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Impacts of drought on electricity production, fossil carbon emissions, and air pollution in Europe

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ABSTRACT

Europe has experienced severe droughts that impacted electricity generation from both renewable and fossil sources. Yet, the response of national electricity systems to drought and the resulting impacts on emissions of CO₂ and air pollutants remain insufficiently understood. This study combines monthly historical electricity generation data (2017–2023) with runoff anomalies, used as a proxy for drought conditions, across 25 European countries. A regression-based counterfactual analysis is applied to quantify the country-level response of electricity systems to drier-than-average conditions. Estimated drought-induced changes in fossil-based generation are subsequently translated into emissions of greenhouse gases and air pollutants using fuel- and country-specific emission factors. We find that electricity generation from hydropower and other renewables is reduced during dry periods, while reliance on fossil fuels and imports increases. Drought induced 141 ± 35 million tonnes of CO₂-equivalent emissions between 2017 and 2023, corresponding to 31 % of the emissions that Europe could release by 2040 under its most ambitious climate goals. Emissions are mainly driven by increased use of natural gas (48 %), coal (22 %), lignite (21 %), and imports (8 %). In France and Portugal, drought-induced emissions account for around 10 % of total fossil-based electricity emissions. The estimated monetized social cost of these emissions is 26 billion USD. Emissions of air pollutants show an average increase of about 2.5 %, though they widely vary across countries. These findings underscore the need for targeted adaptation strategies to reduce the power sector's vulnerability to drought and to maintain progress toward energy security and decarbonization targets

1. Introduction

Drought affected about 40 % of the European land areas and more than 100 million people in recent decades [1]. Drought usually refers to periods of below-average moisture availability over large regions, often accompanied by high temperatures that can intensify its severity [2]. There is strong evidence that anthropogenic emissions of greenhouse gases (GHGs) increased the likelihood and intensity of droughts [1–3], which are expected to become more frequent and severe in the future [2, 4–6]. Under a global warming scenario of +4 °C above pre-industrial levels, average drought frequency is projected to increase by about 60 % in the Mediterranean, 40 % in the Atlantic and 10 % in continental Europe [3]. Limiting warming to 2 °C would reduce this impact but it

would still increase drought occurrence. Economic losses attributable to drought in Europe are currently estimated at € 9 billion per year and, in the absence of relevant mitigation actions, they are projected to exceed € 65 billion by 2100 [3]. The energy sector accounts for roughly 23 % of these damages, rising to as much as 50 % in regions heavily reliant on hydropower [3].

Warm and dry periods typically result in higher electricity prices and increased emissions [7–9]. Hydropower generation is highly sensitive to water availability [10–13]. During droughts, reduced hydropower output can be offset by increased fossil fuel generation, with associated increases in emissions of GHGs and air pollutants [7, 14–16]. Nuclear power is intrinsically a base load and it does not respond to near-term fluctuations [7]. However, changes in water availability can also

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impact other energy sources than hydropower. Droughts can decrease the availability of cooling water for thermal plants and increase risks that their water outlet temperatures are beyond regulatory limits, potentially causing reductions in power supply and operating efficiency [17,18]. Heatwaves during drought can negatively affect power supply from other renewable energy sources such as solar (because of lower efficiencies of solar panels at high temperatures) or wind (as wind speed is typically low during hot and dry spells), while increasing electricity demand (e.g., for air conditioning) and thereby putting stability of power supply under pressure [10,19,20]. Moreover, Europe's highly interconnected electricity markets mean that drought in one country can trigger increased cross-border electricity imports, transferring emissions elsewhere. Such transboundary effects have been documented in the US [14,21].

The complex interactions between drought, operability of hydropower and thermal plants, and connections to international grids make the attribution of GHG emissions and air pollution to drought data intensive and difficult to quantify. Previous research examined drought impacts at the level of individual power plants or single generation technologies, including hydropower [17,22] and thermoelectric units facing cooling-water shortages [19,23]. These studies provide insights into sensitivities and operational constraints at plant scale, but individual plant-level effects do not reveal how national electricity systems respond when multiple technologies and regions are simultaneously affected by drought. The aggregated response is the result of interactions between hydropower deficits, thermal plant constraints, renewable variability, demand changes, and cross-border electricity flows, and it remains poorly quantified for European countries. Most of the available studies are limited to a handful of US states, where electricity generation from natural gas and coal typically increases during droughts [7,9,14,24,25]. The corresponding increase in CO₂ emissions can be up to 12 % of the total emissions from the power sector [7], with associated increases in air pollution and related excess mortality [14]. Comparably lower insights are available in Europe, where the few analyses rely on a coarse spatial (i.e., clusters of countries) and temporal (i.e., annual) resolution [26,27]. In years with remarkable droughts and heatwaves, the annual average capacity factor of hydropower in Europe is found to decrease by 6.5 % and the one of thermal plants to increase by 2.3 % [26]. A combination of adverse weather conditions is identified as a driver of low hydropower output during periods of peak electricity demand in five European countries [12]. Despite the increasing evidence of the vulnerability of the European power system to drought [27], knowledge on how the power mix in each country responds to dry conditions, how import/export flows of electricity are affected, and how emissions of CO₂ and air pollutants vary, is still limited. As extreme events are projected to increase in frequency and intensity under climate change, and Europe is progressively transitioning to higher shares of renewable energy sources in its power supply mix, this knowledge gap prevents the identification of adaptation strategies that can strengthen the resilience of the power system and the achievement of environmental and energy security targets.

This study combines historical electricity data with indicators of monthly runoff anomalies and country-specific emission factors for fossil power plants to quantify how dry conditions alter the electricity generation mix in 25 European countries, and how these shifts translate into changes in emissions of GHGs and air-pollutants. Daily power generation data over a seven-year period (2017–2023) are retrieved from the European Network of Transmission System Operators for Electricity (ENTSO-e) [28]. Runoff anomalies are used as proxy for drier than average conditions and are derived from the ERA5-Land reanalysis dataset [29]. First, an approach based on percentile stratification analysis is used to show how the electricity production mix and other variables change under different hydrological conditions in each investigated country. Then, a counterfactual analysis based on statistical regression is employed to estimate the changes in fossil power production and electricity imports caused by dry conditions. Country- and

fuel-specific emission factors reflecting the average technology mix in each country are finally used to estimate drought-induced life-cycle emissions of GHGs and air pollutants from fossil power plants in Europe [30,31].

2. Methods

This section is structured as follows (Fig. 1). We first describe the method used to characterize drought conditions, followed by the procedures for extracting and processing electricity data. We then introduce the analytical approach underlying the percentile analysis and the regression-based counterfactual approach. Next, we detail the methods used to estimate emission factors for greenhouse gases and air pollutants, as well as the associated social costs and health impacts, and describe the uncertainty analysis. Key input datasets, numerical results, statistical performance metrics, and additional methodological details are provided in the Supplementary Information (SI). A demonstration code to reproduce the regression-based counterfactual analysis is available as a separate attachment.

2.1. Drought characterization

In line with previous studies [7,14,16], we define drought as periods of drier than average conditions characterized by negative cumulative runoff anomalies. Runoff refers to water from rainfall, melting snow, or deep in the soil that does not remain stored in the soil but drains away either over the surface (surface runoff) or under the ground (sub-surface runoff). Runoff is measured in meter (m) and it is a key hydrological variable that affects the recharge of rivers and reservoirs that are the main water sources of the electricity sector [32]. Several drought indicators exist, including meteorological indices and soil-moisture-based metrics. Previous work has shown that runoff anomalies more accurately capture hydrological drought conditions affecting hydroelectric generation than meteorological indices [7,14,22]. In our study, we further tested the recently introduced Daily Evapotranspiration Deficit Index (DEDI) [33], but it exhibited weaker correlations with hydropower production than runoff anomalies across major hydropower-dependent countries (Table S1).

Gridded data of total runoff for Europe were downloaded from ERA5-Land, a reanalysis dataset from the European Centre for Medium-Range Weather Forecasts (ECMWF) with a spatial resolution of 0.1 degree that combines model data with observations [29]. Data of daily average 2 m air temperature and wind speed (as the combination of the zonal and meridional near-surface (10 m) wind speed) are retrieved from the same dataset. We created time series of monthly total runoff anomalies by subtracting the respective monthly value in our assessment period (2017–2023) to the average value from a reference period (1980–2023) for each month of the year and grid cell, aggregating the results at a country level. The timeseries of runoff anomalies quantifies the deviations from the historical mean conditions that occurred in each month, with negative values indicating drier periods and positive values wetter periods.

2.2. Electricity data

Electricity data are sourced from the “Actual Generation per Production Type” dataset of the European Network of Transmission System Operators for Electricity (ENTSO-e) [34], which contains power generation timeseries for individual power plants in most European countries [35]. The data were downloaded at an hourly resolution per electricity source for the period 2017–2023 and aggregated to monthly values to match the temporal resolution of the runoff data and because hydrological drought mostly evolves on timescales of multiple weeks, affecting reservoir inflows, catchment storage, and hydropower output accordingly. As discussed below, monthly runoff anomalies show robust correlations with observed hydropower anomalies, and compensatory

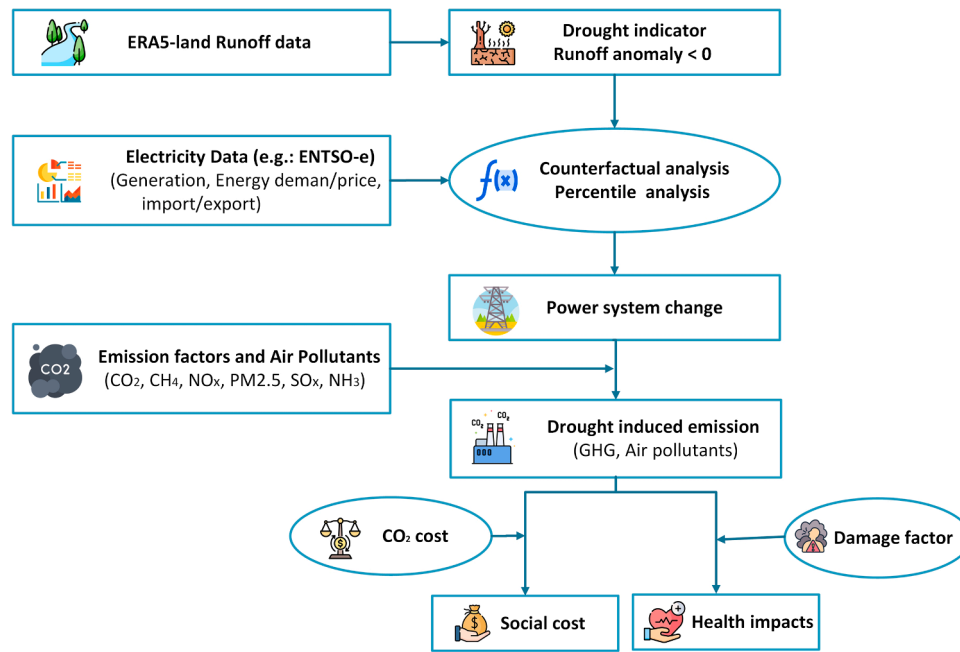


Fig. 1. Diagram illustrating the main datasets and analytical steps used in the study. Hydrological runoff data are processed to derive time series of monthly negative runoff anomalies, which serve as indicators of drier-than-average conditions. These indicators are combined with historical electricity generation data through percentile-based analysis and counterfactual regression to identify drought-induced changes in national electricity systems across Europe. The resulting changes in power production are then coupled with fuel- and country-specific emission factors to quantify variations in greenhouse gas and air-pollutant emissions. Finally, these emission changes are translated into societal impacts, expressed as social costs associated with climate change and adverse health effects. All icons are retrieved from www.flaticon.com.

fossil generation shifts similarly occur on multi-week scales [7,14]. Shorter-term operational fluctuations introduce variability that is frequently connected to market dynamics and fluctuations in demand, and the use of a daily resolution would make the identification of the drought effects less robust. The analysis period is constrained by the initial availability of the ENTSO-e generation data for all 25 countries, as data before 2017 are scarce and unreliable for several countries.

ENTSO-e data are provided for 21 energy sources. Hydropower generation is aggregated by summing power production from the three listed types (hydropower from run-of-river and poundage, water reservoirs, and pumped storage). Wind power (onshore and offshore), solar power and biofuels are aggregated as “other renewables” when needed. The category “other” is unspecified and typically covers a small share of country power mixes (less than 1 %) and it is excluded from the analysis. An exception is Italy, where this category corresponds to about 12 % of the national power production. As this is mostly connected to electricity from natural gas [30], it is added to the natural gas. For countries with multiple market price areas, such as Norway, Denmark, Sweden and Italy, data have been aggregated at a country level.

Import and export data are collected from ENTSO-e at the granular level of the scheduled bilateral commercial flows between individual countries or price areas, and not only at the aggregated country level. This allows a better understanding of the electricity flows and needs of electricity of different countries, under different market conditions. For Bulgaria, Hungary, Greece, Romania, Estonia, Latvia, and Lithuania, ENTSO-e provides only net import data (balance of imports and exports) instead of detailed bilateral commercial flows. For these countries, we use the complete net-import timeseries directly and do not apply imputation, as the regression model (see below) requires the net import variability and not partner-specific allocations. An overview of the average imports of electricity per country is shown in Table S2. When electricity is imported to one country from another, the carbon intensity of this electricity flow only considers the emissions of the fossil-based power, applying the same proportion of the national power mix to allocate the total amount of power exports to the individual fossil fuel

types. The power prices timeseries come from the Nominated Electricity Market Operator (NEMO), and correspond to spot prices, i.e., the purchase price that electricity supply companies pay and it is determined based on supply and demand of electricity exchanges.

2.3. Percentile analysis

An approach based on percentile stratification analysis is used to explore how the average electricity production mix and other parameters vary under different hydrological conditions. This approach is purely data-driven and model-independent. Specifically, we group the timeseries of runoff anomalies into discrete intervals using selected percentile thresholds (5th, 10th, 50th, 90th, and 95th percentile), and the percentile threshold groups are defined as follows: 0th – 5th, 0–10th, 0th – 50th, 50th – 100th, 90th – 100th, and 95th – 100th. We then compute the average electricity generation mix (as well as the electricity price and demand) from the data that correspond to each percentile group. This stratification allows us to assess how the power mix responds to varying degrees of dryness or wetness, using percentiles as a consistent, distribution-based measure of climatic deviation. Power production in periods with runoff anomalies lower than the 10th percentiles can be interpreted as electricity generation during particularly dry conditions (and those below the 5th percentile as extremely dry), and under severely wet conditions in periods of runoff anomalies higher than the 90th percentiles (or extremely wet when above the 95th percentile). The electricity production mix, demand, and price around the 50th percentiles (or between the 10th and the 90th percentiles) can be interpreted to represent moderately dry and wet conditions if falling below or above the 50th percentile, respectively. The mean values (with standard deviation) of the power mix for the various percentile intervals are shown in Table S3 for all the investigated countries.

2.4. Regression-based counterfactual analysis

2.4.1. Model settings and main application

Since electricity production from various sources is simultaneously influenced by changes in demand, electricity and energy prices, and renewable energy availability, and because these factors vary by country, a counterfactual analysis based on a regression model is used to isolate the changes that occur in fossil fuel power production in each country under dry conditions, while holding other variables constant.

First, aligning with previous studies that investigated the effects of drought on power production changes [7,14,16], a regression model is designed to represent the observed total fossil power generation (from natural gas, coal, oil and lignite) in each month ($y_1, \dots, y_n$, where n is the total number of months available), as

$$\log(y_i) = \beta_1 x_i + z_i^T \beta_z + \phi_i^T t_i + \phi_i^T \beta_\phi + \epsilon_i, i = 1, \dots, n, \quad (1)$$

where x_i is the monthly runoff anomaly with the associated coefficient β_1 , z_i is the vector including the other variables that can influence the fossil power generation (including log of power demand, net import, log of other renewable power generation, log of nuclear power generation, log of gas, coal and carbon prices) with the coefficient β_z , t_i is year and β_t the associated coefficient, ϕ is a length 12 indicator vector for each month of the year and used together with the coefficient β_ϕ to capture the monthly variation, and $\epsilon_1, \dots, \epsilon_n$ are independent and Gaussian distributed residuals with variance σ^2 .

This regression framework is designed to include several controls to capture the main drivers of system behavior and absorb major structural trends and market dynamics during the assessed period, thereby isolating the effects of dry conditions. The controls include: changes in power generation from fossil sources, other renewables and net imports; demand fluctuations, explicitly controlled through the demand variable in each country that accounts for changes driven by consumption patterns; market conditions, through the inclusion of fossil fuel prices and CO₂ price that account for short-term market dynamics influencing dispatch decisions independently of hydrological conditions; structural variations captured through monthly indicators and long-term trend captured by t , which control for recurring monthly patterns in system operation and absorb broader system-wide changes over the assessment period (such as those resulting from policy and regulatory developments). Importantly, because the inclusion of long-term trends captures slow-moving or stepwise changes such as gradual coal phase-out and renewable support policies, these factors do not bias the estimated drought sensitivities. The derived counterfactual analysis based on regression models reflects the power system response to dry conditions within the existing policy, market, and technological conditions of the considered study period in each country.

The regression is applied in each country and for each type of fossil power source, resulting in more than one hundred model executions (25 countries for 4 types of fossil fuels, plus analysis of imports and delay effects). In each case, the model is adapted to the national conditions by removing from the equation the log of the electricity source that is not produced in the country and by deleting the variable that shows a signal of co-linearity with the runoff anomalies after application of the multicollinearity test. For example, hydropower is not included in the model since it frequently correlates with runoff anomalies. Before performing the regression, outliers, defined as the elements that are larger than three scaled MAD from the median, are deleted. The scaled MAD is based on the inverse complementary error function.

Then, we use the ordinary least square method to estimate the coefficients in (1), and find the predictor

$$\hat{y}(x, z, t, \phi) = \exp(\hat{\beta}_1 x + z^T \hat{\beta}_z + \hat{\beta}_t t + \phi^T \hat{\beta}_\phi). \quad (2)$$

Only models that passed the significance test (p-values smaller than 0.1) for both the models and the coefficients β_1 (i.e., the one for the runoff) are considered for further analysis (Table S4-S7).

The predictor is related to the true observation as

$$y_i = \hat{y}(x_i, z_i, t_i, \phi_i) \exp(\hat{\epsilon}_i), i = 1, \dots, n. \quad (3)$$

A counterfactual response $y_i(x)$ of what the response would be if x_i were changed to x while the other covariates are kept constant is then considered,

$$\begin{aligned} y_i(x) &= \hat{y}(x, z_i, t_i, \phi_i) \exp(\hat{\epsilon}_i) = \exp(\hat{\beta}_1(x - x_i)) \hat{y}(x_i, z_i, t_i, \phi_i) \exp(\hat{\epsilon}_i) \\ &= \exp(\hat{\beta}_1(x - x_i)) y_i. \end{aligned} \quad (4)$$

Finally, we have

$$y_i(0) = \exp(-\hat{\beta}_1 x_i) y_i \quad (5)$$

as the hypothetical fossil power generation to be observed if runoff anomalies (x in Eq. (2)) were 0. The net changes in fossil power generation due to the runoff anomaly can thus be obtained as

$$\Delta y_i = y_i(x_i) - y_i(0) = (1 - \exp(-\hat{\beta}_1 x_i)) y_i \quad (6)$$

To clear the influence from potential outliers in the estimates, months where the estimated drought-induced monthly power production change for each type of fossil fuel exceed 30 % of the total power generated from that fuel in each month are removed from the analysis. This is a conservative estimate as none of previous studies reported drought impacts on national fossil-based power generation changes to be above 15 % [7,26]. This affects a limited number of estimates (mostly for oil, for which model accuracies are relatively lower), and the use of alternative thresholds (such as 20 % or 50 %) does not significantly affect the results of the analysis.

2.4.2. Analysis of imports

The same analysis is repeated for estimating the impact of runoff anomalies on imported electricity. In this case, only countries with explicit bilateral flows are considered, while those with only net exchange data are excluded to avoid introducing artificial assumptions and bias the estimated drought responses. For investigating changes on electricity imports during dry conditions, the same steps as given in Eq. (1) to Eq. (6) are followed, but in Eq. (1) y is the log of import and Z is updated with log of power demand, log of other renewable power generation sources, log of nuclear power generation, log of gas, coal and carbon prices, the year t , and . Both the multicollinearity test between runoff anomalies and the other variables and the significance test (with p-value smaller than 0.1) for models and coefficients are performed (Table S4 and S5).

In the emissions analysis, given that emissions are geographically tied to the country of generation, changes in imported electricity are reattributed to the exporting countries by applying an inverse allocation of the bilateral import-related power changes (Table S2). Country-level electricity mix profiles are used to estimate the share of exported electricity that is sourced from fossil power plants (Table S8).

2.4.3. Analysis of delay effects

A similar approach is used to estimate the delay effects of drought on power production from fossil plants. This analysis is performed only in the countries with a share of hydropower generation from reservoirs higher than 3 %, such as France, Portugal, Austria, Greece, Spain and Bulgaria. Romania is removed due to poor data quality, and other countries without an appreciable fossil power production in their energy mix are also excluded (e.g., Norway and Switzerland). Hydropower production from run-of-river is excluded because it generates electricity from the flow of a river, with minimal or no water storage in a reservoir. Its response to drought is thus dependent on immediate water flows and it is less sensitive to delay effects [11,22]. Similarly, water availability mainly affects operability of thermal plants during drought events [19, 36], so that direct effects of drought on fossil power production are essentially dependent on the possible prolongation of the negative

effects on hydropower production from reservoirs. For this analysis, the method described in Eq. (1) to Eq. (6) is repeated, but with runoff anomalies from one to three months ahead. For example, in the investigation of one-month delay effect, the runoff anomalies in January 2018 are assessed against potential impacts on fossil fuel power production in February 2018. As in other cases, only models and coefficients passing the significance test are used for further analysis (Table S6 and S7). Delay effects are limited to a 3-month window because the correlation between runoff anomalies and reservoir hydropower production deteriorates rapidly beyond this horizon. Longer-term or inter-seasonal hydrological mechanisms are highly context-specific and affect production plants heterogeneously.

2.5. Emission factors of GHGs and air pollutants

The life-cycle emission factors from supply and combustion of fossil fuels in power plants are country-specific and are collected from multiple sources: the web-based application Electricity Maps [37], a detailed study of emission factors from European power plants [30], and the life-cycle inventory database ecoinvent v.3.9.1 [31]. The procedure is described in detail in the Supplementary Text 1. In general, life-cycle emissions are less than 10 % of total emissions, as direct emissions from fuel combustion are the main driver of climate impacts. The resulting emission factors (mean and uncertainty ranges) used to estimate the carbon intensity of electricity production from different fossil sources and countries are shown in Table S9. The latest characterization factors from the IPCC are used to aggregate emissions of different GHGs (CO₂, CH₄ and N₂O) to common units using the Global Warming Potential (GWP100) [38]. The analysis only considers emissions from fossil fuel plants as the other power sources do not induce emissions of fossil fuels during operation, only for their installation and dismantling. Drought periods are thus not responsible for increased emissions from their operations.

Emissions of air pollutants are specific to country and type of fossil fuel, and are collected from the ecoinvent 3.9.1 database [31]. These emissions represent direct emissions to air from fossil-based power plants for key pollutants such as particulate matter of 2.5 µm or smaller (PM_{2.5}), sulfur dioxide (SO₂), nitrogen oxides (NO_x), and ammonia (NH₃). The emission factors are specific to each power generation technology and country. NH₃ emissions only occur in oil-fired power plants. For countries without specific power generation processes, emission factors averaged from the other available European countries are used. Emission factors for air pollutants by source and country are shown in Table S10. The health effects of cardiovascular and respiratory diseases caused by emissions of air pollutants are quantified in Disability-Adjusted Life years (DALYs), a measure of disease burden expressed as numbers of years of full life lost due to disability and lost to early death. DALY is an estimate of how many years of healthy life are lost due to cardiovascular and respiratory diseases from emissions of air pollutants, encompassing five mortality causes: chronic obstructive pulmonary disease, ischemic heart disease, lower respiratory infections, lung cancer, and stroke. This metric is policy relevant as it allows a comparison with health issues and diseases induced from emissions from other sectors, and it is transferable to monetary costs for private and public entities. To calculate the human health impacts from each pollutant, we used the method recommended by the UNEP-SETAC Life-Cycle Initiative to harmonize practices of studies on pollution from fine particulate matter and enhance inter-comparability [39,40], which is detailed in Supplementary Text 2.

The social cost of carbon is used to monetize the impact of GHG emissions. This is a highly influential metric that shows how changes in climate are likely to affect human wellbeing and it is used to support decision-making by governments and environmental agencies. The recent estimate of 185 USD per tonne of CO₂ (44–413 USD per tonne of CO₂ as the 5 %–95 % range) at a near-term risk-free discount rate of 2 % is used in the analysis [41]. See Supplementary Text 2 for additional

explanations.

2.6. Uncertainty analysis

To better understand the sources of uncertainty in our emission estimates, we conduct two Monte Carlo analyses in parallel. In the first, we vary the estimated power changes while keeping emission factors fixed at their mean values. In the second, we vary the emission factors while holding the estimated mean power changes constant. Running these two experiments separately allows us to isolate the contribution of each component to the overall variability of drought-induced emissions.

Regarding the variability in the drought-induced power changes estimated from the regression model (Eq. (1)), the standard error for the estimated coefficients of runoff anomaly in each application of the regression model is used to define the range of the samples for the Monte Carlo runs, using a triangular distribution with a peak at the estimated coefficient and boundaries at two standard errors from the peak. We generate 10 000 simulations of the difference in Eq. (6) by randomly selecting a value within this range, and then calculate the pooled statistics for each type of fossil power source and country, with mean values and uncertainty ranges representing two standard deviations. The aggregated ranges at a European level are expressed as the sum of the lower and upper bound of each case, with lower/upper bound equal to mean $\pm$ two-standard deviations. These ranges are then combined with the mean estimate of emission factors of CO₂ and other pollutants to estimate drought-induced emission changes.

Regarding the investigation of the uncertainty induced by variability in emission factors, the interval ranges are combined in a Monte Carlo uncertainty analysis with the mean estimate of power changes during drought conditions in each country and for each type of fossil source. The Monte Carlo consists of 10 000 iterations and uses the specified uncertainty ranges of the emission factors to define a triangular probability distribution centered on the mean value. For each iteration, an emission factor is randomly drawn from this distribution and combined with the corresponding power-generation changes. The results from the 10 000 simulations are then aggregated to obtain the associated uncertainty interval, expressed as the two-standard deviation range.

3. Results

3.1. Sensitivity of the European power mix to drought

Between 2017 and 2023, hydropower accounted for approximately 15.5 % of total electricity production across the European countries investigated, and fossil-based thermal power contributed around 33 % (Fig. 2). Among fossil fuels, natural gas covered 19 % of the production, coal and lignite about 7.5 % each and oil about 0.6 %.

Changes in electricity systems under varying hydrological conditions are investigated using a percentile stratification analysis where runoff anomaly time series are grouped into discrete intervals defined by selected percentile thresholds, and average electricity-related parameters are estimated for each interval. The power mix is sensitive to runoff conditions in most of the countries (Fig. 3; see Table S3 for the mean values and standard deviation ranges). In general, the share of hydropower in the national power generation is reduced when monthly-mean runoff anomalies are negative (usually below the 50th percentiles), which denote drier than average conditions. In this case, the share of fossil power is usually higher. In wetter conditions (runoff anomalies above the 50th percentiles), the relative importance of hydropower increases and the reliance on fossil fuels gradually decreases. This trend is mainly observed in countries where both hydropower and fossil-based electricity are a non-negligible fraction of the power mix. For example, the share of hydropower in Spain increases from about 10 % with runoff anomalies below the 10th percentiles up to about more than 20 % when they are higher than the 90th percentiles, while fossil power production shows an opposite trend (from 32 % down to less than 22 %)

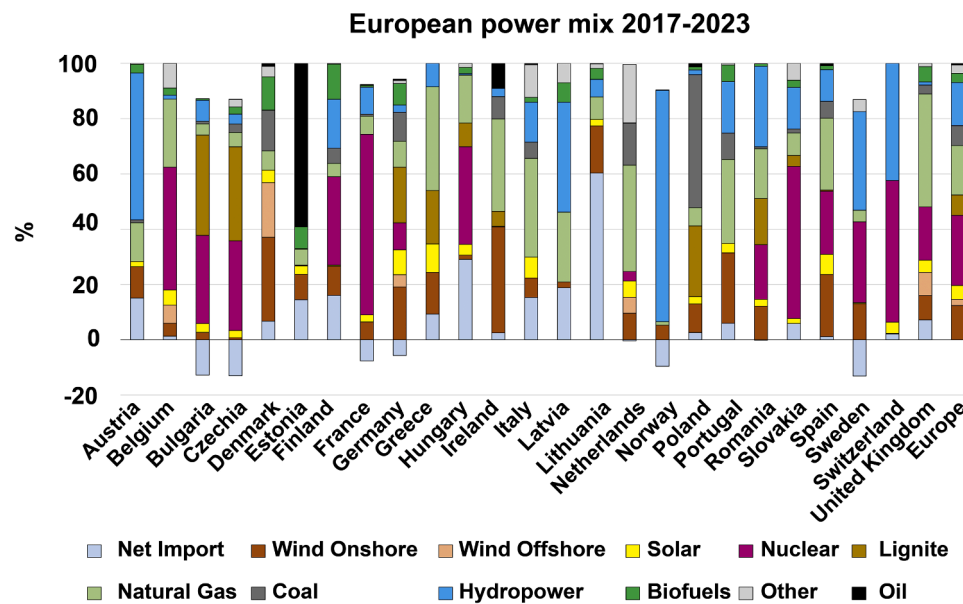


Fig. 2. Average electricity mixes of the investigated European countries for the period 2017–2023. Negative values of “net import” indicate exports.

(Fig. 3a). In Portugal, the share of hydropower can be as low as 11 % in dry periods and beyond 50 % in wet periods (with an average of about 19 %), while the share of fossil power ranges from more than 40 % to about 20 % (Fig. 3b). In both countries, periods of negative runoff anomalies coincide with high spot electricity prices. Similar declines in hydropower shares are observed in Italy, Slovakia, Greece, Finland, Sweden, France, and Austria, among others. Increasing shares of fossil power production at negative runoff anomalies are found in Spain, Portugal, Finland, Germany, France, United Kingdom, and the Netherlands, among others.

An opposite trend, i.e., reduced shares of fossil power during dry periods and higher shares in wetter periods, occurs in Slovakia, Romania, Estonia, Poland, and Greece. In all these countries, the relative decrease in hydropower and fossil power during dry periods is compensated by increased imports. For example, net electricity imports represent more than 20 % of the national power mix during the driest conditions in Greece, whereas they are between 8 % and 10 % at normal times and the country even turns to be a net exporter (−1.83 %) in the most wet conditions (Fig. 3c).

Changes in the power mix during dry periods are also observed in countries with little or no hydropower production. In Germany, the share of fossil-based electricity is higher at negative runoff anomalies (Fig. 3d). This increase is mainly due to higher exports and reduced relative shares of electricity from other renewable sources (mainly wind power). The increased exports are probably driven by the demand in neighbor countries that are simultaneously exposed to drought and that have lower capacity and flexibility in their power mix to compensate domestic hydropower reduction. Austria and the Baltic countries indeed turn from being a net exporter of power in wet conditions to a net importer under dry conditions. In Greece and Germany, negative runoff anomalies and lower average electricity prices co-occur. In the United Kingdom (Fig. 3e), the Netherlands (Fig. 3f), and Denmark there is nearly no hydropower production, but the share of fossil power still increases at negative runoff anomalies, essentially to balance a decline in the electricity supply from other renewables. Droughts are usually associated with high pressure conditions where temperatures are high and wind speed is low [42–45], thereby affecting energy production from wind and reducing efficiency of solar power [42,46]. Efficiency of solar energy production also declines with wildfire smoke, which often coincides with drought [47,48]. During our study period, times of low runoff largely overlap with periods of higher temperatures and lower

wind speed (Table S11). There is a negative correlation between runoff and average daily temperatures in 17 out of 25 countries, with a significant correlation coefficient in 14 of them. Similarly, a positive correlation between runoff and daily average wind speed occurs in 19 countries, and in 13 of them the correlation coefficient is significant. Among the countries with a relatively strong correlation between runoff and temperature/wind speed there are the United Kingdom, the Netherlands, Denmark, and Germany. While dry conditions do not usually correspond to periods of increased power demand, there is a tendency to observe high electricity spot prices in presence of negative runoff anomalies in several countries (Hungary, Italy, Portugal, Romania, Spain and Switzerland) (Figure S1).

The impact of drought on hydropower is also evident when inspecting power generation in presence of main individual drought events (Figure S2). The drought in 2022 was one of the most severe in recent history and affected large parts of Europe, including the Iberian Peninsula, France, Italy, and Germany [49,50]. Relative to the mean hydropower production in the period 2017–2023, hydropower output in 2022 shows an average decrease of −1.02 TWh in Italy (−31 %), with a reduction peak of −1.90 TWh in March (or −58 %). In Portugal, the 2022 average hydropower anomaly has been −0.30 TWh, with a negative peak of 0.71 TWh in October (−93 %). In summer 2018, two prolonged high-pressure events led to persisting dry conditions and heatwaves over Scandinavia [43,51]. The 2018 hydropower production in Sweden shows a mean decline of 0.49 TWh (−9 %), with the highest reduction in July (−2.46 TWh, or −43 %).

Runoff anomalies are usually positively correlated with hydropower production, meaning that hydropower tends to decrease when conditions become drier (Figure S3). The correlation coefficient is usually significant in countries where hydropower is a relatively high share of the power mix. Runoff anomalies and fossil power production show more diversified correlations. Most of the countries are negatively correlated, but in some (e.g., Poland and Slovakia) there is a significant positive correlation. Relatively less robust correlation coefficients are found between runoff anomalies and electricity imports, with only a few countries showing a significant positive or negative correlation.

3.2. Drought-induced power production changes

Because of the simultaneous multiple drivers at play, a regression model based on counterfactual analysis is used to attribute power

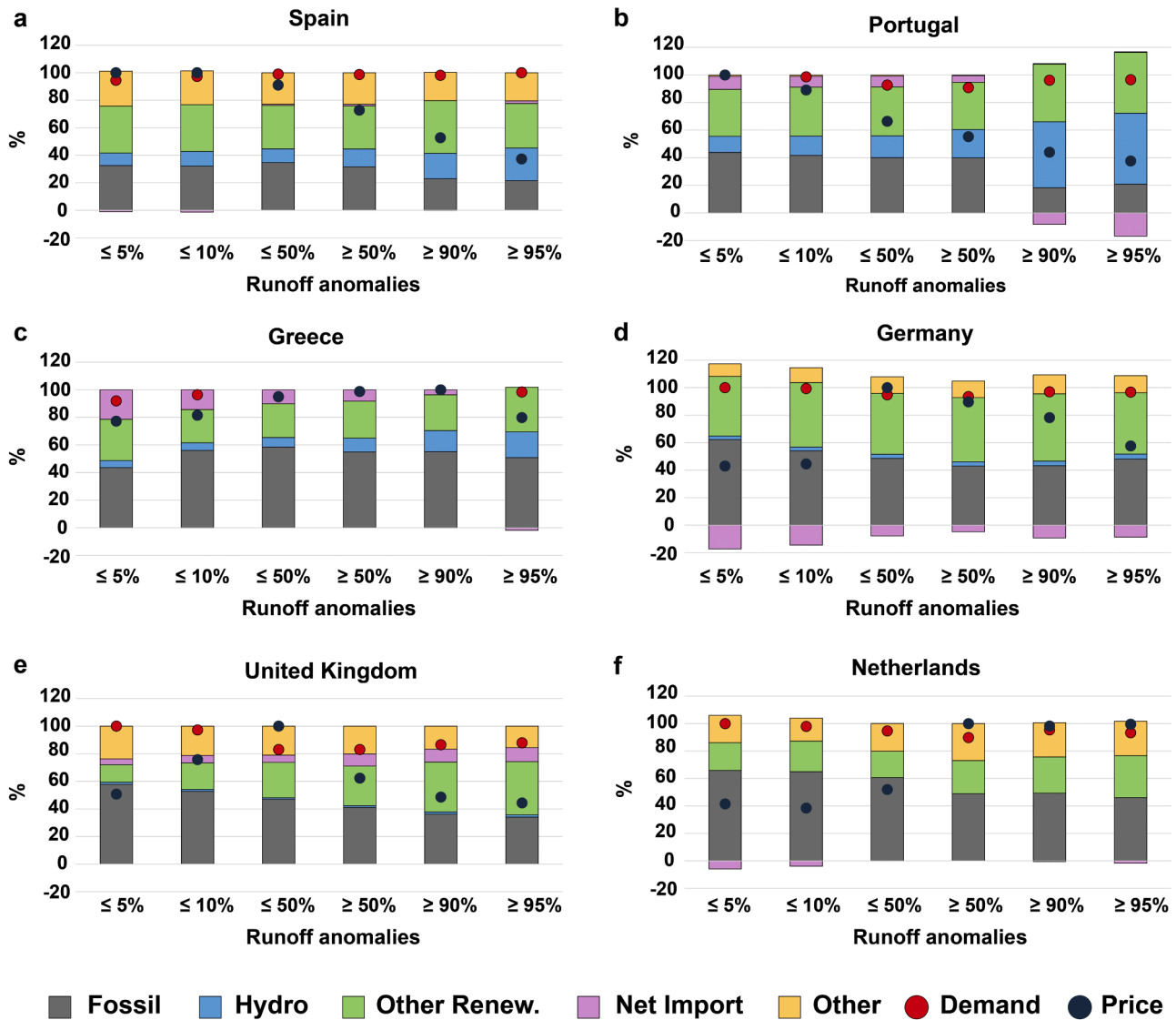
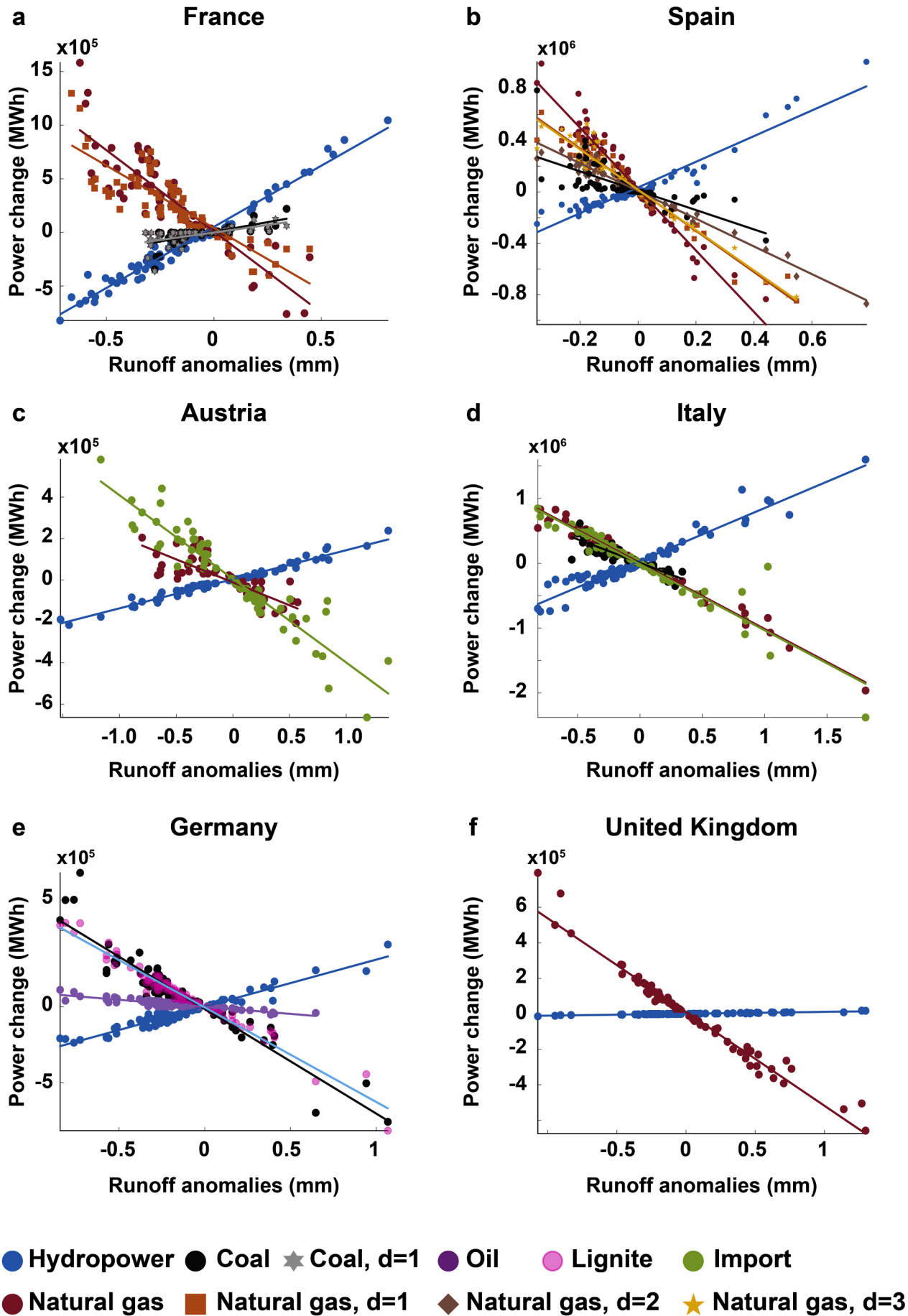


Fig. 3. Average electricity mixes, demand, and spot electricity price of selected European countries for the period 2017–2023 under different conditions of runoff anomalies. The percentile analysis shows the average power mix, demand, and price for the periods corresponding to runoff anomalies that are lower (or higher) than the indicated percentile threshold. Runoff anomalies smaller than the 50 percentiles generally refer to negative anomalies (drier conditions), and those higher than the 50 percentiles to positive anomalies (wetter conditions). Situations with runoff anomalies below the 10 percentiles can be interpreted as severely dry, and those above the 90 percentiles as severely wet. Electricity production sources are grouped into fossil (natural gas, coal, oil, lignite), hydropower, other renewables (offshore and onshore wind power, solar, and biofuels), net imports, and other (mainly nuclear power). Negative values of net imports indicate the country is a net exporter, positive values a net importer. Electricity demand and price are normalized to the highest value across all the percentile intervals of runoff anomalies in each country. The numerical results (average and standard deviations) are available in Table S3.

production changes to variations in runoff conditions. Statistical scores of model performances for each country and fuel type are available in Table S4 and the estimated regression coefficients with corresponding p-value in Table S5. Model performances and regression coefficients (with corresponding p-values) for the analysis of the delay effects are reported in Table S6 and S7, respectively. Model estimates are usually not significant when the specific fossil power source is a small share of the country electricity mix (e.g., mainly for oil, which only covers 0.6 % of the European electricity mix) or the data quality is low (e.g., missing data in the electricity generation timeseries, which mostly affect some Eastern European countries).

Relatively clear patterns emerge when plotting the estimated monthly-mean power changes as a function of runoff anomalies (Fig. 4). There is a sharp decrease in hydropower production with negative runoff anomalies, while electricity generation from natural gas increases. This is the case for France, Spain, Austria and Italy (Fig. 4a-d). A

delay effect in increased power production from natural gas is found in France up to 1 month and in Spain up to 3 months. This effect is gradually reduced when moving from month 1 to month 3. In Austria and Italy, imports of electricity from nearby countries also increase as a response to drought. Either increases or reductions in electricity production from solid fossil fuels can occur. A limited reduction in power production from coal is found in France (Fig. 4a) and Czechia, among others. The underlying reasons vary. In some cases, drought conditions reduce water availability for cooling, leading to curtailments at coal power plants [17,23]. In others, the need to compensate for reduced output from renewable sources may drive increased electricity generation from natural gas, making coal-based power generation less competitive or profitable [8,10]. The net results at a national level can be a balance of contrasting drivers across the power plants in the country that are affected in different ways. The use of coal and lignite generally increases in countries where power production from natural gas is a



(caption on next page)

Fig. 4. Estimated changes in power production for individual power source and selected countries due to runoff anomalies. The values indicate the amount of electricity generation that is attributed to runoff anomalies by the application of the regression-based model to France (a), Spain (b), Austria (c), Italy (d), Germany (e), and the United Kingdom (f). Delay effects are included ($d = 1$ for one month, $d = 2$ for two months, and $d = 3$ for three months are also shown). The statistical scores for the predicted estimates (the dots) per country and fossil energy source are available in Tables S4, and the standard errors of the predictions are used in Monte Carlo uncertainty analysis.

small share of the power mix (e.g., Germany, Fig. 4e), or where water shortages more severely affect basins for hydropower production than those for thermal power plants. For example, thermoelectric power plants in Germany and Denmark are usually connected to water resources that are less vulnerable to drought [23]. Power production from fossil sources increases at negative runoff anomalies also when national hydropower production is low or negligible, such as in Germany and UK (Fig. 4e,f). As discussed above, this can be connected to a decrease in production of electricity from other renewable sources (e.g., wind power) and increased opportunities for exports.

In the period 2017–2023, drier than average conditions induced a net increase of 180 ± 34.1 TWh of power production from fossil fuel sources in the investigated European countries, corresponding to 2.71 % of the total fossil power production (Table S12). Most of the power changes concern natural gas (125 ± 16.3 TWh), coal (26.9 ± 11.2 TWh), and lignite (26.1 ± 5.17 TWh), with smaller net changes for oil (2.6 ± 1.4 TWh). Delay effects contribute with about 42.1 TWh (23 % of the

total), and most of them (74 %) occur with one month of delay. These estimates are a combination of positive and negative effects. A change in power production from natural gas as a response to dry periods is observed in 14 countries, and the response is a positive increase in 12 of them. A net reduction in coal power is found in 3 out of 11 countries, for oil in 1 out of 4, and for lignite there are 4 countries with a positive increase. Electricity generation from natural gas typically has lower water demand than that from other fossil fuels, as the direct average water footprint in European power plants is $130 \text{ m}^3 \text{ TJ}^{-1}$ for natural gas, $437 \text{ m}^3 \text{ TJ}^{-1}$ for coal and lignite, and $175 \text{ m}^3 \text{ TJ}^{-1}$ for oil [52]. Coal and lignite plants with once through cooling are most impacted by water shortages, but also those with water recirculation are affected, despite requiring less water [17]. As such, the risks that their power production is curtailed in periods of drought are more frequent. Dry conditions also triggered an additional 39.5 ± 10.0 TWh of power imports, of which about 12.1 TWh derived from power plants based on fossil fuels. This makes the total fossil power generation induced by dry periods to rise to

Relative emission changes from drought

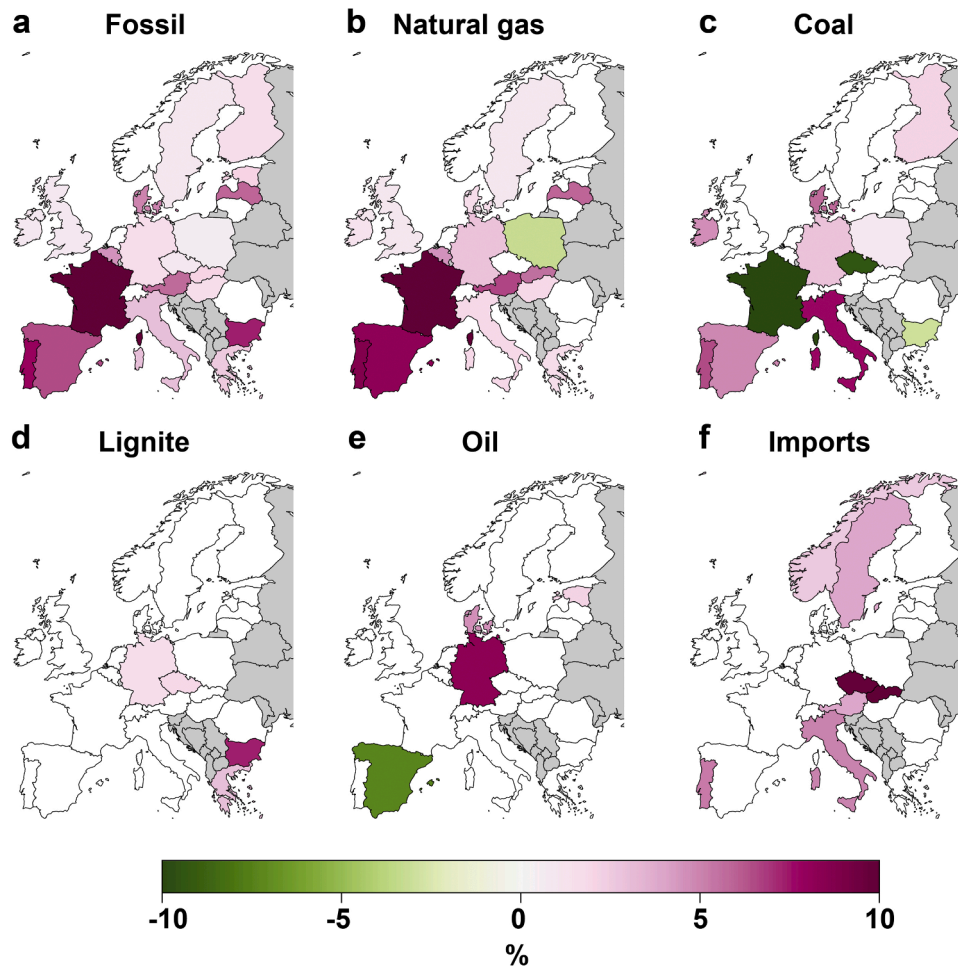


Fig. 5. Emissions of GHGs from thermal power plants induced by dry conditions in Europe. Maps show changes in emissions from power production during dry periods for electricity sourced from all fossil sources (a), natural gas (b), coal (c), lignite (d), oil (e), and imports (f). The changes are relative to the total emissions from the corresponding fossil fuel source in each country, or to the total imports. Positive values indicate an increase in emissions, negative values a decrease. Delay effects are included.

a mean estimate of 192 TWh (or 2.91 %).

These trends in the response of fossil power generation to dry conditions are largely explained with the evolutions of the national electricity mixes analyzed in Fig. 3 and 4. The need to compensate reductions in renewable energy production during dry periods appears as the main driver of the general increase in fossil power supply at negative runoff anomalies.

3.3. Drought-induced CO₂ emissions

The net changes in electricity production from fossil fuels due to drier periods lead to emissions of 141 ± 35.4 Mtonne CO₂-eq. (Figure S4), of which 130 ± 32.9 Mtonne CO₂-eq. are caused by domestic plants and 11.3 ± 2.47 Mtonne CO₂-eq. are embedded in imports. Relative to total emissions from fossil power plants, the largest drought-induced emissions are observed in France (+10.2 %), Portugal (+7.82 %), Bulgaria (+7.32 %), Spain (+6.48 %), and Austria (+5.72 %) (Fig. 5a). Delay effects contribute with about 24.1 MtCO₂-eq., which is about 17 % of the total. Emissions from natural gas power plants are 67.8 ± 11.5 Mtonne CO₂-eq., or about 48 % of the total induced emissions (while being about 64 % of the fossil-based power production change) (Fig. 5b). In France, emissions from natural gas that are induced by drought are about 18 % of the total. France exhibits the highest relative increase in fossil emissions under dry conditions probably because it is the country in Europe with the highest share of nuclear power in its mean electricity mix (71 %). Nuclear energy is essentially a base-load source of power, and it is usually operated at its maximum capacity most of the time. This means that it is unsuitable to respond to short-term fluctuations in demand or to complement temporary reductions in power supply from the other sources of the power mix. As such, natural gas is used to compensate for the shortages in hydropower production during dry periods. Relatively high emissions from natural gas during drought also occur in Portugal and Spain (9 % and 8 %, respectively). In Austria, Slovakia, Belgium, and Latvia, this value is between 4 % and 7 %. In Spain and Italy, the fractions are relatively small because these countries have a relatively large production of electricity from natural gas in their power mixes (42 % in Italy and 26 % in Spain), but in absolute terms their drought-induced emissions are around 9 Mtonne CO₂-eq. in Italy and 20 Mtonne CO₂-eq. in Spain, which are second only to those in France (around 22 Mtonne CO₂-eq.)

(Table S13–15). Coal power production is associated with net emissions of 30.6 ± 14.0 Mtonne CO₂-eq., with the highest relative increase in Italy (7.73 %), Portugal (6.47 %), Denmark (5.74 %), and Spain (4.88 %). Net emission reductions are mainly observed in Czechia (−9.38 %), and France (−5.80 %) (Fig. 5c). In absolute terms, the highest emissions from coal power occur in Germany (12.6 Mtonne CO₂-eq.), Italy (9.65 Mtonne CO₂-eq.), Spain (6.21 Mtonne CO₂-eq.) and Poland (around 4.11 Mtonne CO₂-eq. each). For lignite, drought-induced emissions are above 2 % of the total emissions in Bulgaria, Greece, and Czechia (Fig. 5d). More modest emissions are associated with oil, for which the largest contribution is from Germany (1.46 Mtonne CO₂-eq.) and Estonia (0.91 Mtonne CO₂-eq.), where electricity generation from oil represents 69 % of the national power mix (Fig. 5e). Countries where emissions embedded in increased electricity imports achieve the highest shares are Slovakia (10.1 %) and Czechia (9.84 %), followed by Portugal (5.30 %), Italy (5.06 %), Austria and Sweden (3.85 % each) (Fig. 5f). These emissions origin from fossil-based power plants in the countries from which electricity is imported (Table S8).

In terms of total emissions, the highest are in Germany (26.3 ± 5.86 Mtonne CO₂-eq.), where they represent about 40 % of all the drought-induced emissions from coal and lignite in Europe (Fig. 6 and Figure S5). After Germany, relatively high emissions are found in Spain (25.1 ± 5.78 Mtonne CO₂-eq.), Italy (19.0 ± 4.61 Mtonne CO₂-eq.), and France (16.5 ± 4.37 Mtonne CO₂-eq.). Together, these four countries are responsible for 62 % of the total drought-induced emissions in the investigated European countries.

The Monte Carlo uncertainty analysis shows that variability arising from the regression-based estimates of power changes is substantially larger than the uncertainty associated with emission factors (Supplementary Table S16). For total drought-induced CO₂ emissions in Europe, the two-standard-deviation range driven by power-change uncertainty is 32.9 MtCO₂-eq., whereas the range attributable to emission-factor variability is 10.6 MtCO₂-eq., corresponding to roughly 30 % of the former. Uncertainty in the estimated power response to drought is the dominant contributor to the overall variability in the emission estimates.

3.4. Drought-induced emissions of air pollutants

The estimated drought-induced emissions of air pollutants are 13.1 ± 4.32 ktonne of PM_{2.5}, 200 ± 72.8 ktonne of SO₂, 121 ± 43.9 ktonne

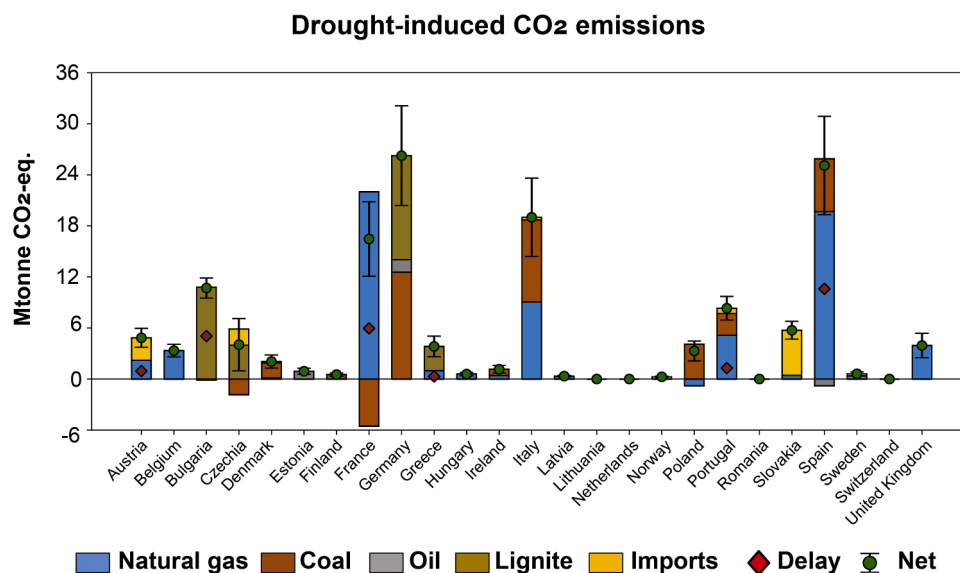


Fig. 6. Total drought-induced GHG emissions per country in (Mtonne CO₂-eq.). Positive values indicate an increase in emissions, negative values a decrease. Delay effects are included. The changes are relative to the total emissions from the corresponding fossil fuel source in each country, or to the total imports. Uncertainty ranges refer to two-standard deviation range around the mean from a Monte Carlo uncertainty analysis based on the standard errors of the estimated power change coefficients. Numerical values of the results are available in Tables S13–15.

of NO_x , and 3.47 ± 1.67 tonne of NH_3 (Fig. 7, Table S17). These emissions correspond to about 2.09 %, 2.32 %, 2.43 % and 2.59 %, respectively, of the total emissions of air pollutants for electricity production from fossil-based plants in Europe (Table S18). These results reflect both increases and decreases in emissions across countries and power sources in response to drought, influenced by emission factors that vary by power plant, energy type, and technology used in each country. Natural gas, which has the lowest emission rates of pollutants, generally increases while electricity production from coal and lignite is more sensitive to dry conditions and can decrease. Although the increase in power production from coal and lignite is about one fifth of that of natural gas, their individual total emissions are about 10 times higher for $\text{PM}_{2.5}$ and about 130 times higher for SO_2 (Table S19 and S20). This is because emission factors for these pollutants are, on average across European power plants, much higher for coal and lignite than natural gas per unit of electricity produced (e.g., 614 times higher for $\text{PM}_{2.5}$ and more than 1 000 times higher for SO_2 ; Table S21). Different power plant technologies and associated emission factors per country also play a role. For instance, Germany shows the highest drought-induced CO_2 emissions due to increased use of coal and lignite. However, it does not rank among the top three countries for $\text{PM}_{2.5}$ and SO_2 emissions, as its air pollutant emission factors are approximately one order of magnitude lower than the European average. As with CO_2 emissions, the uncertainty ranges linked to the regression-based estimates of power changes are larger than those associated with the emission factors of the different pollutants (Supplementary Table S16). The uncertainty attributable to emission-factor variability is substantially smaller (by 57 % for $\text{PM}_{2.5}$, 55 % for SO_2 , 44 % for NO_x , and 50 % for NH_3) than that from the

estimated power changes.

Most of $\text{PM}_{2.5}$ emissions are located in Bulgaria (27 %), Spain (20 %) and Italy (16 %) (Fig. 7a) and mainly originate from lignite plants in eastern European countries and from coal power plants in western countries (Fig. 7d). In France, emissions are negative because coal power production is reduced during dry periods, and these negative emissions from coal are higher than the emissions of $\text{PM}_{2.5}$ from increased use of natural gas. A similar pattern is followed by emissions of SO_2 (Fig. 7e), while the largest shares of emissions of NO_x occur in Spain (19 %), Germany (18 %), and Italy (15 %), and mainly originate from power plants running on coal and lignite (in Germany and other eastern European countries) (Fig. 7f). In general, the increase in emissions of air pollutants is mainly due to domestic use (80–83 %), followed by exports (9–11 %) and delay effects (5–9 %) (Table S22 and S22). In absolute terms, emissions associated with exports are relatively high in Germany, Czechia, and Poland, while delay effects are prominent in Bulgaria, Spain, and France. In relative terms, exports are above 75 % of the national drought-induced emissions of air pollutants in Slovakia, the Netherlands and Norway, while delay effects cause more than 50 % of emissions in Bulgaria, and France. If compared to the total national emissions of air pollutants due to electricity production from fossil sources (Table S18), the highest relative shares are found in Austria, Bulgaria, Denmark, Italy, and Portugal, where drought-induced emissions are around 6–7 % of total emissions. In France, the reduction in coal power production is equivalent to a decrease of $\text{PM}_{2.5}$ and SO_2 of about 13 %. For NO_x , the mean estimate also suggests a decrease, but the uncertainty range is relatively wide and crosses zero. This is primarily due to a simultaneous increase in power production from natural gas

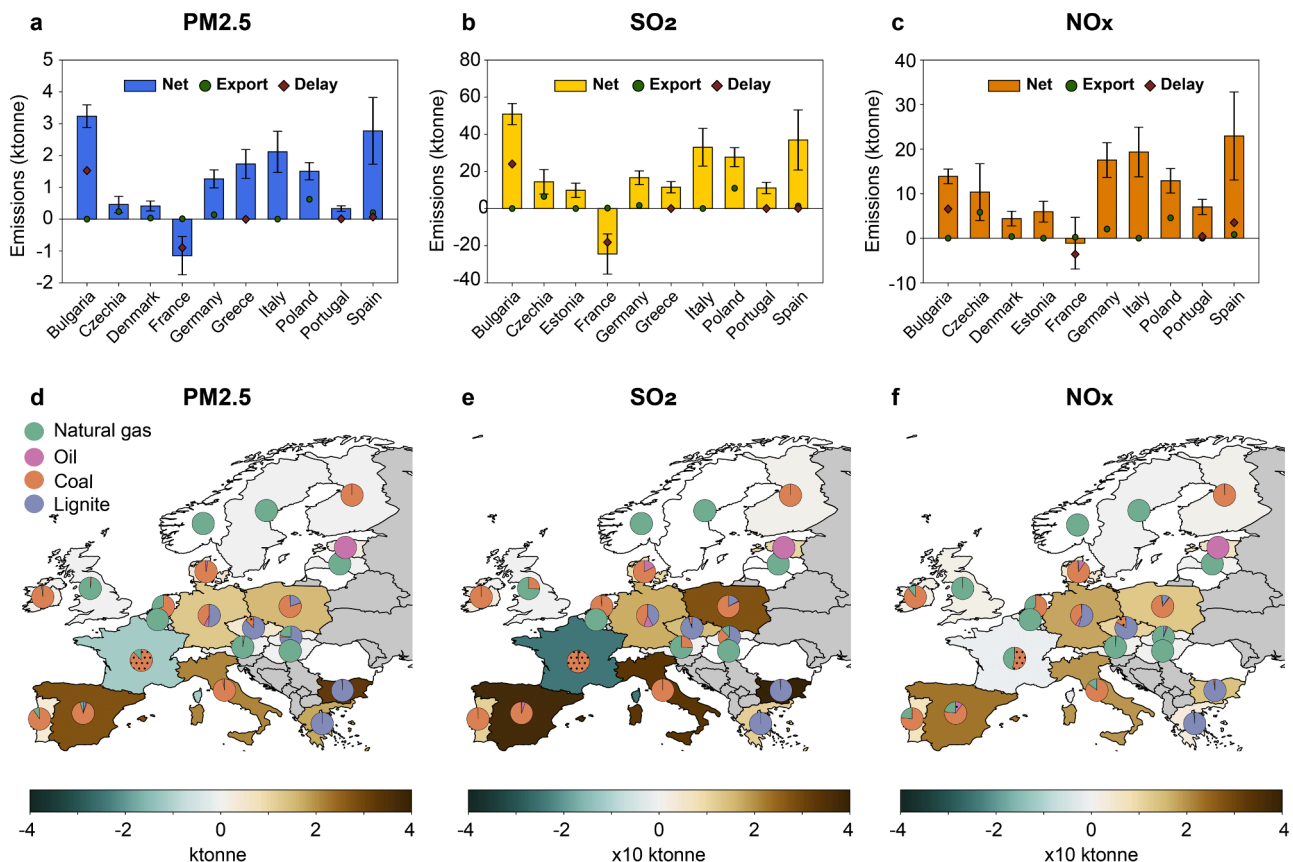


Fig. 7. Drought-induced emissions of air pollutants from fossil-based power plants for the period 2017–2023. Results show the impact of the 10 most emitting countries for $\text{PM}_{2.5}$ (a), SO_2 (b), and NO_x (c). The maps show the main source of emissions of $\text{PM}_{2.5}$ (d), SO_2 (e), and NO_x (f) per country: the color bar indicates the total emissions, and the pie chart the share of emitting power plant. Segments of the pie chart with black dots indicate that emissions are reduced for the corresponding pollutant and type of power source. Uncertainty ranges refer to two-standard deviation range around the mean from a Monte Carlo uncertainty analysis based on the standard errors of the estimated power change coefficients. Detailed results for all the investigated countries are available in Table S17, Table S19–S20, and Table S22–S23.

and a decline in coal power generation, with the natural gas increase that is approximately eight times larger in magnitude than the reduction in coal. Based on France-specific emission factors, NO_x emissions from coal are about nine times higher than those from natural gas per unit of electricity. Thus, while net mean NO_x emissions are negative, the increased use of natural gas and the associated uncertainty in its generation introduce larger uncertainty in the overall NO_x emission profile. The relatively larger NO_x uncertainty ranges for Czechia and Spain have a similar reason. Czechia has a decline in coal generation and an increase in natural gas, oil and lignite, while Spain has an increase in natural gas power generation and a decline in oil. In contrast, the differences for PM_{2.5} and SO₂ are much more pronounced: on average, coal emits roughly 59 times more PM_{2.5} and 960 times more SO₂ than natural gas. As a result, coal has a much stronger influence on the emission profiles of these pollutants. As a benchmark for the relevance in a context of emissions from other economic sectors, energy supply in Europe is responsible for about 20 % of emissions of NO_x (with road transport being the dominant source), 5 % of PM_{2.5} (dominated by the residential sector) and 60 % of emissions of SO_x [53]. Thus, changes in SO₂ emissions are the most relevant at a continental level.

Drought-induced emissions are found to cause a total damage of 5.24 ± 1.88 thousand DALY (disability-adjusted life years), corresponding to about 2.05 % of the impact from the fossil-based electricity sector in all the investigated countries (quantified to be 255 thousand DALY). The air pollutant contributing the most is NO_x (44 %), followed by SO₂ (36 %) and PM_{2.5} (20 %) (Table S24). The highest impacts are found in Germany (1.17 ± 0.26 thousand DALY), Italy (0.99 ± 0.30 thousand DALY), Bulgaria (0.83 ± 0.09 thousand DALY), Poland (0.70 ± 0.14 thousand DALY) and Spain (0.67 ± 0.28 thousand DALY). The net impact is negative in France (-0.41 ± 0.28 thousands DALY). Despite being 3.89 % of the total air pollutants in mass units, impacts on human health from PM_{2.5} are about one fifth of the total damage, indicating the high toxicity potential of this pollutant. Most of the drought-induced PM_{2.5} emissions occur in locations that are already today characterized by high exposure risks to fine particles, such as Germany, Poland, Italy and Bulgaria, thereby exacerbating the associated adverse effects.

4. Discussion

Our analysis shows how electricity production mixes in European countries respond to runoff anomalies and estimates the resulting emissions of fossil CO₂ and air pollutants during drier-than-average conditions over the 2017–2023 period (see Table 1 for a country-specific summary). In general, electricity generation from hydropower and other renewable sources decreases in drier periods, and fossil power production (especially from natural gas) increases to compensate. About 80 % of the investigated countries increase electricity production from fossil sources during drier conditions, and about 30 % increase imports. In some countries, power production from coal and lignite can decline during dry periods. At a European level, 141 ± 35.4 Mtonne CO₂-eq. emissions were induced by drier than average conditions from 2017 to 2023. This amount exceeds the total annual emissions from fossil fuel combustion in the Netherlands' energy sector (121 Mt CO₂-eq.) and represents approximately 31 % (4 % when averaged over the seven-year assessment period) of the net emissions projected to remain in Europe by 2040 under the ambitious target of reducing emissions to 90 % below 1990 levels [54]. Increased emissions from fossil power plants (including coal and lignite) in dry periods are also observed in countries with ambitious plans of coal-phase out and where coal power production has been on a remarkably decreasing trajectory in the last decade (e.g., Spain, Greece, or Germany) [55]. This indicates the challenge posed by drought to national decarbonization efforts and to the achievement of European mitigation goals. At the recent estimates of the social costs of CO₂, emissions from fossil-based power plants induced by dry conditions cause a mean monetized damage to human well-being of about 26 billion USD (6.22–58.3 billion USD as 5 %–95 % confidence range). Drought-induced effects on air pollution are 2–3 % of total fossil-based power sector emissions, but regional patterns and shifts in fuel use (such as reduced coal generation in France or increased use of lignite in Germany) lead to varied national impacts, with Bulgaria, Spain, and Italy showing the highest levels of PM_{2.5} emissions.

Overall, our findings are heavily data-oriented, constrained by observations, rely on robust statistical scores, and are in general agreement

Table 1

Summary table showing the drought-induced effects on electricity production from fossil fuels and associated emissions of GHGs and air pollutants per country. Trade and delay effects are included. Numbers refer to mean values. Uncertainty ranges for each country are available in the corresponding table in the supplementary information file.

	Power change TWh	GHGs MtonneCO ₂ -eq.	PM _{2.5} tonne	SO ₂ tonne	NO _x tonne	NH ₃ tonne
Austria	10.35	4.84	14.99	22.81	768.58	–
Belgium	6.33	3.34	19.50	22.72	1012.84	–
Bulgaria	9.42	10.69	3234.76	50,860.18	13,883.83	–
Czechia	6.96	4.04	460.94	14,426.14	10,368.06	0.01
Denmark	2.32	2.05	414.77	9184.35	4405.68	0.17
Estonia	1.77	0.91	200.76	9833.04	5958.47	2.47
Finland	0.61	0.52	15.33	731.87	346.03	–
France	38.11	16.46	–1146.06	–24,472.10	–1115.37	0.02
Germany	22.84	26.25	1265.49	16,591.26	17,551.56	1.56
Greece	1.71	3.83	1733.58	11,476.64	2567.37	–
Hungary	1.01	0.58	3.73	4.34	193.46	–
Ireland	0.66	1.15	130.31	2701.41	1197.65	–
Italy	37.20	19.01	2115.51	33,024.09	19,366.20	–
Latvia	0.75	0.34	2.24	2.61	116.40	–
Lithuania	–	–	–	–	–	–
Netherlands	–	–	0.32	7.46	14.75	–
Norway	1.57	0.26	0.11	0.13	5.70	–
Poland	2.31	3.31	1505.71	27,699.84	12,902.71	0.04
Portugal	14.06	8.32	332.47	11,068.33	7033.86	–
Romania	–	–	–	–	–	–
Slovakia	10.98	5.73	13.85	30.04	178.16	–
Spain	40.15	25.1	2775.20	36,941.38	22,956.83	–0.80
Sweden	4.04	0.61	1.74	2.03	90.58	–
Switzerland	–	–	–	–	–	–
UK	7.06	3.94	21.46	32.96	1096.85	–
Europe	220.20	141.3	13,116.72	200,191.53	120,900.22	3.47

with previous analyses. In the US, electricity production from natural gas was found to replace hampered generation from renewables during droughts, while the response of coal generation is more variable and depends on local conditions [7,15,27]. CO₂ emissions caused by drought are found to increase for all the investigated US states but one, with values ranging from −0.3 % up to above 12 % [7]. In the years affected by drought and heatwaves, the aggregated fossil power capacity factor at a European level increased from 1.8 % to 2.3 % [26]. Our study achieved comparable conclusions: a European average increase in fossil power production of 2.72 %, an average emission increase of 2.96 %, and emission increases from fossil sources that can be up to about 10 % in a country (e.g., France).

The main limitations and uncertainties of our analysis entail the quality and completeness of available electricity data, the statistical model used to estimate power production changes from fossil fuel plants under dry conditions, and the emission factors applied to the fossil-based power plants. These aspects are discussed in detail in a dedicated supplementary section (Text S3). Results are presented with uncertainty ranges derived from a Monte Carlo approach that incorporates the standard errors of the coefficients estimated from the regression model. These uncertainty ranges, which indicate two standard deviations, vary between 9 % and 47 % of the estimated mean values, averaging around 25 % at the European level. Uncertainty ranges arising from the estimated power changes are substantially larger than those associated with emission factors (averaged at 8 % for CO₂ and 14 % for the other pollutants), indicating that the regression-based power response to drought is the dominant source of variability in the total emission estimates. An additional sensitivity test was conducted with a policy dummy variable on the carbon price data, which reached unprecedentedly high levels by the end of 2020. To capture the potential structural change this may have induced in the power sector, a dummy variable with a value of 0 until December 2020 and 1 from January 2021 onwards was constructed and new model runs were conducted for major drought-sensitive electricity producers in Europe (France and Italy). The outcomes of these runs were in line with those without the carbon price variable, varying between −2 % for natural gas in Italy and +3 % for natural gas in France. The results remained robust even for additional tests where the start month of the dummy variable was progressively shifted forward by up to three months.

Consistently with previous studies [7,14,16], the regression framework is constructed to quantify the changes in fossil power production under drier than average conditions, including controls for demand, renewable availability, fossil fuel prices, carbon prices, nuclear power generation, and monthly indicators and year, which collectively absorb major long-term trends, monthly patterns, and fuel price fluctuations in each country. Individual country-specific policies and structural changes (e.g., coal phase-out announcements, regulatory reforms) are not explicitly modelled, but the analysis includes their cumulative effects during the assessment period. Incorporating detailed information on individual policy measures requires dedicated policy-evaluation studies, which is unfeasible given the scale and objectives of this analysis. Multiple policies operate simultaneously across different administrative levels and energy sources within each country, and their combined influence is already reflected in the observed power-system behavior. Our conclusions remain explicitly constrained to the 2017–2023 system configuration and are not to be extrapolated beyond this period or intended as forecast. Our analysis does not attempt to characterize individual plant behavior, something already investigated in previous studies [23]; instead, it estimates the net, system-level reaction of each national electricity mix to dry conditions. Although country-level aggregation naturally masks some plant-level heterogeneity, this does not affect the validity of the results. Finer operational dynamics may vary across plants, but their net effect is captured in the aggregated national response because all plants (including hydropower, fossil units, and renewables) are implicitly represented through their contribution to aggregated generation.

Our results highlight the need for targeted adaptation measures that directly address the physical mechanisms through which hydrological deficits propagate into the power system. Options exist for the demand and supply side. First, demand-response and end use flexibility provide technically mature means of reducing peak load during periods of constrained hydropower availability or thermal derating. Recent deployments in France and the Nordic region demonstrate that automated demand-response platforms and industrial interruptible-load contracts can deliver 2–5 GW of short-term load flexibility during extreme events [17,56]. Second, cross-border interconnector reinforcement has demonstrably increased the system's ability to absorb regional hydro deficits. The NordLink (between Norway and Germany) and North Sea Link (between Norway and the UK) increased transfer capacity into continental Europe by more than 2.8 GW, improving frequency stability and reducing price volatility during the 2021–2022 Scandinavian runoff reductions. Further cross-border interconnector expansion will help to redistribute surplus from stable or renewable-rich areas to drought-affected regions, thus enhancing system resilience at a continental level. On the supply side, flexible mid-merit gas generation retained as reserve (not baseload) can buffer temporary water-shortfalls [57,58], provided emissions are tightly regulated and ideally coupled with carbon capture and storage. Expanding the use of battery storage and green hydrogen offers an important opportunity to absorb surplus electricity during periods of high renewable generation and redeploy it during hydropower shortages, thereby reducing reliance on fossil-based backup generation and enhancing system resilience [59,60]. Drought-induced generation losses in thermal plants can be mitigated through water-efficient cooling technologies, including dry cooling, hybrid cooling, and reduced water-intake retrofits. Hybrid systems can significantly reduce cooling-water dependence, decreasing vulnerability to river-temperature thresholds and low-flow restrictions [13].

Adaptation options inevitably involve some potential trade-offs and cost considerations. Strengthening thermal backup capacity or expanding interconnectors requires capital investment and may carry environmental or social implications. Conversely, sole reliance on fossil backup during drought periods generates emissions and undermines mitigation efforts. Effective adaptation will require balancing these trade-offs through coordinated policy planning that considers both short-term system security and long-term decarbonization commitments. Integrating hydrological risk into market design, resilience planning, and investment frameworks can reduce the likelihood of drought-induced emission spikes while maintaining affordability and reliability.

5. Conclusions

This study shows the changes observed in the power mix, power trade and carbon intensity of electricity in European countries during periods of drought. These results have direct implications for energy and climate policy in Europe. First, the finding that drought systematically increases fossil-based generation highlights the need for policies that enhance system flexibility while increasing shares of renewables in their power mix and reduce dependence on hydropower during low-runoff periods. This implies integration of hydrological variability into national climate and energy planning frameworks. Second, the observed drought-induced increases in fossil generation, and associated emissions of GHGs and air-pollutants, underscore the importance of diversifying low-carbon flexibility sources, including long-duration storage, geographically distributed renewables, and cross-border balancing. Together, these strategies can reduce the risk of drought-induced emission spikes and strengthen the resilience of Europe's decarbonizing electricity system, consistent with the growing threat that climate-driven extremes represent to operational and environmental risk of renewable energy systems. In the near term, countries can prioritize options that are already technically mature and deployable within existing market structures, such as improving hydropower scheduling

under low-flow conditions, enhancing cross-border balancing arrangements, and expanding demand-response programs to reduce peak reliance on fossil generation during drought episodes. These measures do not require large structural changes to the electricity sector and can be implemented incrementally, offering rapid resilience gains. Medium-term investments, such as reinforcing interconnection capacity, diversifying the flexibility portfolio, and modernizing thermal and hydropower assets, can be prioritized based on the country-specific vulnerabilities revealed in our analysis. In absence of actions, the vulnerability of the electricity system will exacerbate as periods of water shortages are projected to increase with ongoing global warming and increased reliance on renewable energy generation sources in national power mixes. Effective achievement of energy security and decarbonization goals requires timely implementation of solutions to address these issues.

Data availability

Electricity system data are available from the ENTSO-E Transparency Platform (<https://transparency.entsoe.eu/>). Climatological data are available from the Copernicus Climate Data Store ERA5-Land (<https://cds.climate.copernicus.eu/datasets/reanalysis-era5-land?tab=download>). Emission factors and tabularized outcomes of the analysis are available in the Supplementary Information file.

Code availability

A code to reproduce the regression analysis is available as a supplementary file.

CRediT authorship contribution statement

Xiangping Hu: Writing – review & editing, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Vedant Ballal:** Writing – review & editing, Visualization, Investigation, Data curation. **Gabriele Martinelli:** Writing – review & editing, Data curation. **Geir-Arne Fuglstad:** Writing – review & editing, Methodology, Investigation. **Alessandro Nocente:** Writing – review & editing, Data curation. **Roberto Iacono:** Writing – review & editing, Investigation, Data curation. **Bo Huang:** Visualization, Data curation. **Francesco Cherubini:** Writing – original draft, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

Authors declare no competing financial interests.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.nexus.2026.100652](https://doi.org/10.1016/j.nexus.2026.100652).

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