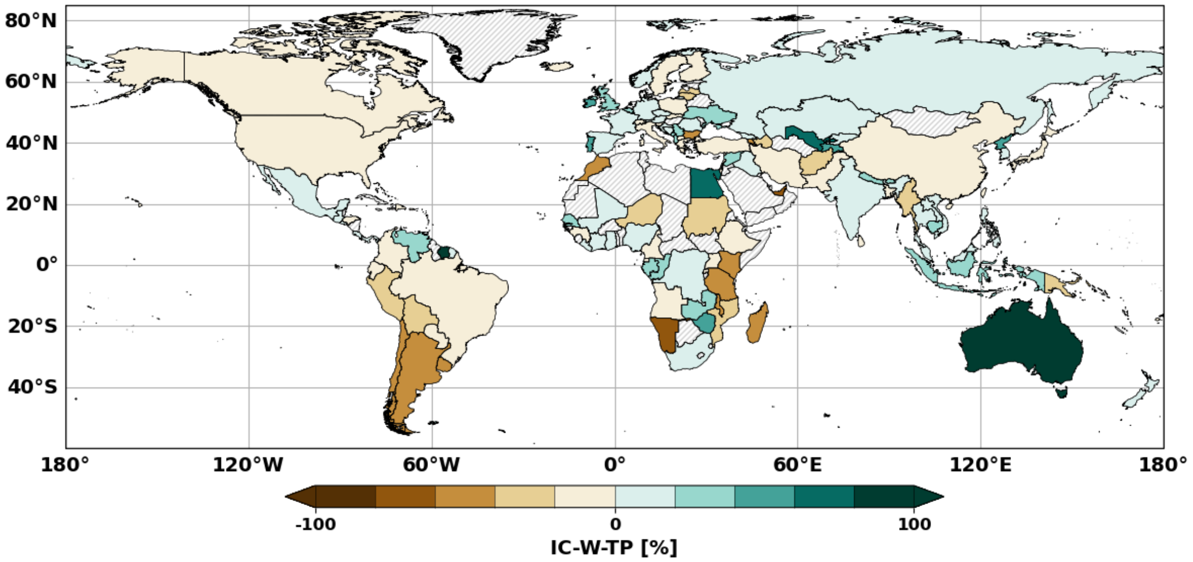

Figure 9. Global anomalies of hydropower proxy annual mean (expressed in %) for November 2022 relative to the average for November in the 1991–2020 reference period. Note that the range of values is twice that for the annual mean in Figure 7. Note: IC-W TP stands for installed-capacity-weighted total precipitation.

1.5 Energy demand proxy indicator

The energy demand indicator is represented by a proxy based on two commonly used indicators: cooling degree days (CDD) and heating degree days (HDD).[11] Usually, these indicators are used separately as they address specific 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 (EDD) as the sum of CDD and HDD[12] (IPCC, 2021, 2022a; Spinoni et al., 2017). Naturally, CDD and HDD (and therefore EDD) do not capture all uses of electricity (for example, industry) 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 2022 EDD variations present noticeable clusters, with relatively strong reductions in demand, of up to about 20%, in Southern Africa and Eastern and Northern Europe (Figure 10). More moderate reductions are seen in many other areas, such as the Russian Federation, Western Asia, Eastern South America, Canada, Saharan Africa and Australia. The largest positive changes are seen in the tropical areas, as well as in the Mediterranean basin. The signature in EDD in these areas essentially stems from CDD, hence EDD is predominantly driven by requirements for cooling. At higher latitudes, poleward of 40°, where typically heating requirements, hence HDD, are prevalent, negative anomalies dominate, as mentioned. Overall, the pattern observed in EDD, accounting for the geographical prevalence of HDD and CDD, closely reflects the pattern in air temperature, which displays large areas of positive anomalies for 2022, compared to the 1991–2020 climatology (see *State of the Global Climate 2022* (WMO-No. 1316) Figure 3). The year 2022 was the fifth or sixth warmest year on record, despite ongoing La Niña conditions, which generally manifest in cooler conditions than in El Niño years (*State of the Global Climate 2022* (WMO-No. 1316)). A few areas where the temperature anomaly was more moderate or even negative were Australia and Southern Africa, for which the negative EDD variations are linked to the direct effect of La Niña with cooler southern hemisphere summer conditions, and Argentina and Uruguay, where the positive EDD variations are linked to lower-than-normal southern hemisphere winter temperatures.

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[11] HDD assesses 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, CDD assesses 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. Two "middle of the road" options are considered here: CDDhum21 and HDDThold18. More details are available in the annex. The individual global gridded CDD and HDD data, which are based on the ERA5 reanalysis, are available from the IEA/CMCC portal: http://weatherforenergydata.iea.org.

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

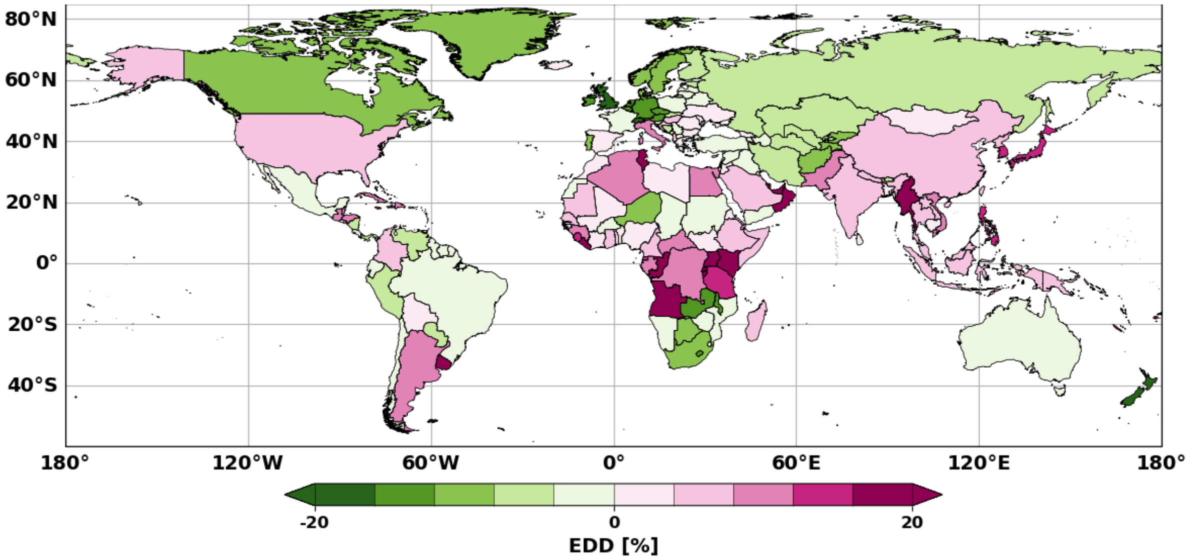

Figure 10. Global anomalies of energy demand proxy (energy degree days (EDD)) annual mean (expressed in %) for 2022 relative to the average of the 1991–2020 reference period.

The May 2022 EDD (Figure 11) changes again closely reflect the temperature anomalies, indicating a decreased need for heating in places like Central Europe and Central Asia, which experienced considerable positive temperature anomalies, at a time when heating would normally still be used. Similar positive anomalies but at lower latitudes, as in Mexico, Morocco, Algeria and Tunisia, as well as in Central and Eastern Africa, instead led to positive EDD variations due to increased cooling requirements (higher CDD). The positive EDD variations in far Eastern Europe, Russian Federation, Argentina and Uruguay reflect higher heating requirements due to the extensive negative temperature anomalies.[13]

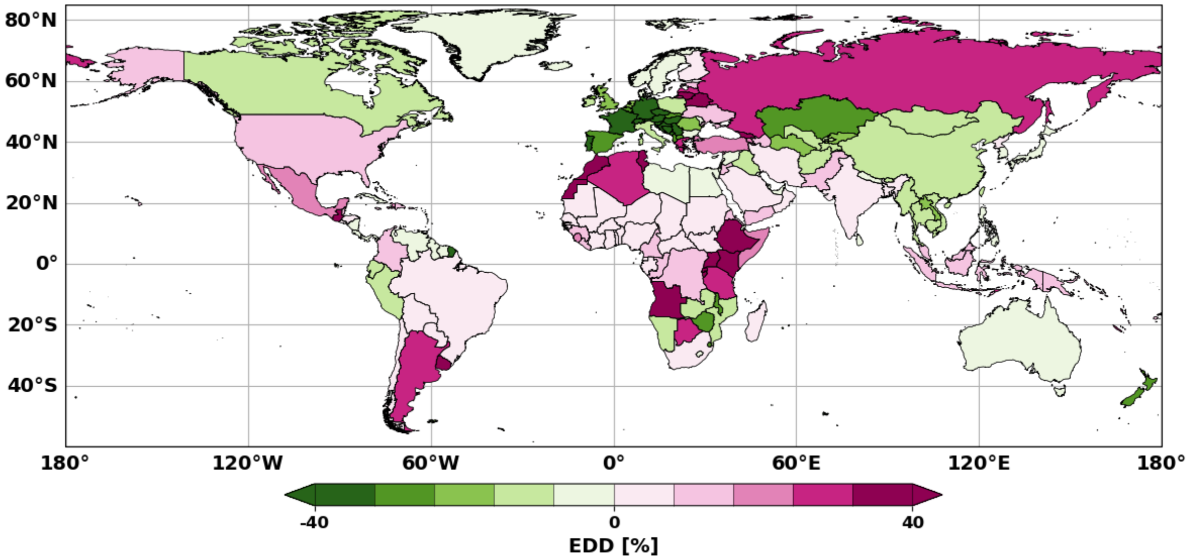

Figure 11. Global anomalies of energy demand proxy (energy degree days (EDD)) annual mean (expressed in %) for May 2022 relative to the average for May in the 1991–2020 reference period. Note that the range of values is twice that for the annual mean in Figure 10.

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[13] https://climate.copernicus.eu/surface-air-temperature-may-2022

In November 2022, the EDD variations are negative overall (Figure 12), but again reasons differ for different regions. Thus, the negative signal in Brazil, Paraguay, Peru and Chile and in a large part of Southern Africa is due to lower-than-normal temperatures,[14] and hence lower cooling demand. Similar negative EDD variations in Europe, North Africa and the central–eastern United States, were instead driven by higher-than-normal temperatures, and therefore were linked to lower heating requirements at a time when heating usually starts to be used. At the same time, positive temperature anomalies over the Arabian Peninsula, Argentina, Uruguay and South-East Asia drove the higher cooling demand, and hence the positive EDD variations.

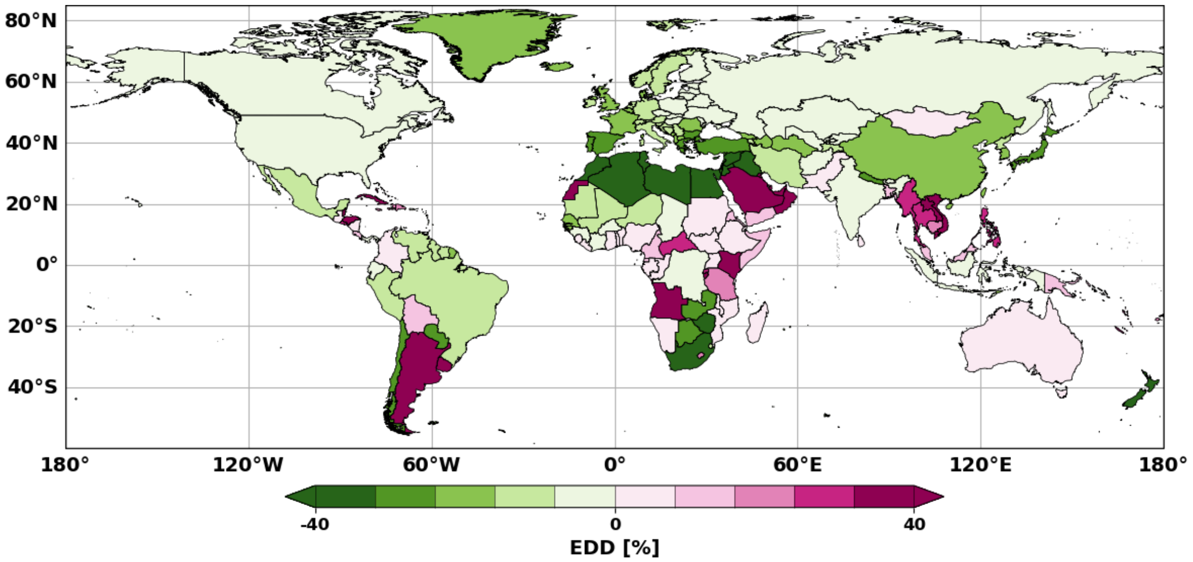

Figure 12. Global anomalies of energy demand proxy (energy degree days (EDD)) (expressed in %) for November 2022 relative to the average for November in the 1991–2020 reference period. Note that the range of values is twice that for the annual mean in Figure 10.

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[14] https://climate.copernicus.eu/surface-air-temperature-november-2022

2 Regional perspective on renewable energy resources and demand in 2022

This section contains assessments at regional level for portions of three continents: Africa, Asia and South America. For each, there is a loose focus on a specific technology, namely solar PV power, wind power and hydropower, respectively. It should be noted that renewable capacity for hydro-, wind and solar power in these regions varies dramatically. For instance, in Africa, power generation is 154, 12 and 20 TWh, respectively, whereas in Asia, it accounts for 1 856, 748 and 550 TWh, respectively. These are represented by their 2022 annual variations relative to 1991–2020, displayed on a map, as in the previous section. However, the main analysis is based on the 2022 monthly percentage anomalies in the four energy indicators for selected countries for each of the three continents. For presentation purposes, the number of countries has been limited to five per continent. While the choice of countries is somewhat arbitrary (for Africa for instance this is less than 10% of the countries), the countries chosen are close to each other and therefore potentially, or actually, connected via power transmission lines. This is important for considerations relating to balancing of electrical power, even if it is beyond the scope of this report to assess the actual possible balancing of energy resources, not least because we are considering relative changes in CFs or proxy indicators, and therefore not the actual demand or generation, or even the RE installed capacity. Thus, the power balancing discussion that follows is mostly qualitative, but it is meant to provide prompts for further analysis.

2.1 Africa

The solar PV power, or solar PV CF for Africa for 2022 relative to 1991–2020 is shown in Figure 13 (as also presented in Figure 4). Once again large country clusters are visible, where positive anomalies are observed in the northern and central parts of the continent, while negative anomalies are mainly observed in the western, eastern and southern parts. In both cases the variations are moderate, up to 6% in either direction.

Five countries within the Southern African Development Community (SADC) are selected for the more in-depth analysis: Botswana, Mozambique, Namibia, South Africa and Zimbabwe. In terms of solar PV CF, SADC shows an almost entirely negative, albeit small, variation, an important reference for the ensuing analysis. The four energy indicators for these five countries for each month of 2022 are shown in Figure 14. The monthly variations make it possible to observe features that are masked by the annual average (and actually even by the individual months assessed in the previous section, May and November), namely that there are also months in which values are positive and comparatively large (around 10%), as in the case of Zimbabwe (February and December), Botswana (February) and Mozambique (October).

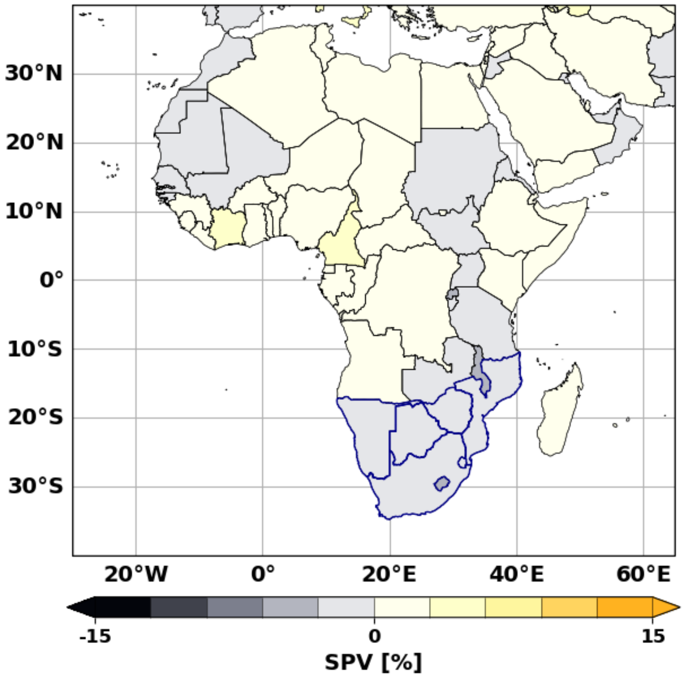

Figure 13. Annual mean anomaly of solar photovoltaic (SPV) power capacity factor (expressed in %) for 2022 relative to the average of the 1991–2020 reference period with focus on Africa (as also presented in Figure 4). Note that the borders of the selected countries have been highlighted in blue.

Although the overall magnitude of the variations in solar PV CF for these countries is modest, it is important to also assess the variations in adjacent months. For instance, for Zimbabwe there is a jump of over 25% from January to February, and a consecutive drop of similar magnitude from February to April. It is these relatively large changes which require close attention when managing energy resources. Naturally these changes must be considered in the context of other energy resources (in this case wind power and hydropower), ideally also considering possible transmissions with neighbouring countries, but especially demand, which is the ultimate driver for generation.

To illustrate how the plots in Figure 14 can be interpreted, consider a month in which the demand is anomalously high such as June 2022. Aside from Mozambique, demand anomalies are positive, and up to 40% higher than the 1991–2020 June average. While solar PV CF in June is reduced, the indicators for wind power and hydropower show strong increases. Therefore, and depending on the installed capacity, wind power and hydropower could more than compensate for the small reduction in solar PV to meet the increase in demand (note however that the large anomaly in the hydropower indicator is due to a low baseline, related to the local dry season, typically occurring from June to September). Thus, in this case no imports or exports of power would be necessary, even if in principle there would be enough potential generation to provide some inter-country balance.

A more problematic situation in terms of supply–demand balance occurs in October when the demand anomaly in all five countries is positive (between 5% and 30%), and at the same time a large portion of potential generation shows a negative anomaly, except for small increases in solar PV CF for Mozambique and Zimbabwe, and wind power CF for Zimbabwe. In this situation, balancing power among these countries would require careful planning, for instance to ensure there is enough water in hydropower dams from the previous rainy season (typically ending in May), and ahead of the next rainy season (typically starting in October–November).

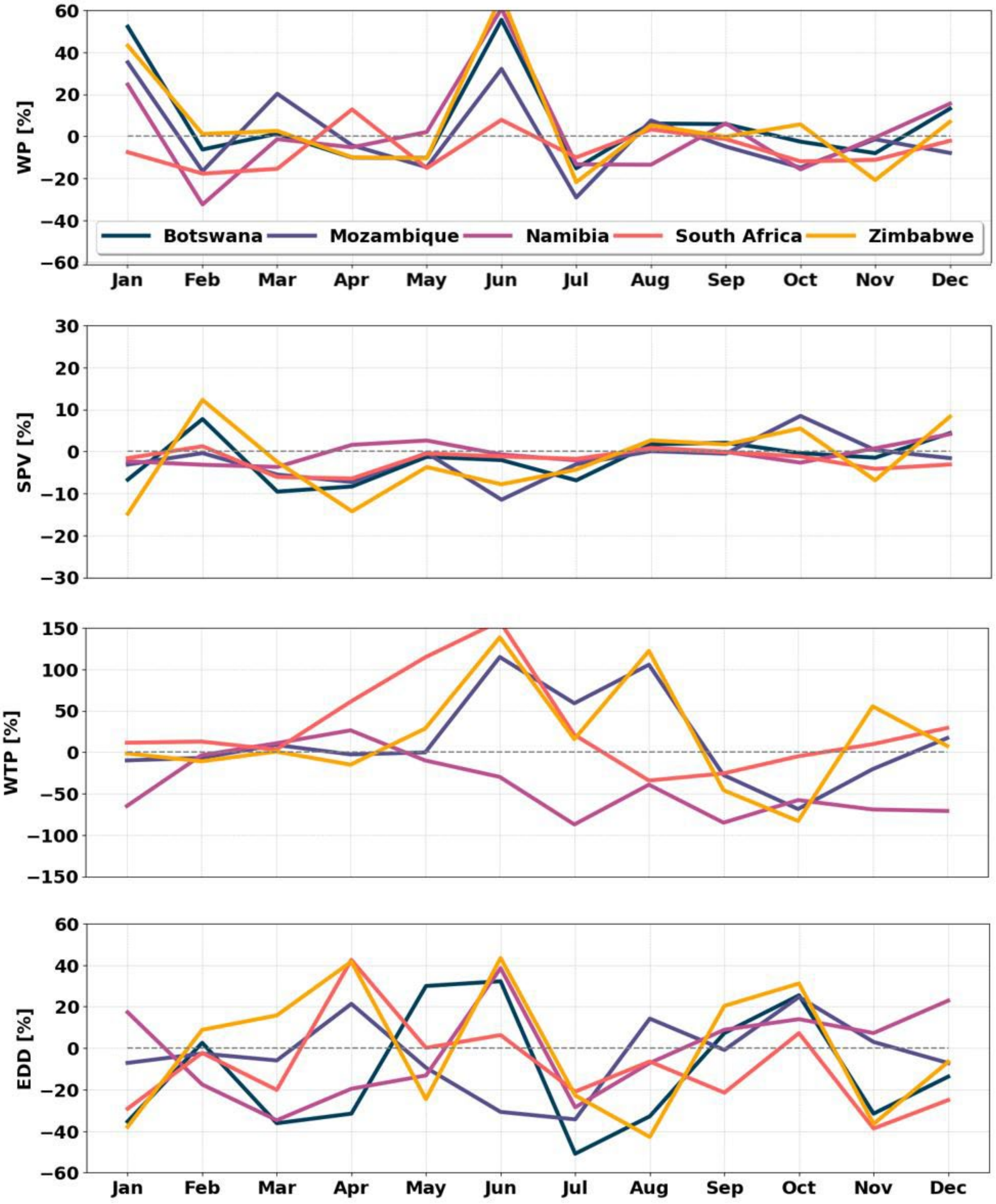

Figure 14. Monthly percentage anomaly for 2022 relative to corresponding months in the 1991–2020 reference period for five countries in Southern Africa. From top to bottom: wind power (WP) capacity factor, solar photovoltaic (PV) power capacity factor, weighted total precipitation (WTP) (hydropower proxy indicator), energy degree days (EDD) (energy demand proxy indicator). Note that Botswana does not have hydropower plants, and therefore no indicator has been computed. Also note that the y-axis varies depending on the range of the indicator.

2.2 Asia

The wind power CF anomalies for Asia for 2022 relative to 1991–2020 are shown in Figure 15 (as also presented in Figure 1). In this case the selected five countries are the major countries in South Asia – Afghanistan, Bangladesh, India, Pakistan – plus China. With the exception of Bangladesh, the wind power CF anomaly is moderately negative for these countries over 2022, on average. The monthly mean anomalies (Figure 16) broadly confirm this negative signal, with a couple of exceptions: (i) China, which after an initial negative anomaly in January (less than minus 20%) and February, hovered around the zero value until the second half of the year when it reached positive values of up to around 10%, which, considering its huge installed capacity (approximately 360 GW in 2022), translates into a very large change in generation; and (ii) Bangladesh, with some large positive signals in a few months of 2022 (April, October and November, with values larger than 30%), even if its CF baseline is small and its potential generation would also be extremely low given its small current installed capacity of just a few MW.

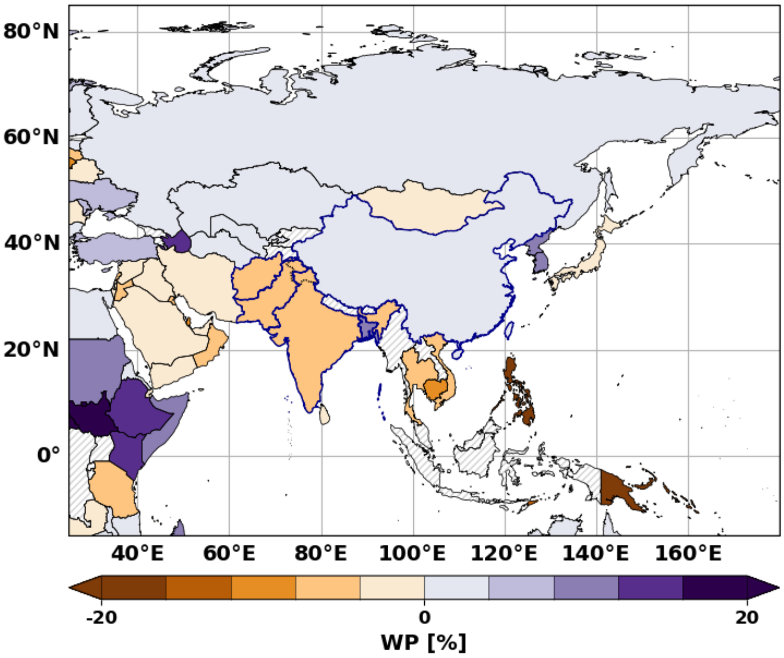

Figure 15. Annual mean anomaly of wind power (WP) capacity factor (expressed in %) for 2022 relative to the average of the 1991–2020 reference period with a focus on Asia (as also presented in Figure 1). Note that the borders of the selected countries have been highlighted in blue.

As in the Africa section, this section considers a problematic situation in which the overall demand anomaly is high for the five Asian countries, and at the same time potential generation is depressed (Figure 16). This happened in June 2022, when the EDD indicators show moderate to high increases for four out of the five countries – notably China shows an increase of about 30% – while indicating a modest decrease for Pakistan. The small increases in wind power CF for Bangladesh (with a very low installed capacity, as mentioned) and Pakistan (which has a sizeable installed capacity, at 1.4 GW), and the marginal increases in solar PV CF of a few percent for Afghanistan (33 MW of installed capacity), India (63 GW) and Pakistan (1.2 GW) would likely be insufficient to counter the reduction in the remaining RE potential generation and meet the increased demand.

There are also months in which the demand is considerably reduced for China, as for instance March and November, when EDD reaches negative 20%, but the demand anomaly shows marked increases in the other four countries, especially in March. Overall, the combination of high average demand anomaly and generally low generation potential for the three RE resources makes a year like 2022 somewhat challenging from the perspective of demand–supply balance for these five countries (see also Figures 1, 4, 7 and 10).

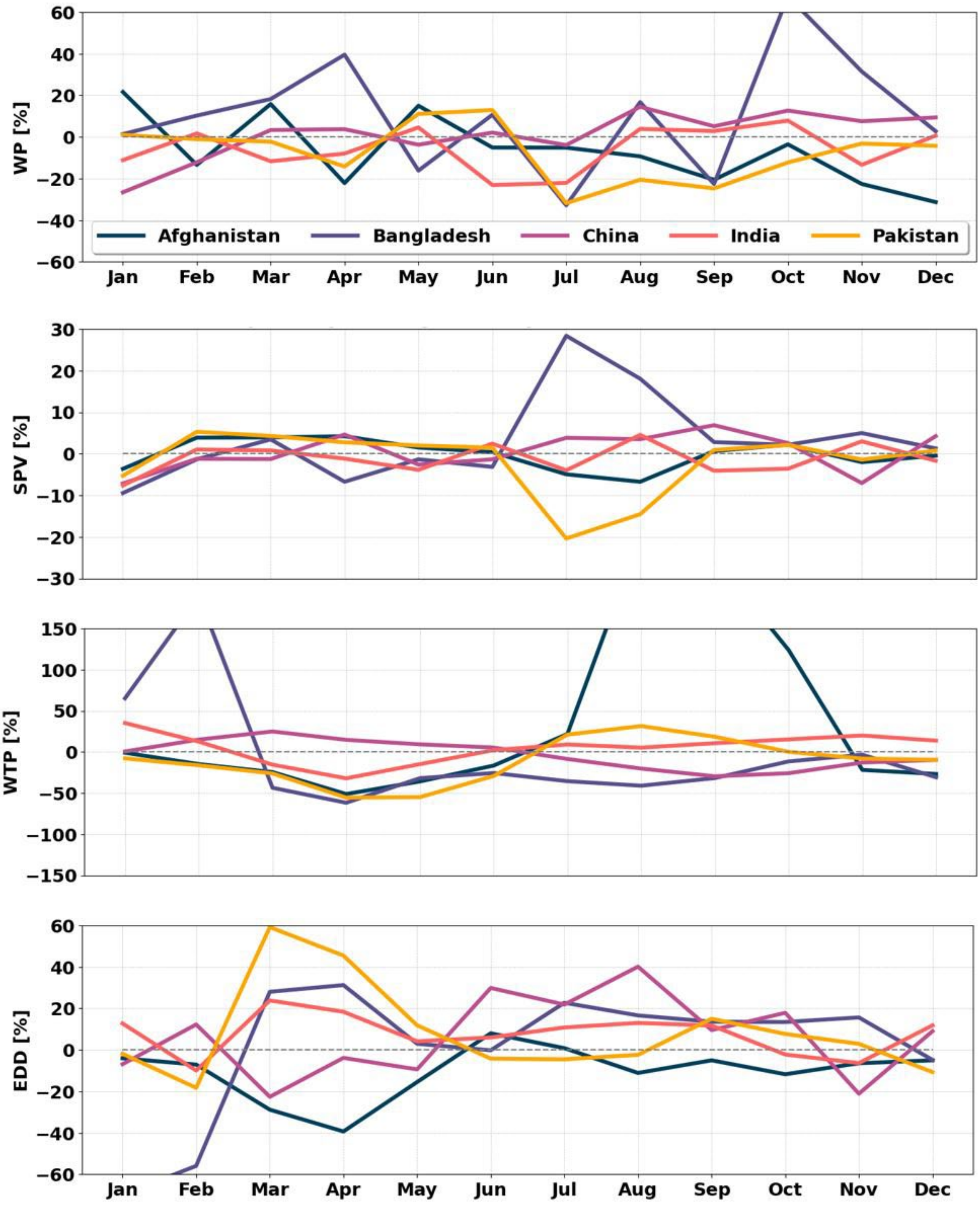

Figure 16. Monthly percentage anomaly for 2022 relative to corresponding months in the 1991–2020 reference period for five countries in Asia. From top to bottom: wind power (WP) capacity factor, solar photovoltaic (PV) power capacity factor, weighted total precipitation (WTP) (hydropower proxy indicator), energy degree days (EDD) (energy demand proxy indicator). Note that the y-axis varies depending on the range of the indicator.

2.3 South America

The hydropower indicator, IC-W TP, for South America for 2022 relative to 1991–2020 is shown in Figure 17 (as also presented in Figure 7). In this case the selected five countries are: Argentina, Brazil, Chile, Paraguay and Uruguay. For all of them the average IC-W TP is negative over 2022, with values as low as negative 30%–40% for Uruguay.

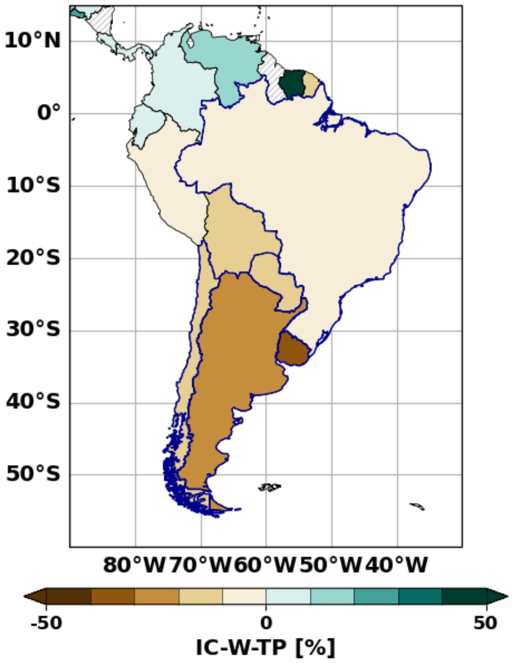

Figure 17. Annual mean anomaly of hydropower proxy indicator (expressed in %) for 2022 relative to the average for the 1991–2020 reference period with a focus on South America (as also presented in Figure 7). Note that the borders of the selected countries have been highlighted in blue.

The overall negative signal is also reflected in the monthly averages, with the exceptions of April (for Chile), and May and October (for Paraguay) (Figure 18). On the other hand, wind power and solar power CF anomalies are generally positive throughout the year, except for the wind power CF in May and June. Incidentally, the EDD is anomalously high in May and June for all five countries, with Uruguay at 40% and Argentina around 25% higher than normal. However, such an increase in demand for these two months could be balanced by solar power, given that its CF is higher than normal. Although the increase in solar power CF is only around 5%–10%, it is occurring for all five countries, which have a current aggregate PV installed capacity of 32 GW (though 75% of that is in Brazil).

A different situation is present in July 2022, when the overall EDD anomaly is negative (only Chile shows a small increase) and at the same time wind and solar power potential generation is generally positive (Figure 18), leading to a potential surplus in generation that could be exported to neighbouring countries. However, this would also depend on the deficit shown by the hydropower indicator, which is computed against a relatively low baseline given the local dry season.

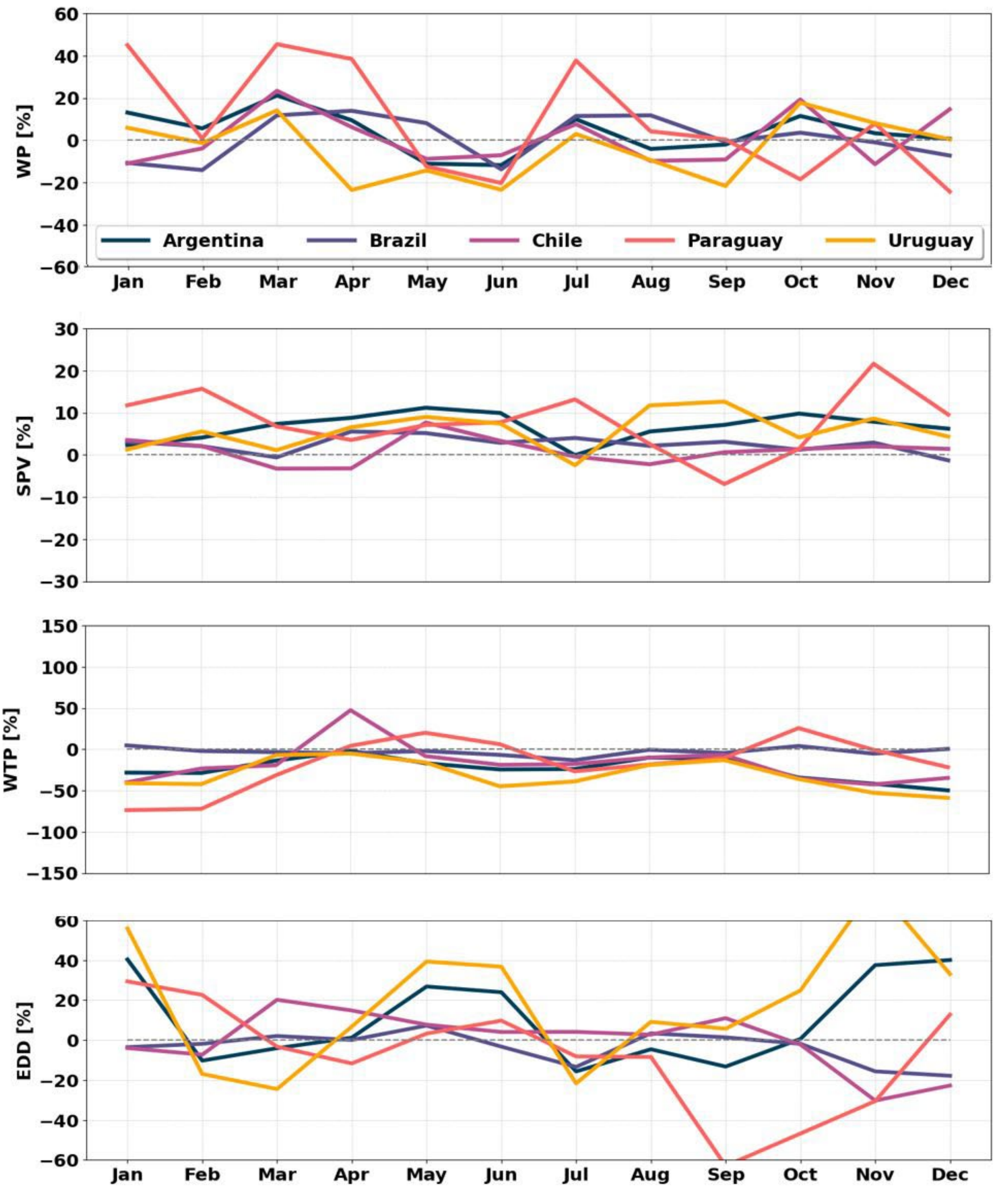

Figure 18. Monthly percentage anomaly for 2022 relative to corresponding months in the 1991–2020 reference period for five countries in South America. From top to bottom: wind power (WP) capacity factor, solar photovoltaic (PV) power capacity factor, weighted total precipitation (WTP) (hydropower proxy indicator), energy degree days (EDD) (energy demand proxy indicator). Note that the y-axis varies depending on the range of the indicator.

3 Potential future climate risks for renewable energy and demand

While the main focus of this report is on the impact of climate-induced variability on RE potential generation and demand, specifically for 2022 relative to the 1991–2020 climatology, an often-asked question is how RE resources and demand could vary over future decades due to climate change. To address this question a brief review of available literature is presented below. More specifically, a broad assessment of the projected changes for each of the four energy indicators is presented, based on one relevant paper each.[15]

3.1 Wind power

A recent review of climate change impacts on wind power generation (IPCC, 2022b; Pryor et al., 2020) concluded that natural variability due to the action of internal climate modes appears to dominate over global-warming-induced non-stationarity over most areas of the globe with large wind energy installations or potential. However, there is evidence for increased wind energy resources by the end of the current century in Northern Europe and the United States southern Great Plains. The authors add a caveat to the results by presenting evidence of some of the challenges intrinsic in this type of assessment, namely quantifying the climate impacts on wind power generation. For instance, in contrast to air temperature and total precipitable water, it is unknown whether anthropogenic warming will result in stilling (decreases in wind speed) or increased windiness at either the regional or the global scale. Reductions in the equator-to-pole large-scale temperature gradient will likely modify tropical circulation patterns (Hadley cell, monsoon circulations and/or tropical cyclone frequency) and the behaviour of mid-latitude jet streams and storm tracks and, hence, cyclone frequency, intensity and tracking.

Moreover, climate drivers such as the North Atlantic Oscillation (NAO) express variance at frequencies from sub-annual to multi-decadal, with the latter (up to timescales of 60 years) being modulated by North Atlantic sea-surface temperatures, the Atlantic Multi-decadal Oscillation and the Pacific Decadal Oscillation. The presence of low-frequency variability greatly confounds the ability to identify and assign causes of long-term tendencies in wind resources. On the other hand, based on historical records, a recent "recovery" of wind speeds has been observed in both individual regions (for example, in China) and across the northern hemisphere. While global annual mean wind speeds at 10 m height between the 1980s and early 2000s exhibited a negative linear trend of <-0.1 m s^{-1} per decade, the trend has since reversed and increases of >0.2 m s^{-1} per decade were reported for 2010–2017.

Overall, there needs to be greater emphasis placed on quantifying the fidelity of projections of wind resources and operating conditions, through regional and global studies. Access to data from operating wind farms would greatly benefit efforts to evaluate and improve our modelling of wind resources and address these challenges and other research questions (IPCC, 2022b; Pryor et al., 2020).

3.2 Solar photovoltaic power

Climate change may affect solar PV power output by increasing the weather variability and extremes, especially in terms of changes in temperature or clouds. By assessing global changes in the frequency of warm and cloudy conditions that lead to very low PV power outputs, Feron et al. (2021) showed that summer days with very low PV power outputs are expected to double in the Arabian Peninsula by mid-century but could be reduced by half in Southern Europe over

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[15] The review is restricted to one paper each because of space limitations, but also due to the fact that currently there are few assessments at the global level. However, there are considerably more papers studying the impact of climate change on RE and demand at the regional level. Many of these papers can be found in the reference lists of the cited, global, papers.

the same period, even under a moderate-emission scenario. Changes for winter, either increasing or reducing the PV power variability, are projected to be less striking, at least in low- and mid-latitude regions.

More specifically, as shown by Feron et al. (2021) and included in the IPCC AR6 WG2 report (IPCC, 2022a), climate change is expected to change average PV power outputs to only a minor to moderate extent under the Representative Concentration Pathway 4.5 (RCP4.5) scenario (that is, the RCP that stabilizes radiative forcing at 4.5 W m^{-2} in the year 2100). Moderate changes (either positive or negative) are expected by mid-century in summer PV potential estimates in parts of the Arabian Peninsula (−4%) and Central Europe (+5%). The changes in PV potential are less pronounced in other regions such as the Atacama Desert (+3%), south-eastern Australia (−2%), eastern China and South-East Asia (+2%), and North-Western Africa (−2%) (Figure 19).

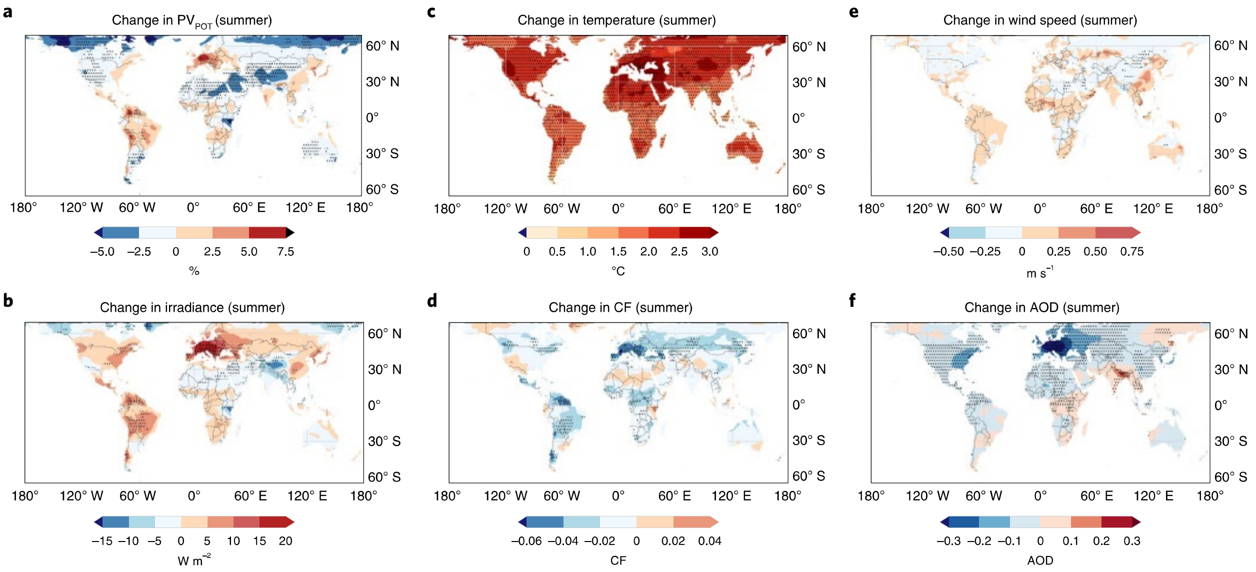

Figure 19. Future changes in solar potential for summer are on average moderate worldwide. (a)–(f) show changes from 1961–1990 to 2036–2065 (RCP4.5) in the multi-model mean (MMM) of General Circulation Model-based summer estimates of: (a) PV potential (PV$_{POT}$), (b) downwelling short-wave (SW) irradiance, (c) surface ambient temperature, (d) capacity factor (CF), (e) surface wind speed and (f) aerosol optical depth (AOD). The plots were made by assembling December–February (DJF) data for the southern hemisphere and June–August (JJA) data for the northern hemisphere. Stippling indicates regions where the detected changes are considered to be significant.

Source: Feron et al., 2021

3.3 Hydropower

Using a set of Coupled Model Intercomparison Project (CMIP) models, van Vliet et al. (2016) showed that there are consistent expected increases in annual mean streamflow for high-latitude regions (Northern North America, Northern Asia), and large parts of the tropics (Central Africa, Southern Asia). For 25% of the global land surface area, increases in annual mean streamflow for the 2050s are consistent among all ten CMIP models. Consistent decreases in streamflow are projected for the United States, Southern and Central Europe, South-East Asia and Southern parts of South America, Africa and Australia (8% of global surface area for 2050s) (Figure 20).

Spatial patterns of changes in hydropower usable capacities strongly correspond with the projected impacts on streamflow, showing overall increases in Canada, Northern Europe, Central Africa, India and north-eastern China (van Vliet et al., 2016). However, most hydropower plants (61%–74% for RCP2.6–8.5) are situated in regions where considerable declines in streamflow are projected, resulting in mean reductions in hydropower usable capacity. Reductions are projected in the global annual hydropower capacities of 1.7%–1.9% (2020s), 1.2%–3.6% (2050s) and 0.4%–6.1% (2080s) based on the General Circulation Model (GCM) ensemble mean for RCP2.6–8.5. Monthly maximum reductions are 8.9%–9.2% (2020s), 9.6%–17% (2050s) and 8.3%–24% (2080s), with 5%–22% of the hydropower plants experiencing strong (>30%) reductions in monthly usable capacity for the 2050s.

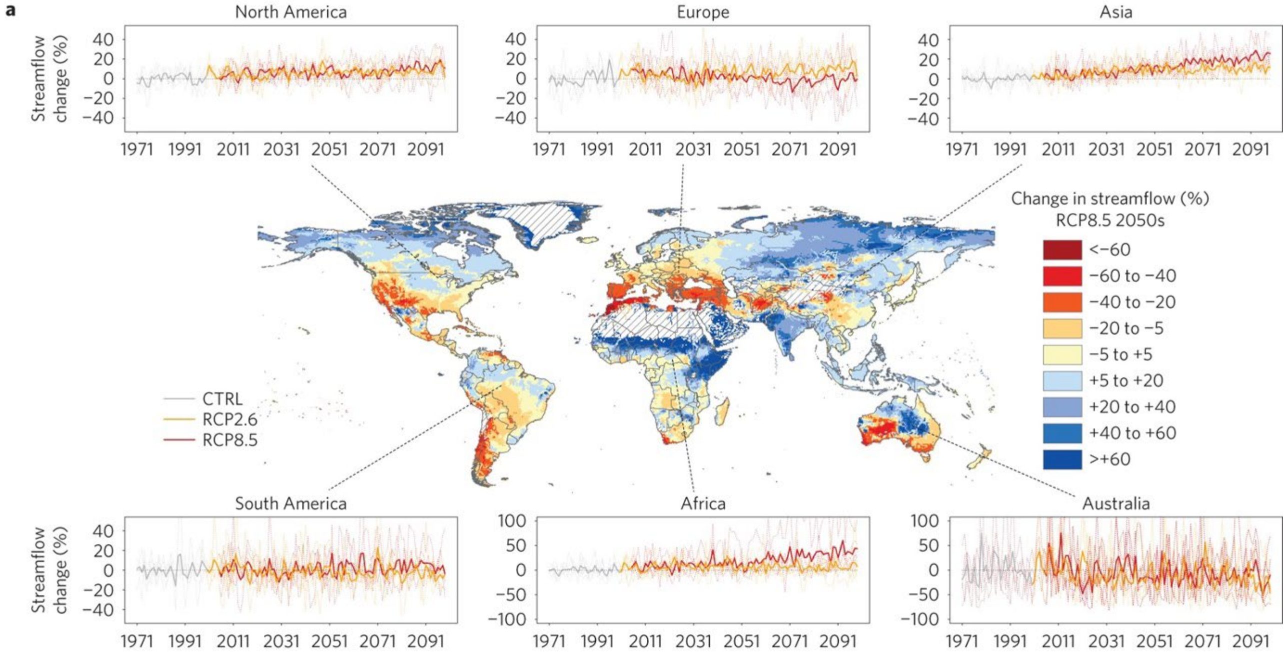

Figure 20. Impacts of climate change on annual mean streamflow. Maps of changes in streamflow for RCP8.5 for 2040–2069 (2050s) relative to the control period 1971–2000. Trends in changes for 1971–2099 are presented based on the General Circulation Model (GCM) ensemble mean results (thick lines) and for the five individual GCMs separately (thin dotted lines) for both RCP2.6 (orange) and RCP8.5 (red). Trends per continent were assessed by calculating mean values in streamflow and water temperature over all continent grid cells. Future changes were then calculated relative to the control period 1971–2000.

Source: van Vliet et al., 2016

3.4 Demand

The projected global temperature increases in the twenty first century are expected to have consequences on energy consumption due to an increase in energy demand to cool the built environment and a decrease in energy demand to heat it. This increase and decrease also depend on the number of end users for such energy; thus it is crucial to include population in the analyses. By studying the projected changes to CDD, HDD and EDD, Spinoni et al. (2021) found that the progressive increase in CDD outbalances the decrease in HDD almost everywhere for most global warming levels (GWLs) and shared socioeconomic pathways (SSPs). A few regions show a decreasing tendency in EDD at high GWLs for all SSPs: Central Europe, and North-western, North-eastern and Eastern Asia. Globally, EDD are likely to double at 2 °C of warming compared to 1981–2010 independently of the SSP. Under the worst-case scenario (SSP3), at 4 °C of warming CDD are approximately 380% higher and HDD approximately 30% lower than in the recent past, leading to an increase in EDD of close to 300%. Moreover, EDD shows the largest increase over equatorial Africa and India and the largest decrease over Central Europe and China. Globally, CDD are likely to increase with all SSPs (the largest increase is with SSP3), while HDD are likely to decrease with less sustainable SSPs (SSP3–SSP5) and show very small change with SSP1 and SSP2. Thus, EDD are projected to increase overall at the global scale, but to decrease over middle and high latitudes in Eurasia and in South-western South America (Figure 21).

Spinoni et al. (2021) caution about the likely large uncertainties of population-weighted degree-day projections for CDD compared to HDD. The areas with the largest uncertainties are the central United States, Amazonia, Southern South America, Eastern Europe, the Mediterranean region, the Sahel, tropical Southern Asia, and southern Australia. However, considering areas with population densities higher than 1 person/km^2, less than 4% of global areas show inter-model spreads larger than 10% – at any GWL – in at least one of the degree-day indicators. Moreover, the agreement among models in the sign of change is significant over 98% of global lands and for all GWLs (over 99% excluding the sparsely populated areas).

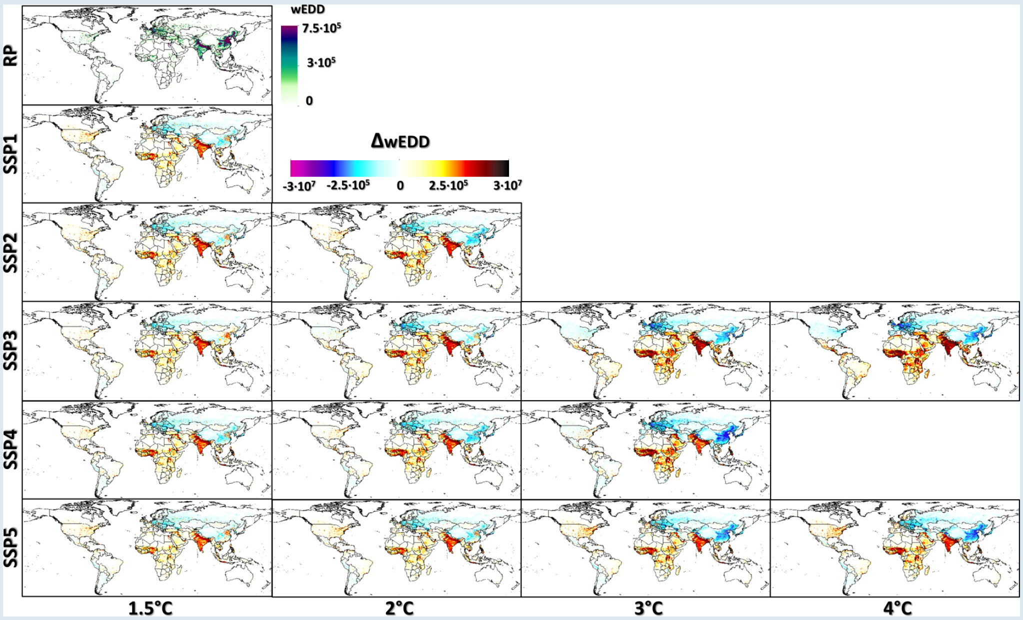

Figure 21. Population-weighted energy degree-days (EDD) for 1981–2010 (recent past (RP)) and projected change at four global warming levels (GWLs) following five shared socioeconomic pathways (SSPs)

Source: Spinoni et al., 2021

4 Conclusions

Climate variability and change modulate both energy demand and RE supply. Given the ambitious global targets to dramatically increase RE generation in line with 1.5 C° emissions scenarios by 2050, it is critical to assess the impact that climate has on RE potential generation and demand. The effect of climate variability has been discussed here by evaluating the changes in four indicators, wind power CF, solar PV CF, a hydropower proxy and the energy demand proxy EDD, over 2022 compared to the standard 30-year average, 1991–2020. The four indicators display considerable percentage anomalies both when averaged over the whole of 2022 and even more on a month-to-month basis, over several parts of the globe, with values considerably larger than a typical threshold reference of 5%–10%[16] (with solar PV CF showing the smallest range of up to approximately 6% on an annual mean). The assessment presented here may be useful both as a retrospective analysis and to manage energy resources in a more efficient way.

This section discusses the relevance of early warning systems for energy security and policy implications for potential growth of RE in the context of climate variability. A subsection with key messages then attempts to synthesise the whole document in short paragraphs.

4.1 Discussion on the importance of early warning systems

Of the four pillars of the Early Warnings for All initiative,[17] two are particularly relevant in the context of the energy sector and the management of RE generation:

- Detection, observation, monitoring, analysis and forecasting;
- Preparedness and response capabilities.

4.1.1 Detection, observation, monitoring, analysis and forecasting

While there is a wealth of data, from observations or models, already being used to create effective services for energy, including forecasts, some limitations in the quality of data are evident. The science and technology are at different levels of development, with weather forecasting more advanced than climate forecasting, but both relevant for effective early warning systems. In each of these areas there is room for improvement. In weather forecasts, for instance, work could be done to improve parametrizations relevant for wind and solar power. In seasonal climate forecasts, improvements could come from the dynamics of climate anomalies, which may involve improving model resolution or improved use of forecast ensemble members, but also increased observation coverage (*Integrated Weather and Climate Services in Support of Net Zero Energy Transition* (WMO-No. 1312)). More specifically, it is important to assess relevant climate drivers and their corresponding large-scale atmospheric patterns and understand their implications for renewable power generation and demand, to be able to provide appropriate advance warnings.

Another key aspect is the sharing of observations: these are fundamental for initializing numerical weather predictions through data assimilation, the assessment of weather and climate model output or even the calibration of parametrizations and post-processing procedures such as bias adjustments. Despite the importance of observations, there are still many areas of the globe, both in developed and least developed countries, which are under-observed, especially in terms of wind speed at different heights or solar radiation.

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[16] An average annual change of this magnitude can be considered significant for both generation and demand purposes. Monthly changes are typically much larger than annual means.

[17] The Early Warnings for All initiative is a ground-breaking effort to ensure that everyone on Earth is protected from hazardous weather, water or climate events through life-saving early warning systems by the end of 2027. The Early Warnings for All initiative is built around four key pillars: (i) disaster risk knowledge and management; (ii) detection, observation, monitoring, analysis and forecasting; (iii) warning dissemination and communication; and (iv) preparedness and response capabilities. More information is available at: https://public.wmo.int/en/earlywarningsforall.

The sharing of data is critical also when it comes to energy, both in terms of generation and installed capacity. These data are essential for accurately modelling power production or capacity factors. However, many gaps still exist in these energy data, also due to commercial sensitivities, and quality is sometimes suboptimal. Even for countries where data are made freely available, such as with the European Network of Transmission System Operators for Electricity (ENTSO-E) Transparency Portal,[18] which is an exemplar in energy data sharing, there are sometimes inconsistencies between generation and installed capacities, partly due to the fact that installed capacities are not updated frequently enough or are not always reported accurately.

Overall, there is a need to further assess gaps and opportunities for early warning systems for energy at the regional perspective and considering different types of REs (*2022 State of Climate Services: Energy* (WMO-No. 1301)).

4.1.2 Preparedness and response capabilities

Preparedness and response capabilities for the operation and management of energy resources are typically the responsibility of energy companies, which directly manage power supply or the grid. However, in less developed countries the organizations in charge of power supply or grid management sometimes lack the tools to properly manage energy resources. The WMO *State of Global Water Resources 2022* (WMO-No. 1333) reports that drought conditions caused a significant drop in hydropower production in 2022, resulting from low river flows. It is therefore important to support early warnings for energy security, particularly for hydropower, which is currently the most common RE source in many less developed countries.

4.2 Policy for potential growth of renewable energy in the context of climate variability

Power system flexibility is the key to coping with fluctuation in electricity generation and consumption patterns, to ensure an equilibrium between supply and demand. Power system flexibility refers to the extent to which generation or demand can be increased or decreased within a time frame ranging from minutes to hours, in response to anticipated or unexpected fluctuations.

In such regard, the role of policymakers is as follows:

- Assist the adoption of weather forecast tools that allow a long- and short-term set of actions to deal with solar PV and wind variability.

- Assist the development of the power system in such a way that solar PV and wind generation complement each other and other renewable sources in the most effective way. This requires accurate planning and provision of long-term price signals that facilitate selection of the best location for variable renewable energy (VRE) plants and a VRE design that is the most "system friendly".

- Foster flexibility resources (batteries, demand-side management, interconnections) through long- and short-term price signals, to both support their commissioning and facilitate their daily operations.

For the last two points, IRENA proposes the "dual procurement" approach (IRENA, 2022) to shape power system organizational structures in the context of the energy transition. This approach recognizes the distinct characteristics and requirements of two essential elements for a successful transition: renewable electricity and flexibility. The dual procurement approach

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[18] https://transparency.entsoe.eu

envisions an integrated system that efficiently incorporates both these elements within the power system, considering their unique attributes and the interplay between them.

Long-term renewable energy (LT-RE) procurement focuses on securing renewable electricity generation for the long term. It involves mechanisms like auctions or direct public investments, specifically designed for capital-intensive renewable technologies. LT-RE procurement aims to align supply and demand over extended time frames, both temporally and spatially, facilitating investments necessary for reliable electricity supply.

Short-term flexibility (ST-Flex) procurement complements the LT-RE pillar by addressing the need for flexibility in the short term. It operates based on marginal prices and employs a granular bidding format. ST-Flex procurement is geared towards matching real-time supply and demand, handling deviations between scheduled and actual load and renewable energy production. It accommodates various flexibility resources, including demand-side resources, storage, distributed energy resources and sector coupling.

Both LT-RE and ST-Flex procurement mechanisms should recognize the value of time and location in electricity and flexibility provision. They should also emphasize the active participation of end users, who can directly or indirectly engage in these mechanisms, shaping long-term forecasts and contributing to system operation. Conducive retail rates and prices play a crucial role in encouraging distributed investments in renewable energy and flexibility assets.

The dual procurement concept is adaptable to different socioeconomic contexts, whether liberalized, regulated or hybrid systems. It seeks to improve governance, align market structures with social value and foster active stakeholder involvement in the energy transition. Ultimately, the aim is to strike a balance between environmental sustainability, human rights and economic performance in shaping the future of power systems. Over time, a convergence of implementation approaches in regulated and liberalized contexts may be expected as they share the common goal of enhancing power system efficiency.

4.3 Key messages

(i) **All assessed indicators show noticeable changes due to effects of climate variability and change, albeit differing by technology and country.** The four energy indicators assessed (wind power CF, solar PV CF, a hydropower proxy and the energy demand proxy EDD), presented as country averages, display marked percentage anomalies for both annual and monthly averages. Aside from Solar PV, which displays limited variability of less than 10% on average annually, the overall inter-annual and intra-annual variability is pronounced; for instance, it is larger than 15% for wind power CF for many countries.

(ii) **Improving our understanding of climate drivers and their interactions with renewable resources is vital for resilience and the efficiency of energy systems and their transition**. It is critical to consider key climate drivers such as the El Niño Southern Oscillation (ENSO), as these normally explain a large portion of the observed variability; accurately predicting them makes it possible to manage energy resources more efficiently than would be possible without such knowledge.

(iii) **Mainstreaming climate variability, in addition to climate change, should be a priority for improved operation, management and planning of energy resources**. This could lead to the establishment of early warning systems to help better manage energy load, resources and maintenance. Moreover, this can inform energy infrastructure modernization and expansion, and trigger the necessary innovation across technologies, markets and policies.

(iv) **Adapting market structures is central to providing the necessary flexibility during the transitional phase from centralized to decentralized power systems.** Power system organizational structures that allow both the procurement of the highest value set of variable renewable resources and the deployment of flexibility resources are necessary. A "dual procurement" system can be an effective avenue in this regard.

(v) **Developing countries, especially in Africa where energy access remains a key priority, can adapt their systems to harness renewable potential with the benefit of knowledge on climate variability**. RE is particularly underdeveloped in Africa, which accounts for only 2% of global capacity despite its abundant potentials. RE is essential to support the continent's development and industrialization. For effective implementation and utilization of RE, it is important to combine knowledge of potential resources and existing infrastructures, but also climate variability as discussed here.

(vi) **Comprehensive and systematic energy data collection and sharing are essential to improving knowledge and understanding of the impact of climate variability and change on energy supply and demand**. The energy indicators presented here are simplified with respect to actual, more representative ones. The computation of more accurate indicators requires more general and systematic sharing of energy data, including installed capacity and actual generation.

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Annex. Methodology

To understand 2022 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.

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 RE 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, 1991–2022) 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 2022 for selected countries are displayed.

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 2022. 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° x 0.25° latitude/longitude
- Coverage: Global
- Temporal resolution: Monthly
- Temporal period: 1991–2020 and 2022

Wind mask

- This product is produced under the C3S Energy project[19] 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.

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[20]

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 2022; (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).

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

[20] 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.

(2) Calculate anomalies for 2022 using 1991–2020 as baseline (monthly means).

(3) Anomaly = monthly mean for 2022 – 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).

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 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.

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 2022 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 2022

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 2022

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 2022

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 2022 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).

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 RE 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, 2021–2022) 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 2022

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 2022 using the same baseline and formulas as for other energy indicators.

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

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 (EDD) indicator – the sum of cooling degree days (CDD) and heating degree days (HDD)[21] – was selected as a proxy for energy (electricity) demand. EDD has been defined and used in various studies in Europe (Spinoni et al., 2017) and globally (Spinoni et al., 2021). Having only a single demand indicator, EDD, rather than two, CDD and HDD, 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). There are several varieties of CDD and HDD. Mid-range CDD and HDD were selected (Table 1), and the EDD was computed. 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 1. Selected indices from the Weather for Energy Tracker

Variable	Short name	Short explanation
CDD (21 °C, humidity)	CDDhum21	Cooling degree days from temperature corrected by humidity (reference temperature 21 °C). Heat Index is used as input temperature.
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 (21 °C, humidity, 18 °C thold)	**EDDh21Thold18**	**Sum of CDDhum21 and HDDThol18**

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[21] 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.

Population data

Provided by CMCC:[22]

- Spatial resolution: 0.25° × 0.25° latitude/longitude
- Coverage: Global
- Temporal resolution: Annual
- Temporal period: 1991–2020 and 2022

Base data

Use HDDThold18 and CDDhum21 datasets (see Table 1):

- Spatial resolution: 0.25° × 0.25° latitude/longitude
- Units: Degree days
- Coverage: Global
- Temporal resolution: Monthly averages
- Temporal period: 1991–2020 and 2022

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 RE sources.

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[22] The 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.

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