Complementarity of wind and solar power in North Africa: potential for alleviating energy droughts and impacts of the North Atlantic Oscillation

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Highlights

- A negative correlation between NAO and wind power in northern coastal regions.
- Energy droughts dominate coastal regions.
- Solar-wind hybridization reduces energy droughts in North Africa.
- Seasonal NAO index does not correlate significantly with energy droughts.

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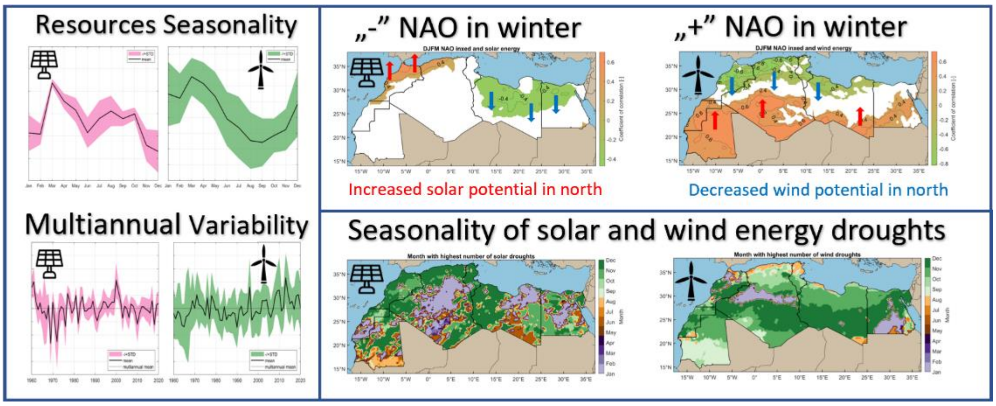
Abstract

With growing gas and oil prices, electricity generation based on these fossil fuels is becoming increasingly expensive. Furthermore, the vision of natural gas as a transition fuel is subject to many constraints and uncertainties of economic, environmental, and geopolitical nature. Consequently, renewable energies such as solar and wind power are expected to reach new records of installed capacity over the upcoming years. Considering the above, North Africa is one of the regions with the largest renewable resource potential globally. While extensively studied in the literature, these resources remain underutilized. Thus, to contribute to their future successful deployment and integration with the power system, this study presents a spatial and temporal analysis of the nature of solar and wind resources over North Africa from the perspective of energy droughts. Both the frequency and maximal duration of energy droughts are addressed. Both aspects of renewables' variable nature have been evaluated in the North Atlantic Oscillation (NAO) context. The analysis considers the period between 1960 and 2020 based on hourly reanalysis data (i.e., near-surface shortwave irradiation, wind speed, and air temperature) and the Hurrel NAO index. The findings show an in-phase relationship between solar power and winter NAO index, particularly over the coastal regions in western North Africa and opposite patterns in its eastern part. For wind energy, the connection with NAO has a more zonal pattern, with negative correlations in the north and positive correlations in the south. Solar energy droughts dominate northern Tunisia, Algeria, and Morocco, while wind energy droughts mainly occur in the Atlas Mountains range. On average, solar energy droughts tend not to exceed 2-3 consecutive days, with the longest extending for five days. Wind energy droughts can be as prolonged as 80 days (Atlas Mountains). Hybridizing solar and wind energy reduces the potential for energy droughts significantly. At the same time, the correlation between their occurrence and the NAO index remains low. These findings show the potential for substantial resilience to inter-annual climate variability, which could benefit the future stability of renewables-dominated power systems.

Keywords: Climate resilience; Energy transition; Hurrel NAO index; Hybrid energy system; Renewable energy.

Graphical abstract



1 Nomenclature

Abbreviations	
AC	Alternating current
CF	Capacity factor
DJFM	December, January, February, March
ENSO	El Niño-Southern Oscillation
ERA5	Fifth generation ECMWF atmospheric reanalysis of the global climate
GII	Global inclined irradiation
HVDC	High voltage direct current
NAO	North Atlantic Oscillation
pp	Percentage points
PV	Photovoltaics
RES	Renewable energy sources
Variables, parameters, and constants	
DI_i	Deficiency index
E_i	Energy generated
e	Actual water vapor pressure
e_s	Saturation vapor pressure
K_t	PV cell temperature coefficient
NOCT	Normal operating cell temperature
P_{PV}	Hourly power delivered from PV
P_r	PV installed capacity
R_d	Specific gas constant for dry air
RH	Relative air humidity
$\mathrm{S_{ref}}$	Solar radiation at standard test conditions
D_T	Threshold for energy drought
T_{amb}	Ambient air temperature
T_c	PV cell temperature
T_d	Dew point air temperature
T_{ref}	PV cell temperature in standard conditions
p	total pressure exerted by the moist air
S	Total solar radiation reaching the PV array surface
v	Wind speed
v'	Air density adjusted wind speed
η	Overall PV system efficiency
ρ_{air}	Air density
ρ_{ref}	Reference air density
ρ	Spearman coefficient of correlation

1. Introduction

North Africa is one of the largest and richest areas in terms of renewable energy sources (RES), such as wind and solar [1]. However, the potential of RE remains untapped in favor of conventional power generation because of the historical dependence on traditional power sources [2].

Theoretically, the Saharan region's solar energy potential could power the world [3]. Several projects have been proposed, such as the Mediterranean Solar Plan (MSP) [4] and DESERTEC [5]. These projects involved the large-scale deployment of RES (i.e., mainly solar and wind) in Morocco, Algeria, Tunisia, Libya, and Egypt in partnership with Europe. For electricity transmission to Europe, several intercontinental grid connections have been created through submarine cables and alternating current (AC) and high voltage direct current (HVDC) systems as part of the MEDGRID project [6]. However, such complex systems require high investment, rigorous resource assessment, solid infrastructure, and a stable geopolitical situation. More importantly, North African countries must meet their electricity needs before becoming green energy exporters.

A comparative study of five different scenarios by Brand and Blok [7] found that large-scale electricity export is only possible if the share of renewable energy meets 60% of the electricity demand in North Africa. Hawila et al. [8] evaluated the readiness of the target area to deploy and promote RES in the region. Their assessment framework shows that Morocco is ahead of its neighboring countries, but the region still exhibits significant weaknesses and threats that remain a hindrance. Komendantova et al. [9] identified the risks of developing concentrated solar power plants in North Africa, with the regulatory risks perceived by the stakeholders as the most significant in terms of probability of occurrence and the negative impacts associated. However, none of the above studies examined the risks associated with the multiscale implications of weather and climate variability on the installation of such projects, which is a critical assessment for renewable energy projects of any scale.

Moreover, one can observe that most of the reviewed studies focused on concentrated solar power and its feasibility for transportation to Europe. On the one hand, concentrated solar power is not as mature or cost-effective as fossil fuel or solar PV-based generators. Additionally, relying on only one renewable source increases the vulnerability to its intermittency. On this matter, a potentially critical issue is energy droughts, i.e., sequences of days where the production from renewable resources is low to very low [10].

1.1. Research questions and contribution of this research

Considering the above, this study aims to answer the following research questions:

- To what extent do solar and wind resources exhibit complementary natures in North Africa?
- What is the spatial and temporal distribution of energy droughts across North Africa?
- Does the North Atlantic Oscillation drive renewable energy droughts over Africa?

This paper explores the potential of hybridization of wind and solar power in North Africa, focusing on mitigating energy droughts and the impacts of the North Atlantic Oscillation (NAO). It examines the complementarity of these two renewable energy sources, the frequency and duration of energy droughts, and the potential of hybrid systems to reduce such events. The research also considers the influence of weather and climate variability, particularly the NAO, on renewable energy resources in the region. These research subjects are relevant and contribute in the context of Sustainable Development Goals (SDG) 7 (Affordable and clean energy) and 13 (Climate Action), which aim to increase the share of renewable energy in the global energy mix and take urgent action to combat climate change and its impacts, respectively.

1.2. Studies about complementarity of renewables and climate variability in North Africa

Analyzing and understanding the duration and frequency of energy droughts and low-resource days is fundamental for designing reliable electricity systems. Research relating to this matter for Africa and considering wind and solar resources includes, for example, the works by Plain et al. [11] and Seyedhashemi et al. [12]. In the same spirit, some recent studies suggested combining different RES, notably solar and wind power, to mitigate this problem and reduce the intensity and duration of energy droughts [2, 13, 14]. However, only a few studies have shown interest in combining renewable resources in North Africa, and none have investigated the role of energy mixes in alleviating energy droughts.

Guezgouz et al. [3] assessed the joint operation of solar and wind power in Algeria. The results showed a favorable complementarity between these vital RES sources. However, the study was limited to only one country and one year of meteorological data, so it could not rigorously assess possible interannual and low-frequency variability impacts. Bloomfield et al. recently drew similar conclusions about favorable complementarity [15] for their multi-decadal ERA5-based study conducted in Senegal and Kenya. In addition, Jablonski et al. [4] investigated the potential of combined wind-solar electricity generation in north-western Africa using nearly four decades of reanalysis data gathered from the ERA5 dataset. Their findings indicate that wind energy projects in the region are feasible. Still, they alone cannot substantially contribute to the Mediterranean Solar Plan goal, emphasizing the need to improve the competitiveness of solar power. Considering the limitations of previous studies, there is a clear research gap in evaluating solar-wind complementarity for North African countries.

In addition, even less attention has been paid to intra- and inter-annual weather variability, which is very important in designing resilient renewable energy systems [16]. Subsequent studies have shown that this variability is mainly the result of the variability in large-scale atmospheric circulations such as the El Nino Southern Oscillation (ENSO) and NAO [5, 6].

Bloomfield et al. [15] indicate that ENSO is often characterized as the dominant mode of climate variability affecting precipitation patterns across Africa, and its magnitude and phase are directly linked to the sea surface temperatures (SSTs) over the tropical eastern Pacific Ocean. The warm anomalies in SSTs, called El Nino, and the cold anomalies, known as La Nina, play a crucial role in the world’s climate. However, their study reveals that the relationships between extreme ENSO phases and the potential for wind and solar power in North Africa are relatively weak, with more significant impacts observed in Southern and East Africa. They suggest further work is needed to understand the meteorological drivers of wind/solar variability over Africa.

Another atmospheric phenomenon of relevance for the region is the NAO. This mode of variability is present due to the difference in surface pressure between the Azores (high) and Icelandic (low) regions in the North Atlantic Ocean, where positive and negative phases can be distinguished [17]. The pressure difference between the two regions is large during positive NAO phases. The North Atlantic jet stream is diverted to the North, resulting in the path of the North Atlantic storm track passing the UK and Northern Europe. This region experiences a warm, windy, wet winter with high cloud cover [18]. At the same time, Southern Europe experiences a cold, still, and dry winter with relatively sunny weather. The difference between Iceland and the Azores is conversely weak for the negative NAO phase, as the jet stream has a more southerly location and more storms move to the south (i.e., South Europe and North Africa), loaded with clouds and rainy weather conditions. At the same time, the Northern part of Europe enjoys calm but cold and dry weather conditions. Fluctuations between the NAO's positive, negative, and neutral phases can happen on several timescales. Passing weather systems may cause daily changes. However, more slowly varying changes are also present due to seasonal and inter-annual climate variability. For example, the 1990s experienced a considerable period of positive NAO phases, and negative NAO conditions were observed between 2009 and 2011 [19].

The NAO has become a key feature for meteorological centers to predict European weather conditions. Many studies have explored the influence of the NAO on RES, variability, and power systems in several European countries [20]. However, a limited number of studies address this issue in North Africa. An analysis by Pozo-Vazquez et al. [21] based on 20 years of reanalysis data showed the particular influence of NAO on the inter-annual variability of solar and wind resources over the Mediterranean area. Given the proximity of North Africa to Southern Europe, it is likely that the NAO also influences it. From this perspective, this research explores the relationship between the NAO index and energy droughts in North African countries.

Additionally, due to global warming, most countries of the North African region are witnessing a rise in average air temperature and more natural disasters such as floods, fires, desertification, and deforestation [22]. Consequently, climate change leads to altered air temperature, solar radiation, wind distribution, and frequency, which directly impact the production of solar and wind power [23].

In summary, the literature review reveals that the current body of knowledge does not provide a dedicated and detailed answer to the research questions raised in Section 1.1. Considering the above in the remainder of this work, in Section 2, the data and methods applied in the analysis will be presented, whereas Section 3 and Section 4 will present and conclude the results, respectively.

2. Data and methods

2.1. Study area

There is no uniform definition regarding the region described as North Africa. The list of countries that form this region varies depending on the consulted source (e.g., United Nations [24], African Union [25], or Encyclopedia Britannica [26]). For this analysis, this study has considered the following: Algeria, Egypt, Libya, Mauritania, Morocco, Western Sahara [27], and Tunisia ([7] (Table 1).

Table 1. Energy and economic statistics for countries under investigation.

Country	Primary energy demand [TWh] in 2019 [28]	Primary energy by source [%] in 2019 [28, 29]	Population in millions as of 2019 [30]	GDP in billion USD [30]
Algeria	695	65% - gas, 34% - oil, remaining % - coal, hydropower, solar & wind	43	145,164
Egypt	1,073	55% gas, 38% - oil, 3% - hydropower, remaining % - coal, wind & solar	100.4	363,069
Libya	175	65% - oil, 32% - gas, remaining % - biofuel & waste [q]	6.9	25,418
Mauritania	18	65% - oil, remaining % - biofuel & waste	4.5	7,779
Morocco	262	60% - oil, 30% - coal, 4.5% - wind, remaining % - gas, solar & hydropower	36.5	112,871
Tunisia	122	49% - gas, 40% - oil, 10% - biofuels and wastes, remaining % - renewables	11.7	39,236
Western Sahara*	1	-	0.6	908

*Disputed region with most of the territory under the administration of the Kingdom of Morocco. GDP: Gross domestic product.

In 2019, North African countries consumed 1,273 TWh of primary energy, accounting for approximately 23% of the continent's energy consumption, despite representing around 15% of Africa's population [30]. Despite abundant solar and wind resources, most energy supply comes from fossil fuels, particularly gas and oil. These two sources cover over 95% of the primary energy demand in Algeria and Egypt [31, 32]. At the same time, the rich renewable resources of North Africa are believed to have considerable export potential via direct current (DC) transmission lines to Europe. Driven by abundant solar and wind resources and mature, cost-competitive technologies, renewable electricity generation has increased by 40% in

North Africa between 2010 and 2020, thanks to 4.5 GW of PV, wind, and solar thermal generation added to the power systems [33].

2.2. Input data

This research uses hourly data from 1960 to 2020 from the fifth-generation ECMWF atmospheric reanalysis of the global climate, commonly known as ERA5 [34], provided by the European Centre ERA5 for Medium-Range Weather Forecasts (ECMWF). This dataset is used to model the potential power generation from solar and wind energy sources within the specified area of interest. Variables considered include hourly: 2 m air temperature, 2 m dew point temperature, air pressure, 100 m v-component of wind, 100 m u-component of wind, and surface solar radiation downwards. Regarding spatial coverage, the datasets covered areas from 18° W to 37° E and 15° N to 37° N, with a horizontal resolution of 0.25° x 0.25°. The North Atlantic Oscillation index covering the period 1960-2020 is from the station-based NAO index, which is based on the difference between the normalized sea level pressure between Lisbon and Reykjavik [19]. Data were accessed for the extended winter season (corresponding to the station-based NAO index: DJFM – December, January, February, and March, denominated here as the winter period) and annual resolutions. DJFM is used here as the period where the NAO pattern is most pronounced [35, 36].

2.3. Methods

2.3.1. Solar power

In this study, the hourly generation of solar PV systems is modeled based on monocrystalline silicon cell efficiency as a function of global inclined irradiation (GII) and air temperature, following Duffie and Beckman [37]. The conversion of ERA5 horizontal irradiation to inclined follows the approach proposed by Duffie et al. [38]. An optimal inclination angle for each grid point has been identified to ensure the maximal multiannual irradiation sum – Fig. A1 presents the mentioned angles.

The hourly PV power (P_{PV}) is calculated according to the following equations, Eqs. 1 and 2 [39]:

$$P_{PV} = P_r \times \frac{S}{S_{ref}} \times [1 - K_t\,(T_c - T_{ref})]\eta \qquad (1)$$

where the cell temperature (T_c) reads:

$$T_c = T_{amb} + S\left(\frac{NOCT - 20}{800}\right) \qquad (2)$$

where P_r is the installed capacity (i.e., assumed to be 1 kW in this research), S and S_{ref} refer to the total solar radiation reaching the PV array surface and its value at standard test conditions [1 kW/m^2]. Based on values available at [40], K_t [%/°C] is the temperature coefficient of power, which indicates the dependence of the PV output power on the cell temperature (here set to -3.7*10^{-3}), T_{amb} denotes the ambient air temperature, T_{ref} is the standard ambient air temperature set at 25 °C, *NOCT* is the normal operating cell temperature given by the manufacturer (here assumed to be 50 °C), and η is the overall system efficiency (de-rating factor) set to 0.85.

2.3.2. Wind power

The wind turbine power output has been modeled based on the power curve (Fig. A2) of a commercially available 3 MW Vestas V90/3000 wind turbine with a 100 m hub height. This turbine was selected based on current trends that show that these units are slowly replacing 2 MW on-shore wind turbines because of their greater nameplate capacity [41, 42]. In addition, wind data at 100 m are directly available from ERA5 reanalysis.

Air density might significantly impact the performance of wind turbines [43], but this variable is not directly available in the ERA5 database. This study employs the approach proposed by Ulazia et al. [44] to correct the wind power output from the Vestas wind turbine for air density. In their method, the wind speed (*v*) at a given time (denoted by subscript *t*) is corrected for the change in air density, as follows:

$$v'_t = v_t \left(\frac{\rho_{air_t}}{\rho_{ref}}\right)^{1/3} \quad (3)$$

where v' is the wind speed adjusted for air density [m/s], ρ_{ref} is the reference air density (kg/m^3) here equal to 1.225 [kg/m^3].

A relative air humidity (RH) parameter is needed to estimate the hourly air density, and even if this is not available from ERA5, it is possible to estimate it from air temperature and pressure variables available in this reanalysis dataset. Hence, it has been calculated based on the procedure described in the literature [45, 46] :

$$e = 611 \times exp\left(\frac{17.27 \times T_d}{237.3 + T_d}\right) \quad (4)$$

$$e_s = 611 \times exp\left(\frac{17.27 \times T_a}{237.3 + T_a}\right) \quad (5)$$

$$RH = \frac{e}{e_s} \quad (6)$$

where e is the actual water vapor pressure [Pa], e_s is the saturation vapor pressure [Pa], T_d is the dew point temperature [°C], and T_a the air temperature [°C].

Having the relative humidity estimated, it is now possible to calculate the air density based on the following equations [45, 46]:

$$e = e_s * RH \quad (7)$$

$$p_d = p - e \quad (8)$$

$$\rho_{air} = \frac{p_d}{R_d T_a} + \frac{e}{R_v T_a} \quad (9)$$

where p_d is the partial pressure of dry air [Pa], p is the total pressure exerted by the moist air, T_a the air temperature [K], R_d the specific gas constant for dry air (287.058 J/ kg·K), R_v the specific gas constant for water vapor (461.495 J/kg·K), and ρ is the air density [kg/m^3].

2.3.3. Complementarity – energy droughts

The energy droughts were investigated using the approach by Raynaud et al. [10]. A low generation below a defined threshold characterizes the energy drought. In other words, energy droughts can be defined as periods of prolonged low availability of renewable energy or significant mismatch between demand and supply. Following the procedure described by Raynaud et al., analyzing energy drought events involves the calculation of the deficiency index (DI). In summary, the process requires converting the generation time series into a binary time series whose values are equal to 0 when the generation is greater than a set threshold (D_T) or to 1 when lower (Eq. 10). In the calculation process, the total number of days with DI = 1 per year and per winter (i.e., as in the NAO index definition) were used for further evaluation. The threshold (T) is usually set as a certain percentage of the multiannual mean generation. As in Raynaud et al. [10], it is assumed to be 0.2 in this research. In Eq. 10, the available energy during the day can be associated with, for example, an average daily capacity factor. Then, for example, if E_i = 0.3 (or 30%), then considering threshold T = 0.2 (or 20%), such a day was not considered an energy drought day. Alternatively, an approach can be used when the actual generation (ex., MWh) or generation per unit of installed capacity (MWh/MW) can be used instead of capacity factors.

$$DI_i = \begin{cases} 0 & if\ E_i \geq D_T \\ 1 & otherwise \end{cases} \quad (10)$$

where E_i is the available energy during the day 'i', and D_T is the set threshold. Energy droughts can be assessed from the perspective of local or regional resource availability [47]. The energy drought event was considered a day meeting the criteria defined for an energy drought regardless of the characteristics of the previous or the following day. In other words, the total number of days falling under the definition of an energy drought is calculated for each grid point. For each region, the longest energy drought was also identified, assuming that the energy drought event is an interrupted time series of "1". For example, [0 1 1 1 0] is an energy drought event lasting three days.

2.3.4. Complementarity – optimal capacity of generators

Investigating the impact of hybrid system structure on the frequency of energy drought events provides helpful insight from a planning perspective. By the hybrid system structure, one should understand the capacity ratio of solar and wind generators – naturally, other variable renewable energy sources can also be investigated. The following steps summarize the procedure employed for this purpose:

- First, the frequency of energy drought events is calculated for individual solar and wind generators.
- The next step involves an energy drought analysis conducted for a hybrid solar-wind power plant with equal nameplate capacities [10, 48].
- The last step aims to find an optimal capacity sharing between solar and wind energy in a solar-wind hybrid system. For this purpose, the initial configuration considered is a solar-only system. Then, it is converted to a solar-wind system by changing the solar-wind ratio. The analysis considered increments of 1 percentage point (pp). For example, one can envision a 100 MW solar park hybridized into a solar-wind park. The procedure above implies that the following hybrid system structure is 99 MW installed in solar PV and 1 MW in wind power. This procedure is continued until reaching a 100 MW wind park only. The hybrid system with the lowest frequency of energy droughts over the 1960-2020 period was considered and was identified for each site. Its capacity ratio was archived under the constraint that the hybrid generator's capacity factor (CF) was not less than *k* percentage points compared to the generator with the most power (i.e., either PV solar or wind) at a given site. The *k = 0.5 pp* was an arbitrary value considered here.

2.3.5. NAO index

The statistical relationship between the NAO index and the analyzed parameters of solar and wind energy in North Africa is based on the Spearman coefficient of correlation, assuming statistical significance of correlations at *p-value* < 0.05.

3. Results and Discussion

After collecting and processing the relevant meteorological data from the ERA5 database, the corresponding CF of each RES was calculated. Next, solar-wind potential, complementarity, energy droughts, and their relationship with the NAO index are explored and presented in the form of maps in the following sections.

3.1. Solar and wind resources

Consistent with previous research findings [3, 49-51], solar and wind resources in North Africa exhibit significant spatial (Fig. 1) and temporal (Fig. A3 and Fig. A4 in the appendix) variability. The highest potential for solar power (CF) is observed in the northwestern part of the Sahara Desert. In contrast, regions with favorable wind conditions are unevenly distributed: the western coast of Morocco/Western Sahara [49, 52] and the Gulf of Suez. For the whole region presented in Figure 1, the average CF for solar and wind power based on 1960-2020 data are 21.59% and 16.93%, respectively - with the latter characterized by a much higher spatial variability (Standard Deviation = 6.44 pp) compared to solar (Standard Deviation = 0.78 pp). Considering the above, the resources exhibit significant spatial and temporal variability.

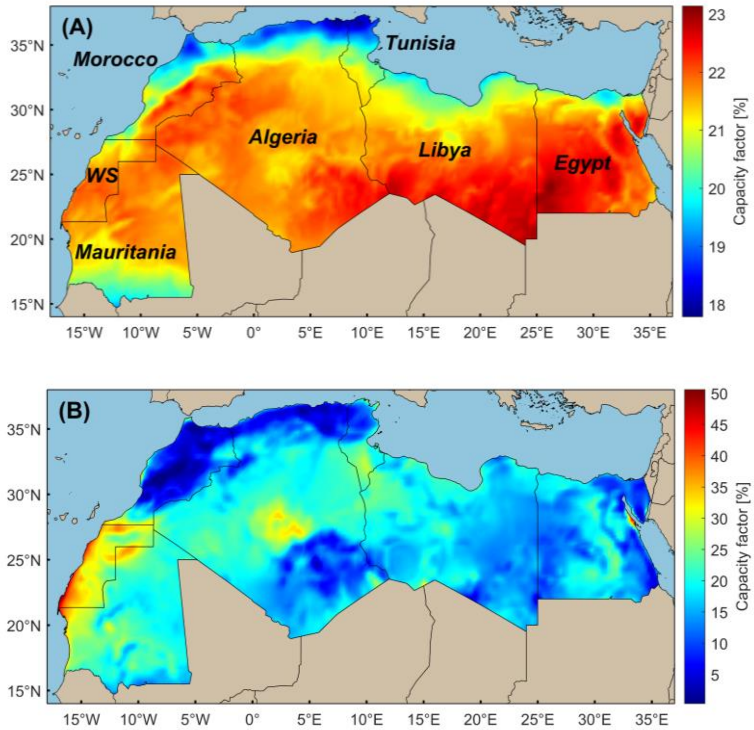


Fig. 1. Mean capacity factors over 1960-2020 based on the ERA5 dataset for (A)Solar PV and (B) wind generation. WS – stands for Western Sahara.

The availability of RES changes over time. The diurnal, seasonal, and multiyear variations are one of the major challenges in establishing power systems dominated by renewable energy [21]. Such changes in availability from RES often require additional flexibility measures in the form of enabling the rapid adjustment of power output from conventional generators, flexible loads, or energy storage, which is often considered the ultimate solution associated with successful power sector transformation and has therefore drawn the attention of the research community in recent years to exploring conventional [53] and unconventional storage options [54]. Thus, this raises the question of the potential of low-cost solutions (i.e., optimal capacity allocation) to reduce the need for energy storage, the occurrence of energy droughts, or the impact of global weather patterns on renewable energy generation.

According to previous studies, the North Atlantic Oscillation might drive inter-annual changes in renewables availability [20, 21]. Figures 2 and 3 present the correlation between the NAO (annual and seasonal) index [19] and the potential of the two RES under consideration, covering years from 1960 to 2020. It is observed that a moderate, statistically significant, positive correlation (values ranging from 0.4 to 0.6) for solar resources exists in the northern part of the analyzed region, particularly for north Morocco and Algeria. In contrast, negative correlations were found in northern Egypt and north-western Libya (Fig. 2).

In other words, for the positive values of the winter NAO index, the western part of North Africa faces a relatively cool and dry climate associated with higher potential energy yield from PV systems. Additionally, it can be observed that the correlation coefficient values decrease further to the south for solar energy, indicating less connection between renewables and large-scale weather phenomena over the North Atlantic Ocean.

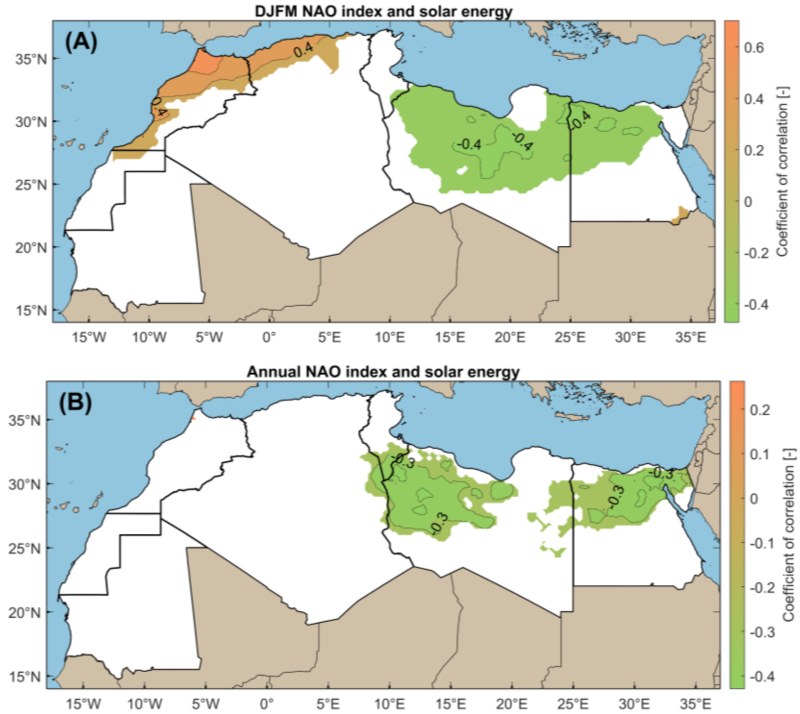


Fig. 2. Spearman correlation between NAO index and Solar resources in the North Africa region. Please note the different scales on the color bar. Only significant correlations (p <0.05) are shown.

The situation is considerably different in the context of wind energy and its relationship with the NAO index. Stronger correlations are observed, often surpassing ρ = |0.6|, with opposite signs compared to those of solar resources. A negative correlation is noted between the NAO index and wind resources in the northern part of the region under consideration (i.e., the coastal area of North Africa). Conversely, in its southern part, the correlations are positive, as depicted in Fig. 3. Negative NAO index values are likely to coincide with reduced wind potential in the northern coastal regions of North Africa and with higher wind potential in the western coast. However, the uneven spatial distribution of wind resources suggests limited advantages from spatially distributed generation from this RES. The correlations for the annual NAO index are also lower than for the seasonal one, similar to solar energy.

Nevertheless, the reversed correlations are a positive sign from the perspective of the potential multiannual complementarity of these two resources - meaning years with lower solar potential might be compensated by higher wind potential and vice versa. This issue will be discussed in section 3.4.

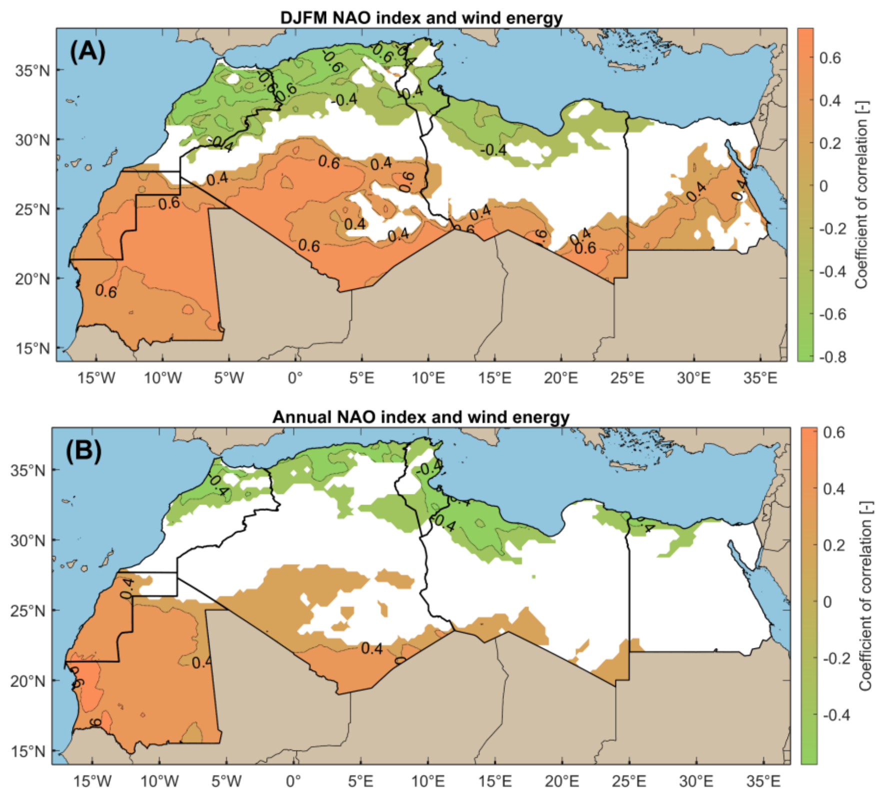


Fig. 3. Spearman correlation between NAO index and wind resources in the North Africa region. Please note the different scales on the color bar. Only significant correlations (p <0.05) are shown.

3.2. Energy drought for single RES

The occurrence of energy droughts is a relevant phenomenon, enabling a more in-depth analysis of the complementary nature of solar and wind resources. Figure 4 displays the energy droughts from the perspective of individual RES. As observed, energy droughts are extremely limited due to the low variability of solar resources over the Sahara Desert. Energy droughts are as rare as one event per year in the region, indicated by the green color. A higher number of solar energy droughts is observed for northern parts of Morocco and Algeria, potentially exceeding five and up to seven events per year. Compared to solar, wind energy droughts are more frequent, and, on a regional level, they tend to exceed at least ten events per year, with the highest concentration in northwest Morocco and northern Algeria, where they can exceed 200 days per year. This behavior indicates a very high variability of wind resources in this region.

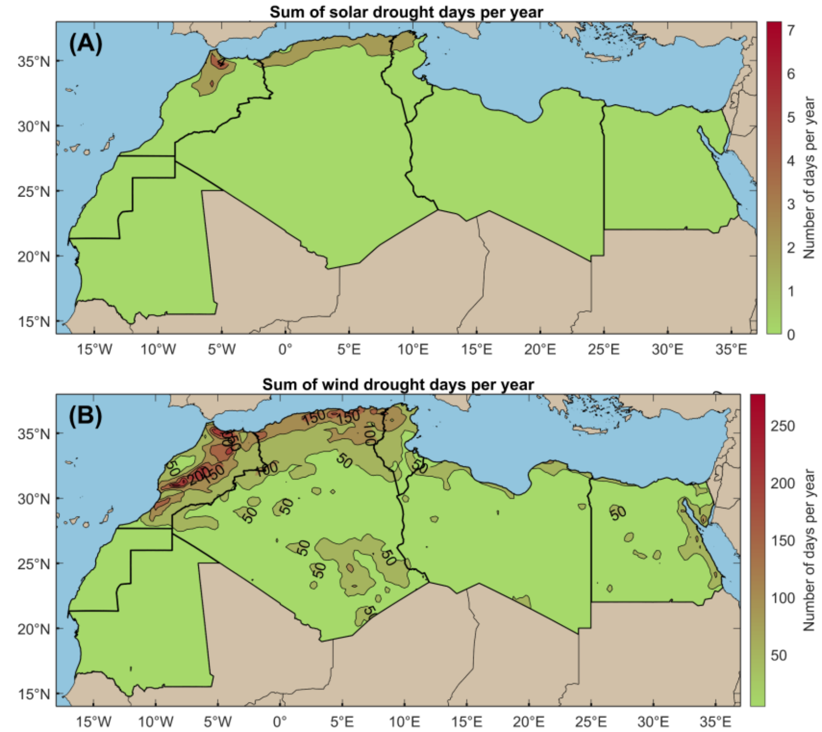


Fig. 4. The average number of energy droughts per year, based on daily time series from 1960 to 2020.

Individual energy droughts can vary in length. Figure 5 presents the most prolonged events recorded between 1960 and 2020. For solar resources, the energy droughts, on average, do not exceed two consecutive days, with the longest ones observed in northern Algeria, Morocco, and southern Egypt, with lengths exceeding four days. The situation is more extreme for wind energy due to the high variability of resources in the Atlas Mountains, where the energy droughts lasted as long as 80 consecutive days; in other words, the generation from wind turbines was below 20% of the multiannual average during an 80-days period. This behavior aligns with the area's low CF, as shown in Figure 1.

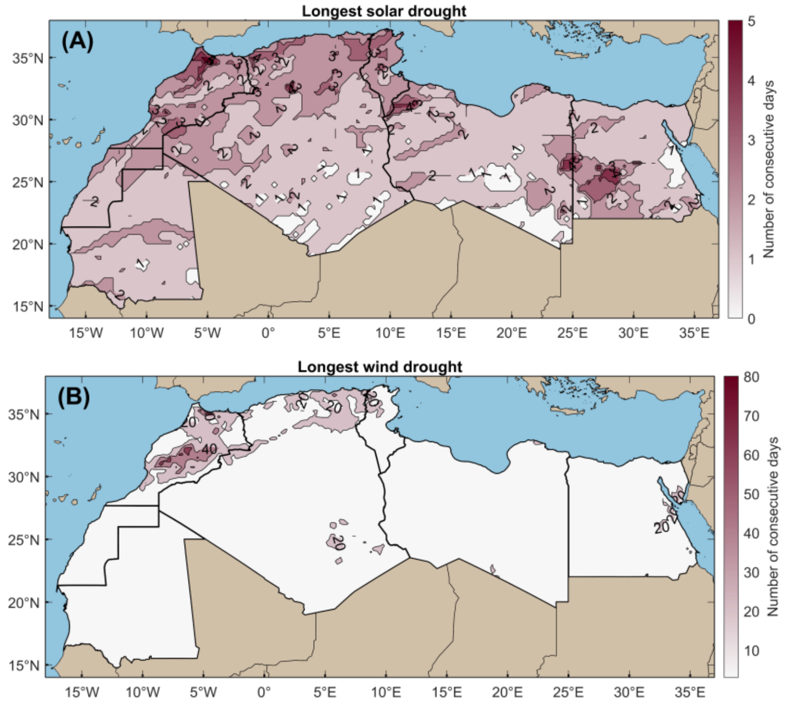


Fig. 5. Severe energy droughts recorded during the period 1960-2020. The color bar indicates the maximum number of consecutive days classified as energy drought days at each location.

The probability and occurrence of energy droughts vary throughout the year, mainly because of the RES seasonality, and are further influenced by interannual variability. This pattern becomes evident when establishing the energy drought threshold based on multiannual resource potential averages (threshold parameter equal to 0.2) without considering seasonal variations. For that purpose, Figure 6 displays the months where the highest number of energy droughts can be observed. For instance, in Algeria, solar energy droughts occur mainly from December to February, as also noted in the findings by Guezgouz et al. [3]. In contrast, energy droughts from May to August prevail in southern Mauretania and southern Libya. The situation is different for wind energy, with distinctive horizontal zones and most energy droughts occurring from September to December, and the northern coast of Algeria facing most of the energy droughts in August.

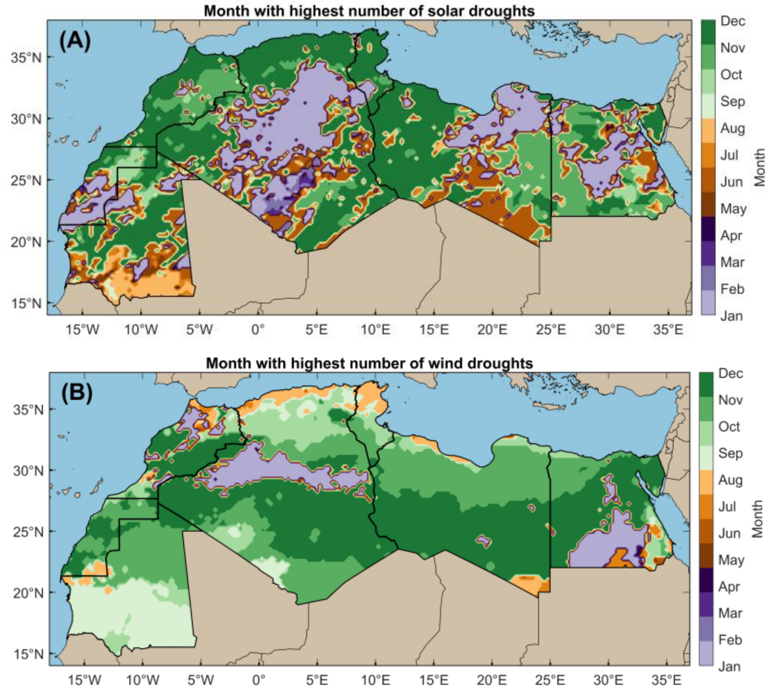


Fig. 6. Spatio-temporal distribution of severe energy droughts from 1960-2020.

3.3. Energy drought – sources of hybridization

Considering the previous results, it is relevant to explore further the characteristics of energy droughts in power generation from a hybrid generator. To address this, a random location was first modeled within the research area to highlight a relevant aspect of hybridization. The selected region has a relatively high solar PV capacity factor of 22% and a very high capacity factor of wind generation of 52.3%. However, the analysis of the energy droughts for the latter indicates a potential occurrence of 2167 such events for 61 years (i.e., 35 energy drought days on average per year). In the case of the solar generator, such events were not identified – confirming the region's considerably higher stability of solar resources. Suppose one combines those two energy sources as a hybrid generator, assuming the installed joint capacity will not exceed 1 kW (or any other constant number). In that case, the observed CF of the hybrid generator will start to decrease, as shown in Fig. 7. Adding an energy source with a lower CF (here solar PV) drops the hybrid system CF; however, it simultaneously reduces the frequency of the energy droughts, as shown on the left axis of Fig. 7. Please note that for each configuration of the hybrid system capacity structure, the energy drought's threshold was set in two ways:

- The threshold value is calculated based on the mean value of hybrid system generation (i.e., blue dots in Fig. 7 "threshold-hybrid").
- The threshold for each hybrid system configuration is taken from the generator characterized by the highest CF here, the wind one (blue stars of Fig. 7 "threshold-wind).

The interpretation of Fig. 7 is as follows: systems on the left are dominated by wind power, while those on the right are dominated by solar power. As stated earlier, adding solar power decreases the system's CF; however, it simultaneously and significantly reduces the system energy droughts. When the solar capacity exceeds 40% of the generator installed capacity, the energy droughts are: 1) as rare as one event per two years (i.e., if the threshold is based on hybrid generator performance), and 2) as frequent as almost ten events per year from the perspective of the wind generator only based threshold. The above results raise questions regarding the acceptable decline in CF, which usually drives the final cost of electricity delivered [55]. The earlier research on the sizing of the hybrid system indicates that the optimal capacity of generators depends on the objective function formulation, and the generation profile matches the load and investment costs of generators [56]. Since such analysis is outside the scope of this study, in this research, it is arbitrarily assumed that the acceptable decline in CF should not exceed 0.5 pp (k = 0.5, as indicated in section 2.3.5). Furthermore, to observe the benefits of hybridization, it is assumed that the threshold for energy droughts would be set based on the mean generation time series of the generator with the highest CF in each location.

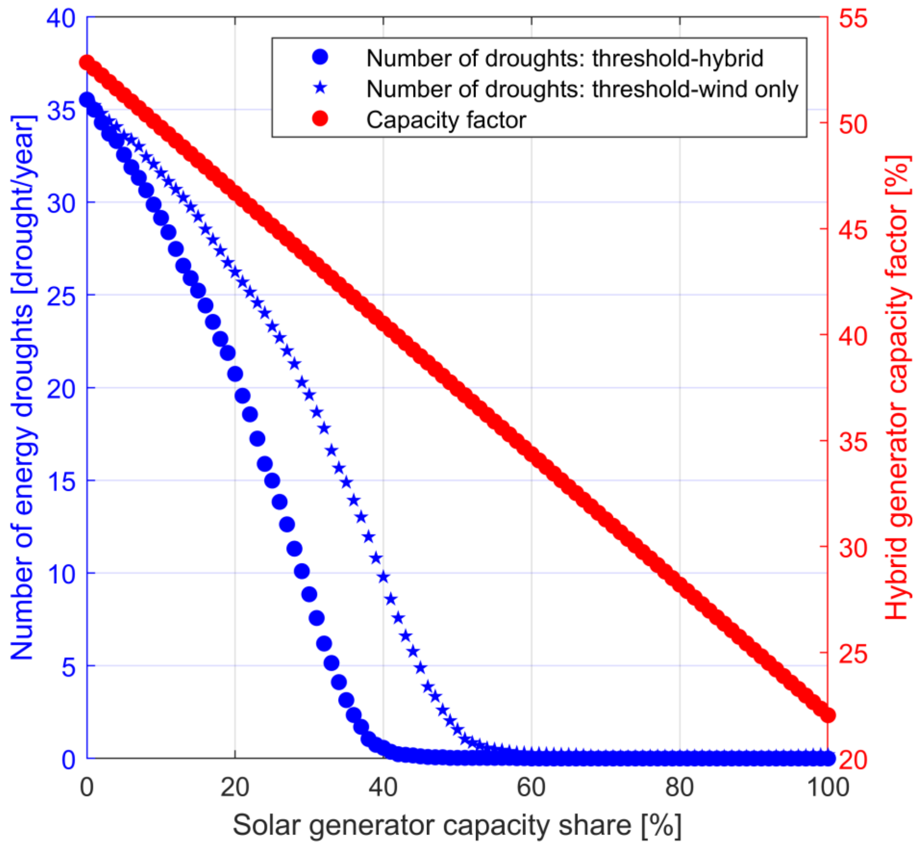


Fig. 7. Number of energy droughts per year (blue) and capacity factor (red) as a function of hybrid generator capacity structure (wind generator capacity = 100-solar generator capacity).

Fig. 8 displays the results of the above-presented procedure when applied across North Africa. Solar generation should be prioritized over wind power in most North African regions (top row left panel). However, wind energy should be the primary option in certain areas (i.e., mostly Western Sahara and western Mauretania) because of its higher CF in those regions. It is worth mentioning that areas where wind energy has higher CF also exhibit the highest frequency of energy droughts. When hybridization is considered (Fig. 8 middle row), one can observe a significant decrease in energy droughts (Fig. 8 middle row, right panel, and Fig. 8 bottom row). The region most prone to energy droughts remains the western part of North Africa, central Algeria, and southern Tunisia. Although the optimal option for many regions (Fig. 8 middle row, left panel) is a system purely solar or wind (no benefits from hybridization within the range of allowed decrease in CF), hybridization occurs mainly at the border between solar and wind-dominated regions. The detailed regional analysis revealed that hybridization makes it possible to reduce the number of energy droughts by 100% (for example, at the Algerian-Tunisian border) while losing only 0.5 pp of CF, thus indicating the complementary nature of solar and wind energy sources in certain regions.

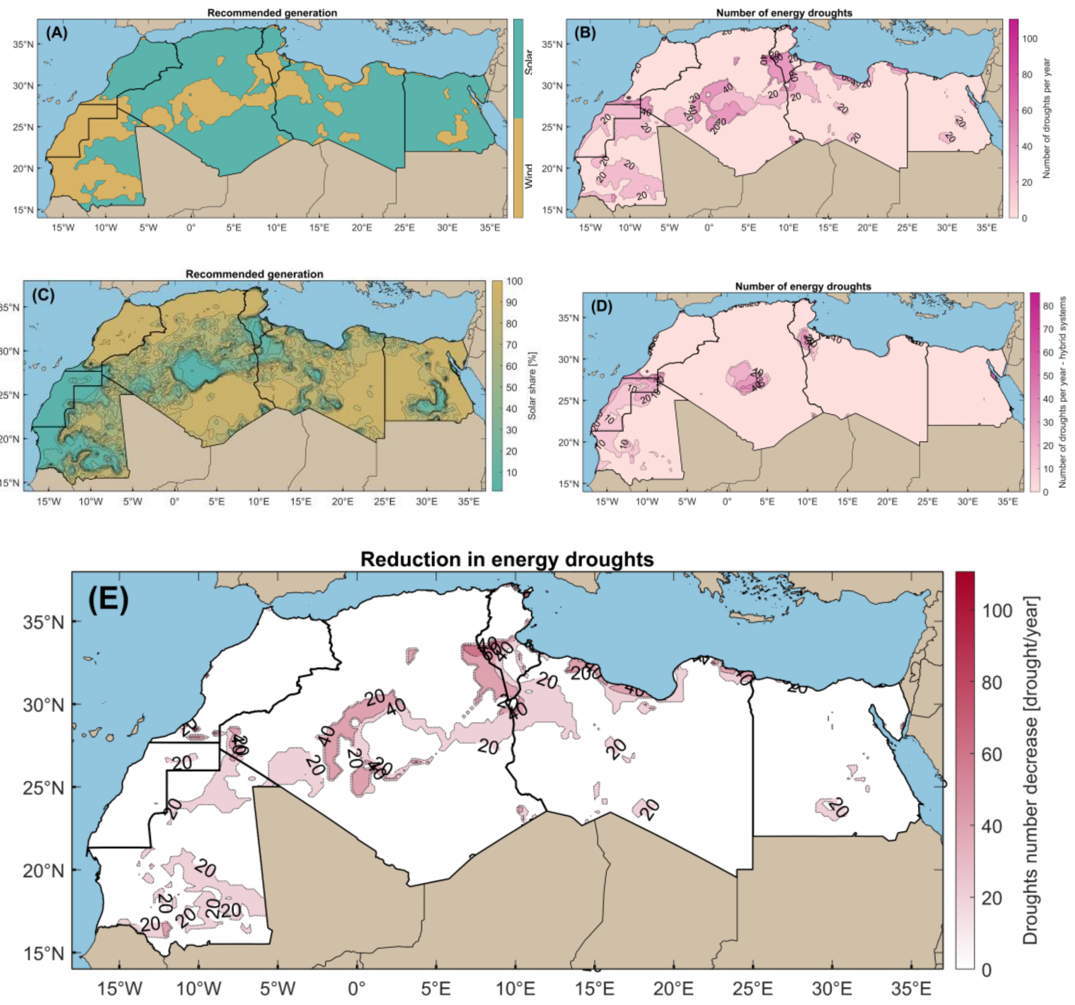


Fig. 8. Top row – recommended energy source considering local availability of resources; in each grid cell, the generator with the highest CF is regarded as a reference. Middle row – hybrid systems with changing solar-wind capacity ratio considering allowed 0.5 pp drop in capacity factor due to hybridization. Bottom row – reduction in many energy droughts comparing top and bottom rows results.

3.4. Relationship between hybrid system's energy droughts and NAO

The last part of the results section is dedicated to the potential relationship between the North Atlantic Oscillation and the occurrence of energy droughts in the case of the hybrid system. Fig. 9 presents the statistically significant correlation between the energy droughts for the hybrid system and seasonal (DJFM) and annual values of the NAO index. The analysis was performed for a hybrid system with solar-wind ratios as presented earlier in Fig. 8, top row left – namely the system structure ensuring minimal energy drought events while maintaining CF equal to the best-performing energy source. The only statistically significant correlations for the seasonal NAO were found for central Algeria, with a mean value of 0.28 and the highest not exceeding 0.39. In general, more significant correlations on the spatial scale were found for the annual NAO index, where positive NAO mode implies lower energy drought frequency in the Western Sahara and central Algeria (i.e., correlations as low as -0.56) and increased energy drought frequency in southern Tunisia (i.e., correlations up to 0.52). A similar exercise was conducted for hybrid systems with an optimized solar-wind ratio (Fig. 8 middle row, left panel). It can be observed that the signs of these correlations are strongly impacted by whether the system is wind- or solar-dominated (see Figures 2 and 3).

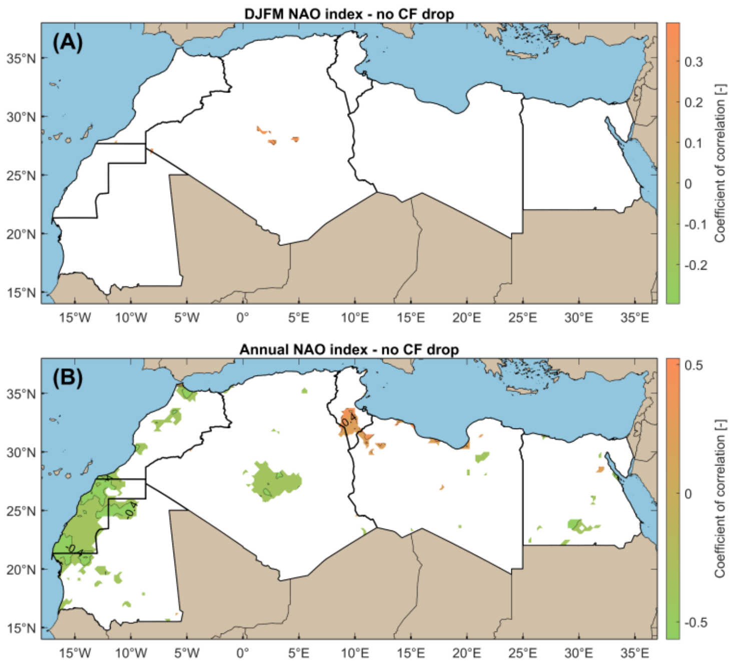


Fig. 9. Relationship between seasonal (DJFM) and annual values of NAO index for solar-wind hybrid system-related energy droughts. The solar-wind capacity ratio was adjusted to minimize the number of energy droughts while maintaining the system capacity factor of no less than the best-performing energy source in each location, as shown in Fig. 8, top left panel. Only significant correlations ($p < 0.05$) are shown.

The results revealed neither an existence of a significant change in the correlations in the spatial domain (i.e., there was no change regarding the region where significant correlations exist) nor concerning the observed values, which remained almost the same. The analysis proves a relatively weak correlation between the North Atlantic Oscillation and the frequency of energy droughts in North Africa. Regarding spatial distribution and intensity, the correlations are more evident for the annual NAO index than the seasonal one. System hybridization has no significant benefits regarding the correlation between NAO and their occurrence, even though hybridization enables a substantial reduction in energy drought events in individual regions, as shown in Fig. 9 (bottom row). These findings are helpful in the planning and transition to systems with widespread participation of renewable energies in this region, where fossil fuels currently predominate in its generation matrix [28]. Additionally, it contributes to the actions against global warming and to adapt to climate change, simultaneously contributing to SDG7 and SDG13.

4. Conclusions

This study examines the temporal and spatial variability of solar and wind resources in North Africa from the perspective of energy droughts and their connection with variations in the NAO index. This section will concisely answer the research questions based on the analysis and literature review results.

One of the purposes for assessing complementarity is to evaluate the ability of hybrid systems to reduce the number of energy droughts. In that case, such a situation has been observed in some areas of North Africa, particularly in central Algeria, Southern Tunisia, and the eastern border of Western Sahara. Despite the conservative assumption used in this research that a hybrid system should be characterized by a loss in CF of no more than 0.5 pp compared to a single source, the best-performing generator in each region revealed that the occurrence of energy droughts could be limited by as much as 100% (case of the southern Algerian-Tunisian border).

Solar energy droughts are most frequent in the northern parts of Algeria, Tunisia, and Morocco. In contrast, wind energy droughts are most frequent in the Atlas Mountains, southern Algeria, and eastern Egypt. Thanks to the stability (low temporal variability) of solar resources below 30 °N, the energy droughts are limited to none or a single event per year in many regions. Regarding energy drought length, solar energy droughts tend not to exceed five days (northern parts of Tunisia, Morocco, Algeria, and southwest Egypt). In contrast, wind energy droughts can be as prolonged as 80 days in regions with low resource potential (in the Moroccan part of the Atlas Mountains).

Although evident and moderately strong correlations have been identified between mean solar/wind energy resources availability and the NAO index, further analysis has revealed a lack of significant correlations between the NAO index and energy droughts apart from small parts of Western Sahara, central Algeria, and southern Tunisia (in the case of annual NAO index). The same observations were found for the hybrid solar-wind system, implying that the hybridization of these two variable sources not only has the potential to reduce the number of energy droughts but also makes the connection of global teleconnection (in this case, NAO) and the performance of renewable generators weaker and the energy system based on renewables have the potential to be more robust. Understanding how the hybridization of renewables could allow for more reliable and sustainable power systems aligns with SDG 7, which aims to increase the share of renewable energy in the global energy mix. Additionally, To summarize, this work attempted to quantify the spatial and temporal variability of solar and wind resources in North Africa from the perspective of energy droughts and global teleconnection in the form of the North Atlantic Oscillation. Although valid only for North Africa, the results come from a universal method that can be used for any other region. Future research should address the following limitations of the current work:

- The availability of renewable energy should be juxtaposed with the energy demand on the local, national, and North African levels. The two later consider the transmission system limitations and suggested development.
- Instead of analyzing only the past/historical data, future research should also look at long-term climate change projections, particularly those considering solar and wind resource availability from the different plausible CO_2 concentration pathways.
- The economic value of energy drought avoidance through hybrid systems should be assessed from the perspective of alternative solutions like long-term energy storage.

As a final remark, examining the complementarity between wind and solar power reveals that although adding solar power decreases the hybrid system's CF, it might considerably reduce energy droughts. This finding is relevant to SDGs 7 and 13, as it explores a way to optimize renewable energy resources, thereby promoting sustainable energy use and climate action.

5. Appendix

5.1. Wind and solar generation

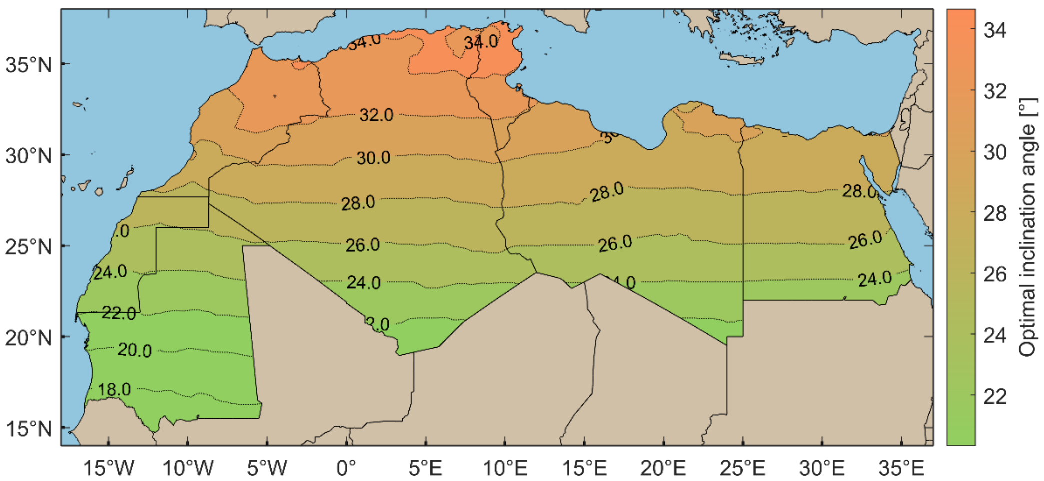


Fig. A1. Optimal PV modules inclination angle that maximizes the annual energy yield from the PV systems.

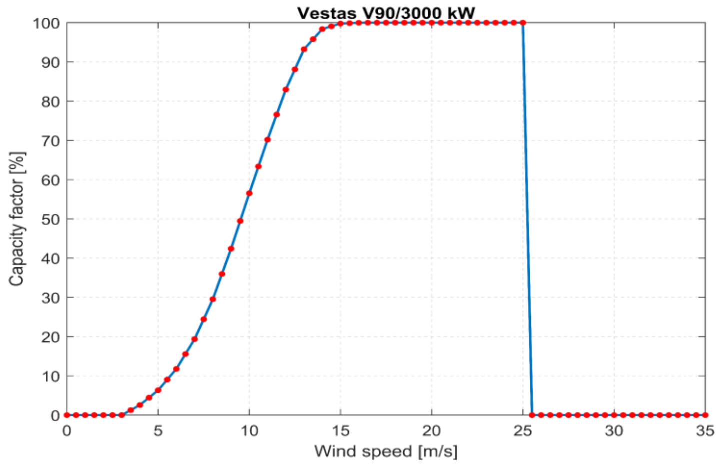


Fig. A2. Vestas V90/3000 kW power curve [57]. Dots represent data provided by the manufacturer; the line is a polynomial approximation, particularly for the cut-in-cut-off wind speeds.

5.2. Multiannual and seasonal variability

Averaged over the whole region, temporal and spatial solar (left) and wind (right) variability of generation regarding multiannual (1960-2020) mean value is shown in Figure A2. Spatial variability is introduced by shaded area marking +/- standard deviation from the mean. Regions' generation potential (local CF) is treated equally – meaning equal weight was assigned to each one of the individual grid nodes falling within the investigated region.

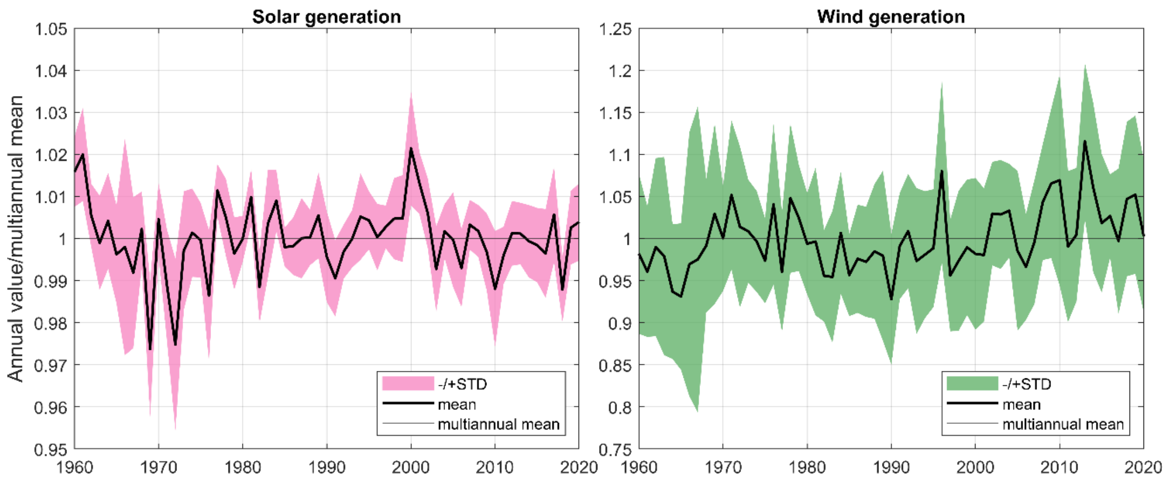


Fig. A3. Solar and wind resources multi-annual variability in the region.

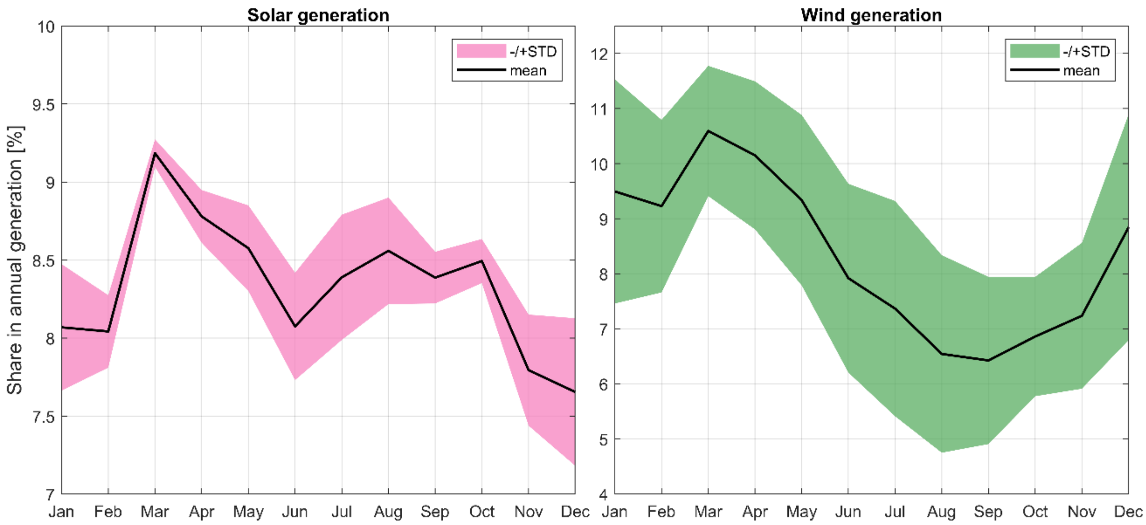


Fig. A4. Solar and wind resources seasonal variability in the region.

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